INVESTIGATION OF SKIN TRIBOLOGY AND ITS EFFECTS ON COEFFICIENT OF FRICTION AND OTHER TACTILE ATTRIBUTES INVOLVING POLYMER APPLICATIONS

A Thesis

by

MATTHEW AGUIRRE DARDEN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2010

Major Subject: Mechanical Engineering

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Approved by:

Chair of Committee,	Christian Schwartz
Committee Members,	Yoonsuck Choe
	Hung-Jue Sue
Head of Department,	Dennis O'Neal

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ABSTRACT

Investigation of Skin Tribology and Its Effects on Coefficient of Friction and Other Tactile Attributes Involving Polymer Applications. (December 2010)

Matthew Aguirre Darden, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Christian J. Schwartz

Perception and sense of touch are extremely important factors in design, but until recently, the exploration of skin tribology related to tactility has been relatively untouched. In this emergence, skin-on-polymer interactions are becoming more widely investigated due to the prevalence of polymers in everyday life, and the ability to define these interactions in terms of tactility would be hugely beneficial to the engineering and design process.

Previous work has investigated polymer textiles concerning tactility, examining environmental and material properties that affect skin on fabric coefficient of friction. In this study, similar friction procedure was used to compare coefficients of friction of a fingerpad across varying polymer fabrics. Forces were applied in both longitudinal and lateral directions, and it was discovered that force directionality greatly affects coefficient of friction. Specific causes have yet to be determined, but it is suspected that material weave and microscopic surface properties play a major role in this directional behavior. To complement these studies and relate them to tactility, trained human evaluators rated the samples against four tactile attributes: abrasiveness, slipperiness,

sensible texture, and fuzziness. These ballots were then analyzed with Quantitative Data Analysis and shown to be repeatable among the participants, and each of the attributes were shown to be statistically independent of coefficient of friction. It should be noted, however, that fuzziness showed the greatest correlation coefficient of R^2=0.27.

Material selection plays an integral role in frictional behavior, and researchers have been studying contact theory on both microscopic and macroscopic levels to determine how surface topography affects skin-polymer tribology. To negate material effects discussed in the Greenwood-Williamson contact model, frictional tests were performed on identical polypropylene plaques with textured grooves of varying dimensions. Both geometry and directionality proved to be major frictional contributors; as groove size increased, finger friction in the longitudinal direction decreased, but friction increased laterally. In addition to testing a fingerpad, friction was measured with a silicone wand to simulate a finger with different material properties. The silicone exhibited the opposite trend as skin; as groove width decreased, frictional forces increased longitudinally and decreased laterally. While topography affects frictional behavior, counterface stiffness, and intrinsic material properties may cause the trend shift between skin and silicone.

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NOMENCLATURE

COF	Coefficient of friction
μ	Also coefficient of friction
QDA	Quantitative data analysis
μm	Micrometers
mm	Millimeter
in.	Inch
s	Second
Hz	Hertz
V	Volt
N	Newton
μ_a	Adhesive coefficient of friction
μ_d	Deformation coefficient of friction
μ_g	Grazing coefficient of friction
θ	Angle of attack

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CHAPTER I

INTRODUCTION

The most fundamental interaction between a user and a product is physical touch. In fact, a significant amount of the perceived value of a product results from the initial touch experience by the potential customer, whether the product is an automobile interior or a portable music player. Therefore, the ability to engineer a product's tactile characteristics to produce favorable sensory perceptions has the potential to revolutionize product design. Another major consideration is the potential for products to produce friction-induced injuries to skin such as blistering. Much research has investigated skin tribology with regards to coefficient of friction, perceived surface roughness, and other tactile attributes, but investigations are beginning to reveal that skin-surface contact is an extremely complex process. Progress in this field has been hindered by the difficulties in drawing correlations between human sensory outcomes (e.g. softness, smoothness, leather-like feel) and quantitative physical properties (e.g. friction coefficient, elastic modulus).

This thesis aims to investigate the effect of coefficient of friction of skin on polymer surfaces for different polymer applications where tactility plays a key role. In the first study, a framework is proposed to address this issue with regards to polymer fabrics, which are used everywhere from clothing to protective wound-care. Human evaluators were used to identify four specific tactile attributes of fabric materials—

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This thesis follows the style of Wear.

sensible texture, abrasiveness, slipperiness, and fuzziness. The friction coefficients of the same fabrics against skin were measured to examine a potential relationship with the tactile descriptors.

Primary friction theory discusses the impact of contact area, material properties, and surface geometries on a microscopic level. Little has been done to see how macroscopic surface textures and geometries influence coefficient of friction in large scale tribological settings. The second study focuses on relating coefficient of friction of skin on simply textured polypropylene samples consisting of repeated ridges and grooves of varying dimensions. The concept of a macroscopic component of friction, or grazing coefficient of friction, μ_g is proposed. A secondary counterface, a silicone tipped probe, was also used to see how different materials of similar mechanical behavior compare with regards to the grazing coefficient.

CHAPTER II

INVESTIGATION OF SKIN TRIBOLOGY AND ITS EFFECTS ON TACTILE ATTRIBUTES OF POLYMER FABRICS

2.1 INTRODUCTION

One of the most fundamental interactions made with a product is that of touch. A great deal of the perceived value of the product depends on its sensory attractiveness. However, it has been extremely challenging for firms to optimize the tactile attributes of their products because little systematic work on correlating tactility with material parameters has been published. A key challenge in this pursuit is the complexity of the somatosensory system and human perception, and as such, both microscopic and macroscopic scales must be considered. Due to the prominence of the interactions between human skin and textiles, polymer fabrics have been an area of focus for studying perception [1-6]. Qualitative descriptors of fabrics have been described by researchers, and include softness, scratchiness, smoothness, or pleasantness [6]. To make matters more complex, societal factors have led to multiple paradigms as to what is comfortable or unpleasant [1, 2, 4-7]. It is therefore obvious, that the fabric and fiber producer requires a more quantitative set of models to affect tactile parameters at a materials and processing level.

Currently, many manufacturers have limited technical knowledge of how specific material properties affect skin tribology and tactile attributes. In large part, the appropriate manufacturing and material parameters to produce acceptable tactility in a particular product are found through an iterative optimization procedure, without model-based reasoning to guide the procedure [1]. One method of investigating skin-on-fabric interactions has been the measurement of friction coefficient [2, 4, 5, 7, 8]. This work has not been limited to hands and fingers, but rather the interaction with large contact areas such as forearms [7, 8], and subsequent rating of a degree of tactile agreeability of the material. Empirical studies have shown that friction coefficients during skin-to-fabric contact are virtually independent of load applied [2], but dependent on the level of moisture of the surfaces [4, 5]. This indicates some of the sources of variation in results that have been reported in the literature. However, it also suggests that the measurement of friction coefficient along with fabric weave parameters, fiber sizes, and material composition may provide the necessary foundation to developing a reliable model for efficiently optimizing a specific tactile attribute. With the ability to engineer fabrics to exhibit desired tactile properties, firms could specifically functionalize fabrics for a multitude of applications. Examples include sports applications, automotive interior materials, simulated leather products, and even medical consumables such as gauze and wraps for various skin conditions [2, 8].

One of the greatest challenges in studying human sensory perception of a material is being able to describe and quantify the sensation in a manner that allows for a normalization of results for a large group of evaluators. This problem is twofold: metrics must be identified that have the same concrete meaning to various evaluators, and a quantitative scale must be established to assign a value to the fabric with respect to a particular metric. Techniques have been developed, largely in the arena of food evaluation, to produce quantitative and translational metrics for qualitative sensory assessments. One such technique is termed Quantitative Descriptive Analysis (QDA) and has been successfully implemented in a number of studies involving sensory evaluation [9]. With QDA, a panel of evaluators that are familiar with a particular class of product identifies a number of well-defined descriptors that describe an aspect of the sensory experience with the product class, and they agree on particular products within the class that exemplify "low" and "high" values for these descriptors. These descriptors can then be used to train to other evaluators if required. Because QDA produces quantitative results, outcomes can be analyzed using standard statistical techniques such as analysis of variance and other means of statistics [9].

Methodologies for sensory evaluation, such as those related to tactile behavior, must pay particular attention to the influence of auxiliary human senses that are not directly of interest. This is the case with regards to visual bias in tactile research. Investigators have reported that if not closely controlled, visual cues take precedence over the other senses. Ramachandran and Rogers- Ramachandran describe an early experiment, where visual bias produced by seeing an object will dominate the sensory evaluation regardless of tactile variations between materials [10]. Confounding this issue however, Yenket and Gatewood tested this concept with regards to fabrics, with a study to determine the impact of fabric color on the way consumers perceive the tactile attributes of the fabric. They concluded that material color does not influence the way a material feels. They further conclude that vision as a whole does not have a significant effect on the way individuals describe sample feel [11]. There is concern with the study that there was not significant use of control groups in a blind situation to draw such far-reaching conclusions. What these contradictory results suggest is that it is mandatory in tactile investigation that the effects of visual bias be accounted for and minimized when possible.

The purpose of this investigation was to determine if coefficient of friction can be used as a metric to characterize various commercially available polymer-based fabrics and to identify useful tactile descriptors for such materials. Another aspect of the work was to begin to determine if any correlations could be identified with friction coefficient and the sensory descriptors that might lead to a predictive model in the long term. The study involved both human evaluators and instrumentation-based research in order to accomplish these objectives. Furthermore, the study involved a model of a useful protocol for performing future tactile research.

2.2 MATERIALS AND METHODS

2.2.1 Fabric samples

Fourteen commercially available fabrics of varying compositions were used in this study to determine descriptors for tactility. These materials were chosen to enable a diversity of material types, blend ratios, and weave styles. Commercial descriptions for each material, with appropriate materials balance, can be found in Table 1. One sample of interest, nylon fabric, is shown at two magnifications (Figs. 1 and 2) to illustrate a simple weave pattern and representative directionality of the fabrics.

Table 1. Descriptions of fabric samples experimented.

Sample	Description
A	100% Satin, knit acetate
B	90% Polyester, 10% Spandex (Synthetic Velvet)
C	65% Polyester, 12% Wool, 8% Rayon, 8% Acrylic, 6% Cotton, 1% Metallic
D	100% Nylon
E	100% Cotton (Denim)
F	100% Cotton (T-shirt knit)
G	100% Polyester (Bed linen)
H	65% Polyester, 35% Cotton (Broad Cloth)
I	50% Polyester, 50% Cotton
J	100% Polyester (Costume Satin)
K	Textured velvet blend with unknown fibers
L	Corduroy
M	100% Polyester (Suede)
N	100% Polyester (Shawl knit)

Each of these materials exhibit topographic directions that can be discerned by either the senses of sight or touch. This directionality can be visible on the microscopic level for some specimens, or macroscopically for others. Samples D (nylon) and L (corduroy) can be seen in Figures 1 and 2 with their directionality clearly evident.

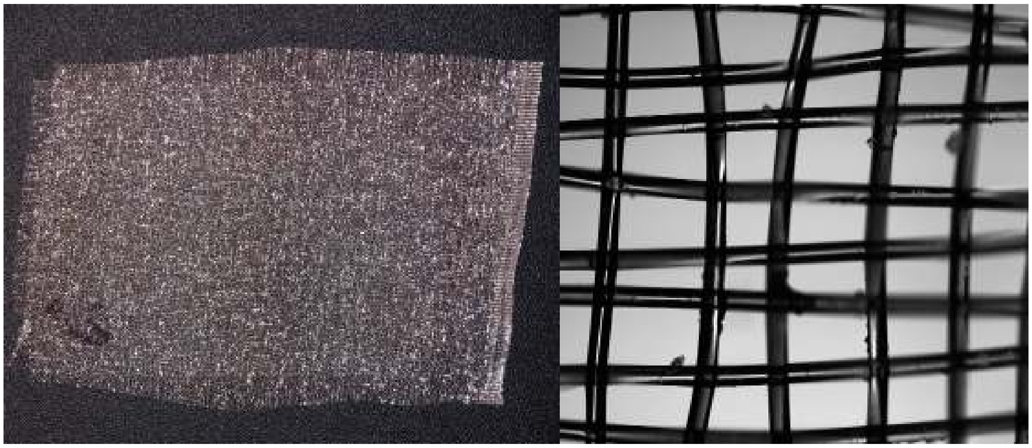

Figure 1. Representative swatches of nylon (sample D) at (a) low and (b) magnifications.

Figure 2 Representative swatch of corduroy (sample L), showing the ribbed directionality.

2.2.2. Human sensory evaluation

2.2.2.1 Quantitative data analysis

One emphasis in this investigation was to determine if quality tactile data could be acquired from a panel whose membership may change over time, so long as appropriate training and benchmarks are given during the studies. Therefore, a panel of untrained evaluators convened to determine appropriate descriptors for these polymer fabrics. This process involved individuals feeling each of the fourteen samples and writing qualitative descriptions for notable sensations such as texture or slip. When the panel was convened, similarities in the individual lists were identified and discussed until the entire panel could clearly define a number of descriptors and agree upon which of the fabrics represented low and high amounts of a particular descriptor. The following tactile descriptors were identified: (a) abrasiveness, which is the degree to which the material feels to have a sharpness or damage potential while sliding against a fingertip, (b) fuzziness, which describes the feeling that the material has fibers that radiate normal to the fabric surface, (c) sensible texture, which is the degree to which the fabric feels that it has texture instead of being a smooth homogeneous solid, and (d) slipperiness, which is the perceived amount of friction required to slide the fingertip across the fabric.

Sensory evaluators involved in this study were comprised of both male and female participants of varying ages, who were not part of the original panel that convened to identify the descriptors. None had previous training in sensory evaluation but were guided by the investigators in following the QDA process. A ballot was created for evaluators to score samples with respect to assigned descriptors. The ballot consisted of a horizontal line with a minimum and maximum tick mark, with the left vertical bar signifying the minimum and the right vertical bar the maximum (Fig. 3) [9, 12]. To avoid confusion regarding the ballots, the ends of the spectrum were labeled with both the descriptor of interest and the respective fabrics that were chosen to represent the maximum and minimum. The distance between the two vertical lines measured 120mm

(4.72 in.), and the evaluator was instructed to indicate on the spectrum with a single vertical marking the appropriate position relative to the extremes that would describe the specific fabric being assessed. The distance between the evaluator's mark and the minimum was measured and represented the score of the particular sample with respect to the descriptor of interest. Evaluators were initially given pre-assigned calibration fabrics to indicate benchmarks for both the minimum and maximum extremes of each descriptor under investigation. They were permitted to handle and examine the benchmark samples at any point in the procedure. The designated minima and maxima for abrasiveness, fuzziness, sensible texture, and slipperiness were samples J/E, D/B, I/L, and E/J, respectively.

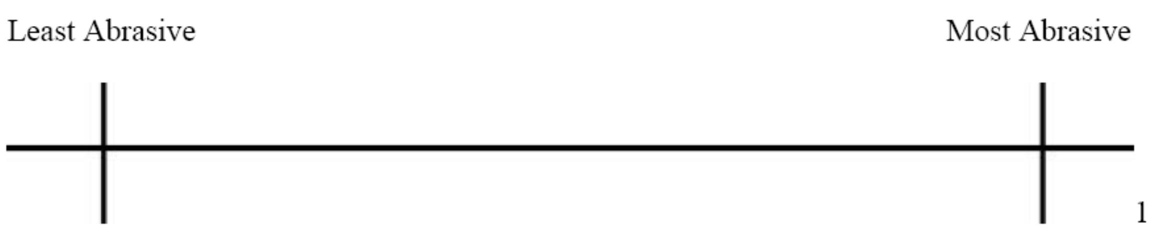

Figure 3. Example of ballot used for human sensory evaluations.

2.2.2.2 Testing apparatus and evaluations

Swatches of each of the fourteen samples measuring approximately 8 cm×8 cm in size were used for human evaluations. A shielding cover was fabricated to prevent the participant from seeing the samples being evaluated and thus eliminate the possibility of visual bias affecting the results. This is shown in Fig. 4.

Figure 4. Cover used for sensory testing, preventing the individual from viewing the sample. Manipulation of fabrics was performed under the cover and thus concealed from sight.

To avoid fatigue, each participant assessed only two descriptors of the four: either abrasiveness and sensible texture, or fuzziness and slipperiness. Once the respective descriptors were introduced and defined, the evaluator placed his/her hands into the shielding cover until their hands could not be seen. Seven of the fourteen samples were selected by the investigators to be scored with respect to each descriptor, and each fabric sample was encountered three times during an evaluation session per descriptor. Evaluators were handed samples in a random order from the opposite side of the cover by the facilitator. Each sample was placed flat on the table under the cover, and the evaluator was only allowed to feel a designated “front” side and could not pick up the sample. After each sample was encountered, the sample was scored using the ballot procedure described above. Following evaluation, data was organized and analyzed using fundamental statistical methods.

2.2.3 Friction measurement

2.2.3.1 Sample preparation

To account for the directionality evident in each of the fabrics, two orientations were defined: one designated as "parallel", and the orthogonal direction as "perpendicular." In readying the samples, all fourteen were cut into 6 cm×6 cm squares. Using rubber cement adhesive, the samples were mounted to rigid polyethylene plates in a 3×1 configuration (Fig. 5) for connection to a three-axis dynamometer. During application, the adhesive was applied directly to the plate and allowed to cure for approximately 15 s before placing the sample. This provided sufficient time for the cement to partially cure and avoid penetration of the porous fabrics. Two sets of mounted samples were produced, one each for parallel and perpendicular testing.

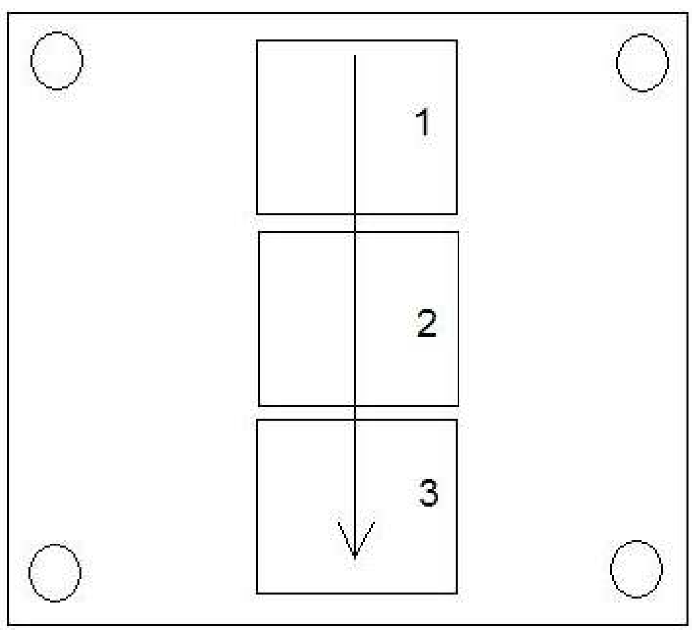

Figure 5. Arrangement of samples on a polyethylene plate for friction testing.

Sample B (synthetic velvet) had a distinctive fiber arrangement that was significantly different from the rest of the samples. It was composed of tufts of fibers affixed at their base to the fabric, as shown in Fig. 6. There was visual evidence of a preferred direction of leaning of these tufts. Therefore, the parallel and perpendicular orientations for this fabric were defined with respect to the visual indication of directionality.

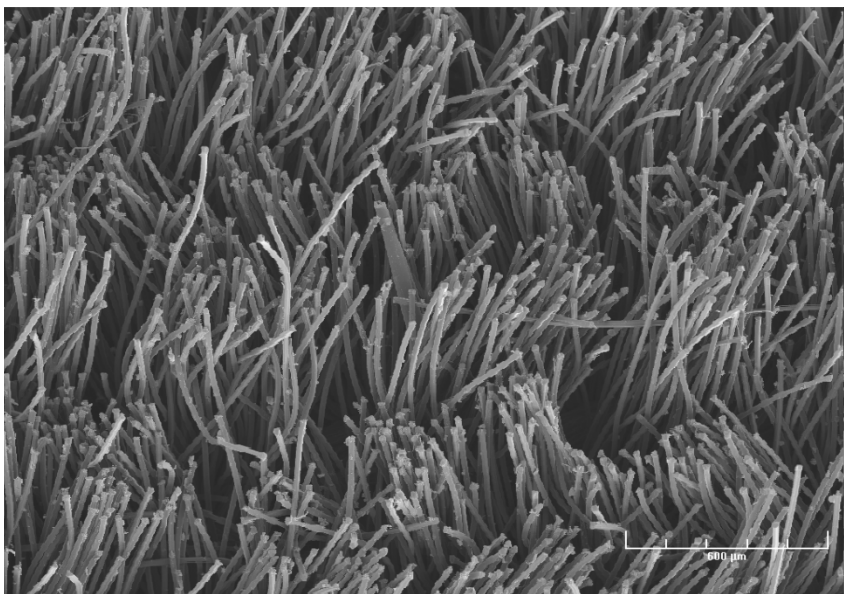

Figure 6. Tufted structure of synthetic velvet (sample B). Bar is 600 µm.

2.2.3.1 Coefficient of friction measurement

The coefficient of friction of a fingertip sliding against each fabric sample in a particular orientation was determined by recording the normal and shear forces produced during a finger swipe against the sample. Forces were measured using a three-axis dynamometer and amplifier (Kistler 9254, Fig. 7) and exported to a data acquisition system. Previous work has shown that moisture can have a significant effect on a friction coefficient [5, 7, 8] of a material against skin. To minimize the potential effects of skin moisture and operator error, one investigator conducted all of the finger swipes under consistent conditions of humidity, temperature and hand cleanliness. Data were taken at a sampling rate of 100Hz and written to data files for processing and analysis. To minimize noise, a low-pass hardware filter was constructed for the input channels providing a cutoff frequency of 6.9 Hz.

Figure 7. Kistler 9254 three-component dynamometer.

The populated polyethylene mounting plates were mounted to the dynamometer in a random sequence based on the experimental design. For each sample, the operator used the right index finger and made three swipes across the sample along the longitudinal axis of the dynamometer. Each individual sample was measured four times for friction with respect to each orientation. A data acquisition software program was written to conditionally record data only when the normal force exceeded 0.6 N. This prevented the dynamometer from recording non-essential data points detected at zero load. For the calculation of friction coefficient, the maximum normal force for each swipe was identified, and all data points that exceeded 90% of the maximum were collected. The tangential force data that correlated to these collected normal force data were then used to calculate friction coefficient. Analysis of variance with post hoc analysis was applied to the data in order to determine whether sample type and orientation had an observable effect on friction coefficient. Furthermore, these methods were also used to determine whether friction coefficient was an indicator of the fabric attributes with respect to the QDA descriptors. Student t-tests were also used to compare selected means in order to draw conclusions about the results.

2.3 RESULTS AND DISCUSSION

2.3.1 Human evaluations

Because of the measuring instruments available to the researchers, English units were used in the measurement of the attribute ballots, therefore the maximum possible value for a material with respect to any of the attributes was 4.72. The results of human evaluation with respect to abrasiveness are shown in Fig. 8. It is shown in the figure that the selected extremes of the descriptor, samples J and E (costume satin and denim),were indeed assessed as the fabrics with the lowest and highest abrasiveness, respectively. Furthermore, this data, along with previous experiments, show that human assessment can be represented in quantitative terms allowing for statistical analysis [13].

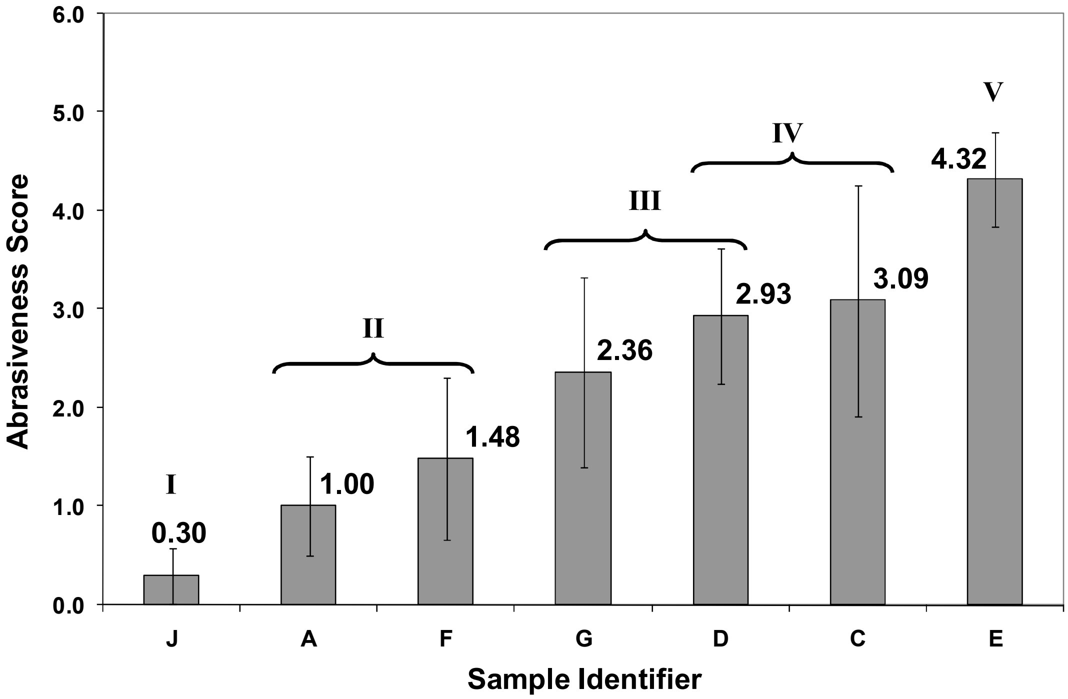

Figure 8. Abrasiveness scores assigned by evaluators for seven samples (n=18). Error bars represent one standard deviation for each side of the mean. Roman numerals indicate subgroups with statistically similar means identified by Tukey post hoc analysis at 95% confidence.

Tukey's post hoc analysis produced five subcategories of abrasiveness, shown in the figure, and thus indicates that the evaluators were reliably discerning among the materials with regards to abrasiveness. Fig. 9 shows the fuzziness results. The data show again the selected extremes (nylon and synthetic velvet) were evaluated as such, but also that no difference could be established in fuzziness between nylon and broad cloth (sample H). This highlights one of two possibilities. Either the sensitivity of human evaluators is not sufficient to discern the minimal fuzziness of these two materials, or there is in reality no difference with respect to this descriptor. This may indicate that a more precise definition of fuzziness will be required in future work.

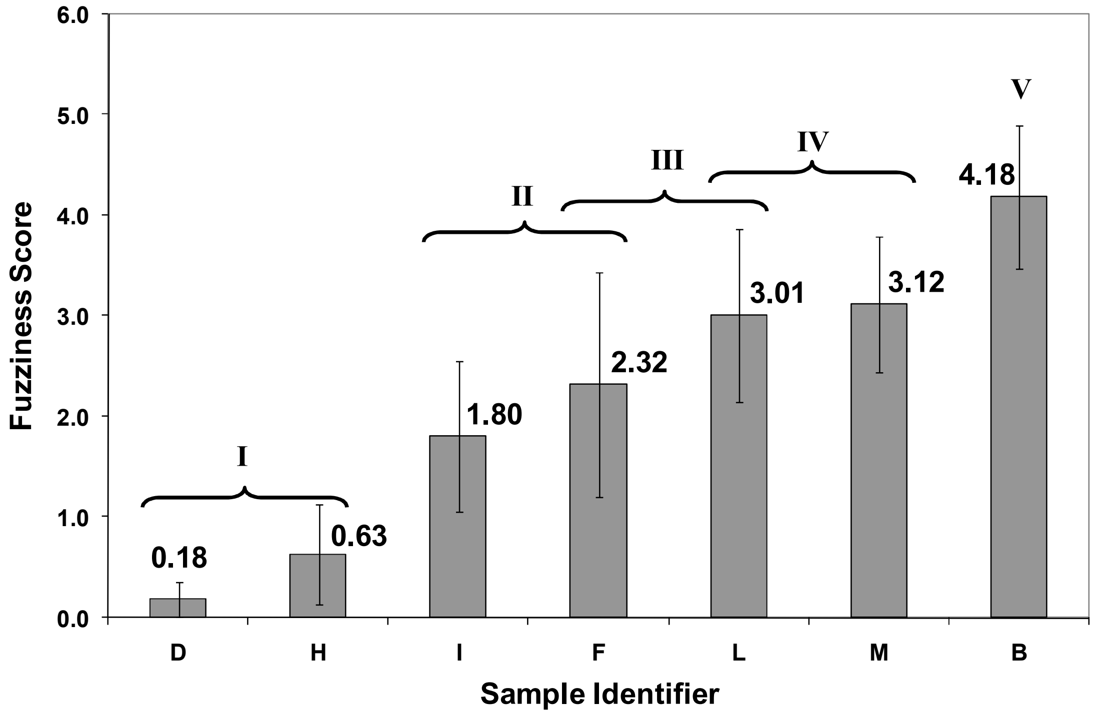

Figure 9. Fuzziness scores assigned by evaluators for seven samples (n=18). Subgroups indicated.

Fig. 10 shows the results from the evaluation of sensible texture. The results are somewhat intriguing because the assigned extreme samples did not stand alone as the minimum and maximum in sensible texture. The low sensible texture 50/50 cotton/polyester blend (sample I) was shown not to have a discernable mean from that of costume satin (sample J) using Tukey's analysis at 95% confidence, and furthermore, textured velvet (K) was shown to be inseparable from corduroy (L). In contrast to the previous two descriptors, the evaluators' scores produced three distinct subgroups of sensible texture with respect to the means, with no overlap. This suggests that separation in the means between the subgroups is sufficiently large to overcome the natural variance of scoring with respect to each sample.

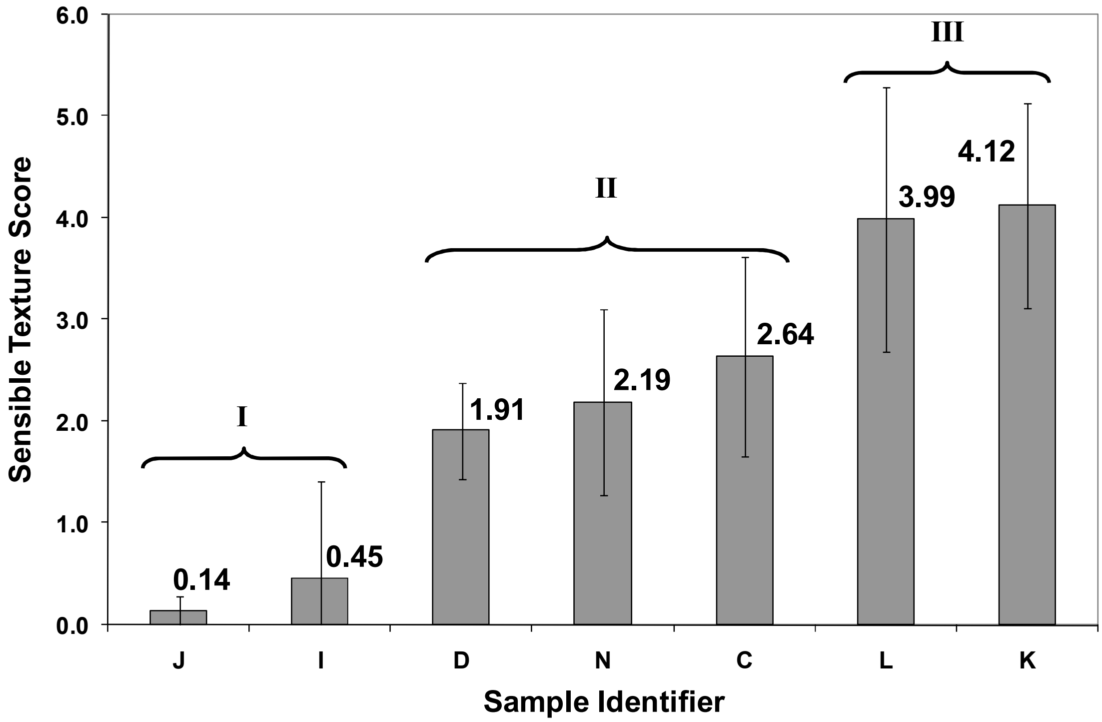

Figure 10. Sensible texture scores assigned by evaluators for seven samples (n=18). Subgroups indicated.

Fig. 11 illustrates the slipperiness results. Here, denim and the poly/wool/rayon/acrylic/cotton/metallic blend (C) share the position of least slippery, while knit acetate (A) and costume satin share the most slippery rating by means of post hoc analysis. There were four subgroups of slipperiness values, with some overlap as shown in the figure.

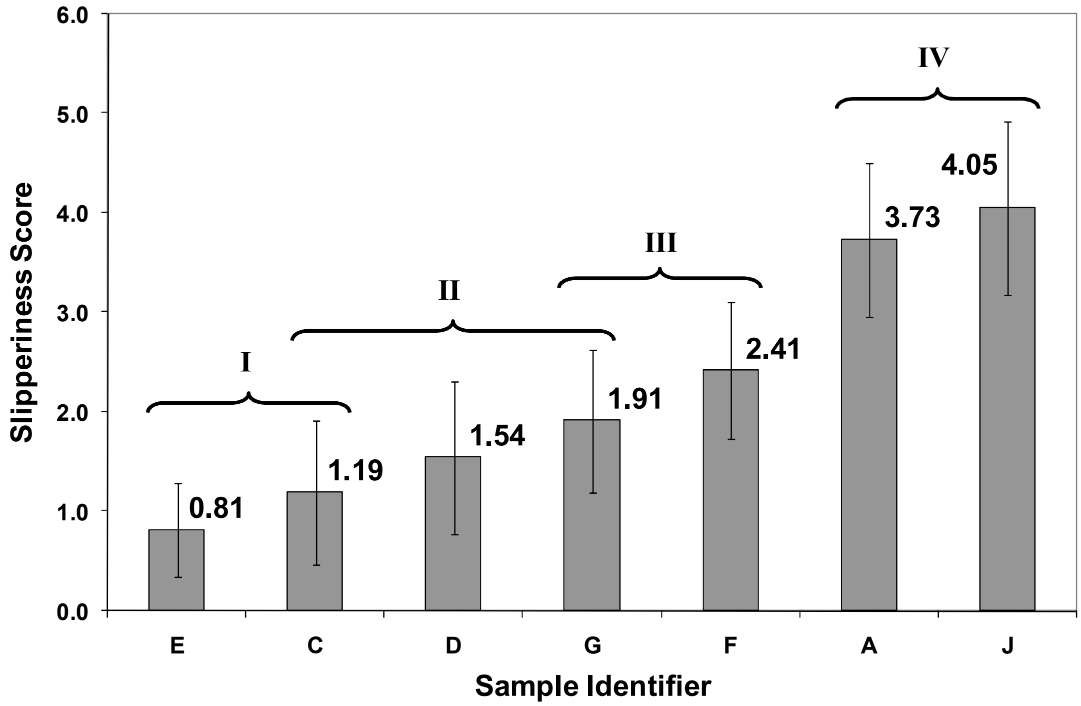

Figure 11. Slipperiness scores assigned by evaluators for seven samples (n=18). Subgroups indicated.

These results show that there is a consistency in the way individuals perceive the feel of materials so long as clear instructions are given to assess the sensory experience. However, it was clear that care must be taken in determining the characteristics and wording of the descriptors in such a way that minimizes ambiguity during evaluation sessions. It is the fundamental assumption of the investigators that these tactile attributes are dependent on complex models involving a number of material properties such as friction coefficient and surface roughness as well as others.

2.3.2. Friction testing

To determine whether fabric type and orientation play a significant role in a material's coefficient of friction, an analysis of variance was performed. The results are shown in Table 2. The p-values clearly indicate that both sample and orientation played definitive roles in friction, as well as an interaction between the two. Furthermore, this analysis shows that the experimental setup was very well equipped to discern differences in friction coefficient among the samples, in spite of the fact that human input was used in the form of the finger swipe.

Table 2. Analysis of variance of fabric friction data.

Source	SS	df	MS	F	p-Value
Sample	0.929	13	0.071	10.217	<0.001
Orientation	0.123	1	0.123	17.638	<0.001
Sample×Orientation	0.662	13	0.051	7.28	<0.001
Error	2.154	308	0.007		
Total (corrected)	3.867	335			

Through statistical analysis, the reported data shows that the experimental setup provided sufficient sensitivity to discern friction coefficients among samples, with respect to the baseline variation of the setup. The mean friction coefficients for the samples ranged from 0.280 to 0.536 in the parallel direction and from 0.333 to 0.624 in the perpendicular direction. Fig. 12 provides a summary of friction coefficient values for all of the samples in both the parallel and perpendicular orientations.

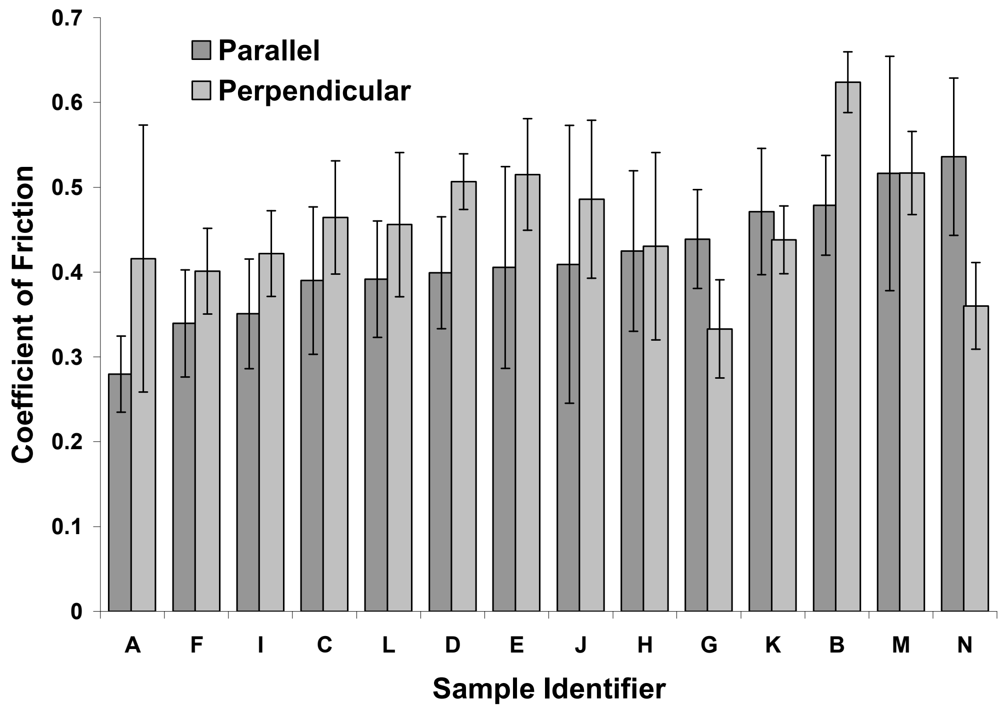

Figure 12. Friction coefficients for the 14 samples ordered by mean value (n=12) in the parallel direction. Error bars represent one standard deviation in each direction.

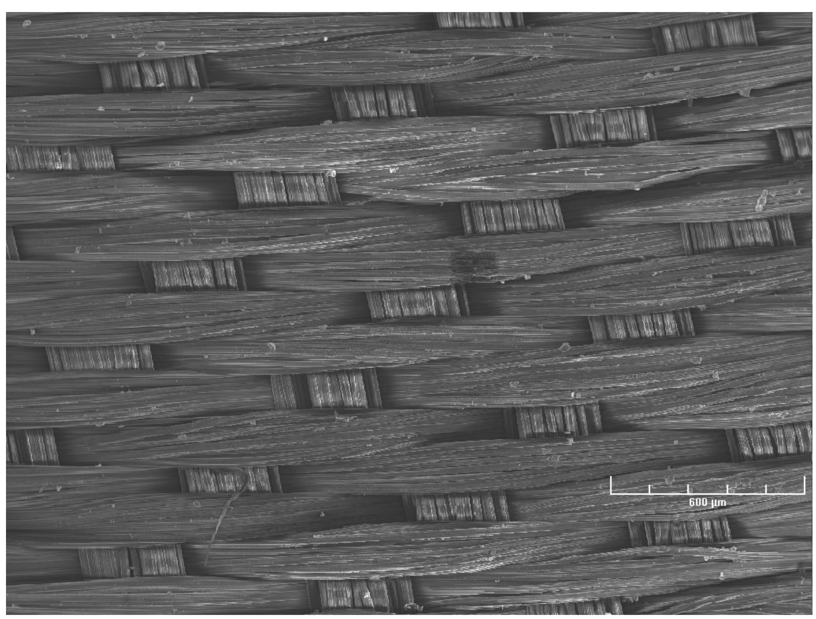

Figure 13. Knit acetate satin (A) Bar is 500 µm.

Several observations can be made upon examination of the friction data. Firstly, of the fourteen fabrics examined, only two have friction coefficients that are higher in the parallel orientation than the perpendicular orientation, samples G (polyester bed linen) and N (polyester shawl knit). This indicates a property that may be unique to the polyester fabric types that were investigated. However, this same behavior is not observed with the only other fully-polyester fabric studied, costume satin (J). The reason why the parallel orientation friction coefficient is lower than perpendicular for costume satin is likely due to the fabric structure. A material with similar frictional behavior, knit acetate satin (A), has a structure as shown in Fig. 13.Under high magnification, it clearly exhibits a primary fiber trend from left to right, corresponding to the parallel direction. This directionality likely serves as a guide or track for motion to easily slide the fingertip along the surface. Movement transverse to this direction (perpendicular) leads to an effectively rougher surface where there will be more encounters between the skin and the edges of fiber bundles. Another observation from the friction data that was made was the fact that the mean perpendicular friction coefficient for the two satins (A and J) could not be shown to be different, while there was a significant statistical difference in the parallel friction means between the fabrics, with 95% confidence. This suggests that there are intrinsic differences between the inherent friction of acetate and polyester that may account for this behavior.

The correlation between the tactile descriptors of the fabrics and the friction coefficient of the fabrics was examined for each descriptor and both orientations. It was anticipated that correlations would be very weak, at best, because of the fact that tactility likely involves a complex model that incorporates a number of mechanical and physical properties of the fabrics. The resulting analysis showed that none of the tactile descriptors were well correlated to the friction data; however, there was some indication of possible, though extremely weak, correlation between fuzziness and friction, having a linear correlation coefficient of 0.27. This low value of correlation is understood to be of limited predictive value, but is noted because it was substantially larger than the correlations coefficients of the other attributes. Most puzzling is that there was very little correlation between slipperiness and friction coefficient, as would have been expected. This may be due to the fact that slipperiness has very significant non-frictional components that the somatosensory system detects. This indicates that considerable investigation must still be undertaken to begin to elucidate these complex dependencies between material properties and tactility of fabrics.

2.4. CONCLUSIONS

The sensory determination of tactile attributes of fabrics can be reliably assessed by the use of Quantitative Descriptive Analysis. Four descriptors that were identified to characterize these fabric samples could be reliably measured by various human evaluators, and the data can be analyzed using standard statistical techniques. Using fingertip swipes, the human hand in conjunction with a three-axis dynamometer can be used to effectively measure the coefficient of friction of fabric polymers. Friction coefficient of the majority of the fabrics was higher in a perpendicular orientation than a parallel orientation. The four tactile descriptors are not correlated well with friction coefficient, possibly due to the fact that numerous other fabric properties are likely involved in tactile assessment. Fuzziness had the greatest correlation with friction coefficient, though it was extremely small.

CHAPTER III

INVESTIGATION OF COEFFICIENT OF FRICTION AND ITS ROLE IN SKIN TRIBOLOGY INVOLVING SIMPLE POLYMER TEXTURES

3.1 INTRODUCTION

The sense of touch is the most fundamental way an individual can interact with the physical world. Myriad sensations are experienced via touch, and this perception affects how one views any given product and elicits certain feelings based on this experience. While designing any product, manufacturers have limited technical knowledge of how specific material properties affect skin tribology and tactility.

Due to the relative youth of tactility and skin tribology, researchers are still working on developing models that can accurately predict skin on surface interactions. Greenwood and Williamson developed one of the earliest general models predicting contact behavior, and their theory focuses on interactions between nominally flat surfaces [14]. In this model, they describe surface interactions on a microscopic level, where although it may be perceived as smooth, the surface is in fact composed of tiny peaks, or asperities, of certain heights and radii of curvature. When two surfaces come into contact with each other, these asperities interlock on a molecular level as rigid bodies and develop adhesive forces between the molecules of the counterfaces. This adhesion plays a vital role in coefficient of friction when the surfaces transversely slide across each other. Because this takes place on a molecular level, the key properties affecting adhesive friction, or μ_a, are material dependent properties such as asperity radius of curvature, as well as the stiffness, surface bonding energies, and external normal loading of the surfaces.

Some researchers such as Ciavarella have taken the Greenwood-Williamson model and tailored it to clarify some vague assumptions made by the original mode, such as no longer assuming an infinitely long sample and applying the model to fractal surfaces [15]. Others have used this backbone to consider a secondary parameter, deformation of asperities and bonding linkages occurring between interlocked surfaces [16, 17]. This deformation coefficient of friction, μ_d, assumes the surface asperities undergo both elastic and plastic deformation, considering additional material properties such as hardness and Poisson's ratio.

These general contact theories are being applied to different facets of skin tribology, relating coefficient of friction to surface roughness [18, 19] or perceived coarseness of a surface [20]. Other advances have begun investigating skin on macroscopically textured surfaces, involving both textiles [2, 21, 22] and patterned rigid polymers [18, 23, 24]. Interestingly, contact theory generally considers microscopic material and mechanical properties independent from counterface topology, barring surface roughness. Directionality of forces across patterned surfaces has been shown to play a large role in coefficient of friction in textiles [21], but the specific mechanics and scientific explanations are still being investigated. Even less is known about simple textures such as ridges and grooves on rigid polymers. There have been studies that have examined longitudinal [23] and lateral [25] applied forces and the resulting friction in comparison to perceived roughness, but discovering a relationship between macroscopic texture geometries with friction directionality has been relatively untouched.

This investigation aimed to isolate a frictional relationship of skin and skin replacement on defined simply textured polypropylene samples (parallel ridges and grooves). Assuming a constant sample material, the μ_a and μ_d components of friction remained constant. It was believed that as the counterface (fingerpad or silicone sphere) passes across the samples, skin/silicone deformation into the grooves would affect frictional behavior, independent of adhesion or small-scale deformation, and exhibit large scale rigid body behavior. This grazing coefficient of friction, μ_g, can then be isolated from μ_a and μ_d and compared to the geometric parameters through statistical analysis. To demonstrate how surface geometry affects the grazing coefficient of friction, lateral forces at 0°, 45°, and 90° were considered.

3.2 MATERIALS AND METHODS

3.2.1 Textured samples

Ten polypropylene samples were used in this study to determine coefficients of friction. Nine samples, A-I, contain uniformly distributed ridges and grooves of varying independent dimensions. Images of each sample were taken with a low-resolution digital microscope, and the ridge and groove widths were dimensioned with a calibrated millimeter scale with image analysis software. A sample’s pitch, p, is described as the total period distance for a given ridge/groove pairing. Figure 14 shows a cross-sectional representation of a sample and the dimensions considered. It should be noted that samples A, B, and C measured 65 mm x 70 mm, while D through I were slightly smaller at 50 mm x 65 mm. The tenth sample, J, was nominally flat, without any discernible texture, and its average surface roughness was measured with a Zygo white light non-contact profilometer.

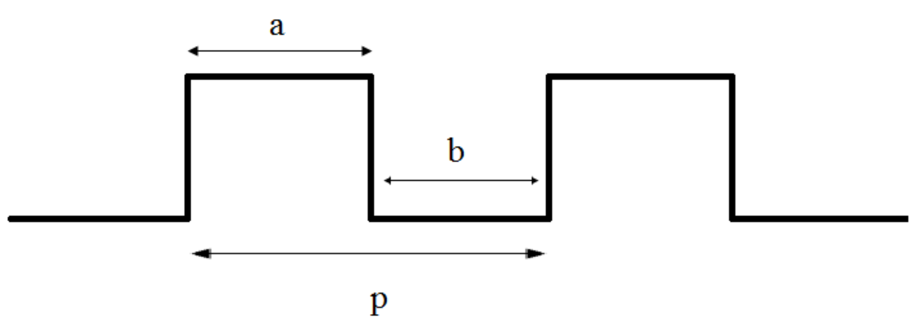

Figure 14. Cross-sectional diagram of a ridged sample and the attributes considered.

The specific dimensions for each attribute can be seen in Table 3. Additionally, for statistical analysis, the dimensions of each sample's attributes were collectively organized by approximate value to compare the dimensions' trends to the measured coefficient values. These categories were defined by a Tukey's post hoc analysis for each attribute, grouping them in ascending order for each respective attribute.

Table 3. Geometric dimensions of the ten polypropylene samples investigated. Bracketed numbers represent categorical assignments per feature for friction correlations.

Sample	Ridge Width, a (mm)		Groove Width, b (mm)		Pitch, p (mm)		Groove Area as Fraction of Total Area (%)	
A	0.15	[1]	0.20	[2]	0.35	[1]	0.57	[3]
B	0.30	[2]	0.30	[3]	0.60	[3]	0.49	[2]
C	0.60	[5]	0.85	[5]	1.45	[5]	0.59	[3]
D	0.15	[1]	0.15	[1]	0.30	[1]	0.50	[2]
E	0.40	[3]	0.15	[1]	0.55	[2]	0.27	[1]
F	0.50	[4]	0.20	[2]	0.70	[3]	0.29	[1]
G	0.50	[4]	0.20	[2]	0.70	[3]	0.29	[1]
H	0.50	[4]	0.45	[4]	0.95	[4]	0.47	[2]
I	0.50	[4]	0.45	[4]	0.95	[4]	0.47	[2]
J (Smooth)	0.152		μm Surface Roughness					

3.2.2 Sample preparation

Prior to receiving them, the production samples were partitioned and molded into sheets containing multiple textures. For testing, samples A through C were on one plate, with J on the reverse side. Samples D through I were located on a second plate. The two plates were later machined such that three sets of notches allowed the plate to be bolted directly to the force dynamometer (Figure 7) and centered with respect to the sample being tested. An example of the mounting can be seen in Figure 15.

Figure 15. Plate 2 in the central mounting position for samples E and H.

3.2.3 Silicone counterface

A silicone counterface was selected to complement fingerpad friction testing because it behaves mechanically similar to skin [2, 26]. Human skin measures approximately 30 Shore A in terms of durometer rating [27], and the chosen silicone sphere measures at 70 Shore A. This is ideal in that while analogous to skin, it exhibits properties that differentiate itself to be examined for the grazing coefficient. The wand used for friction testing was constructed from a 5/8 in. silicone sphere attached to a threaded metal dowel. The silicone wand can be seen below in Figure 16.

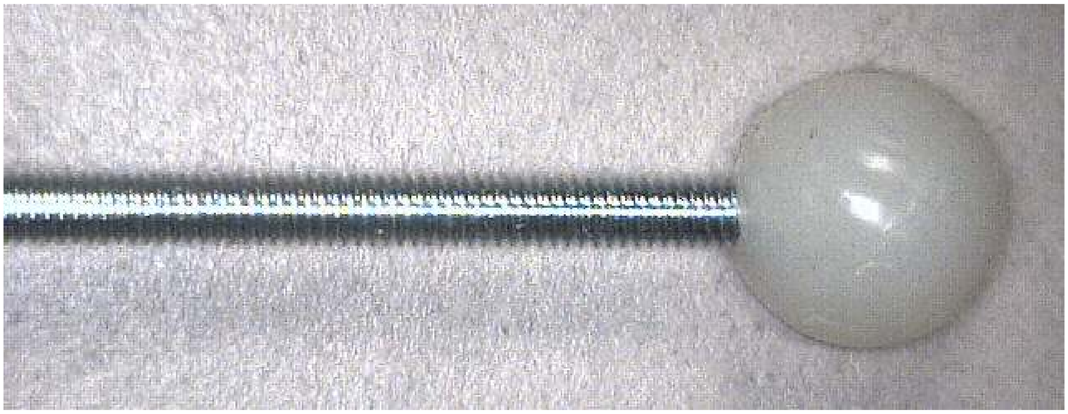

Figure 16. The silicone tipped wand used for friction testing.

3.2.4 Coefficient of friction measurement

The coefficient of friction of a fingertip sliding against each texture in a particular orientation was determined by recording the normal and transverse forces produced during a finger swipe against the sample. Forces were measured using a three-axis dynamometer and amplifier (Kistler 9254, Fig. 7) and exported to a data acquisition system. Previous work has shown that moisture can have a significant effect on a friction coefficient [5, 7, 8] of a material against skin. To minimize the potential effects of skin moisture and operator error, one investigator conducted all of the finger swipes under consistent conditions of humidity, temperature and hand cleanliness. Data were taken at a sampling rate of 125Hz and written to data files for processing and analysis. To minimize noise, a low-pass hardware filter was constructed for the input channels providing a cutoff frequency of 6.9 Hz.

The polypropylene plates were mounted to the dynamometer in a random sequence based on the experimental design. For each sample combination of angle of attack (0°, 45°, and 90°) and counterface, the operator used the left index finger and made three swipes across the sample along at the assigned angle. Figure 17 shows how the angle orientations relate to the position of the ridged patterns.

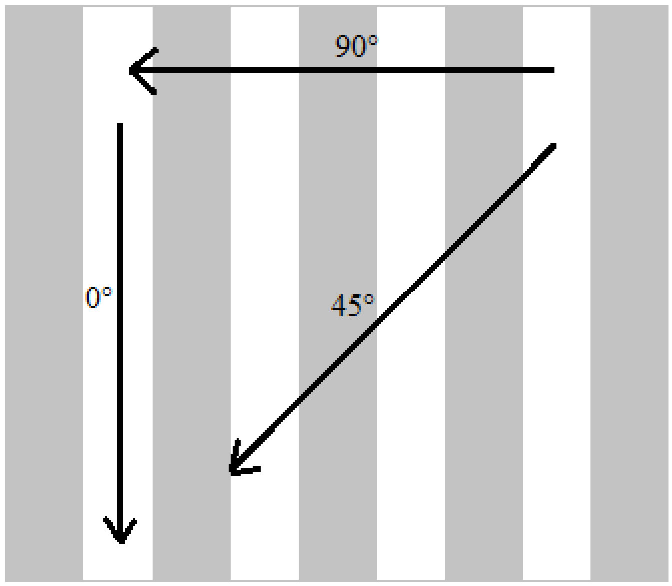

Figure 17. Displays the force angles in relation to ridge pattern orientations.

Each individual combination was measured three separate times. A data acquisition software program was written to conditionally record data only when the transverse force exceeded 1.5 N. This prevented the dynamometer from recording non-essential data points detected at zero load. Because normal load plays a significant role in skin-on-polymer friction behavior [25], the normal force for each trial was maintained between 6-7 N. Across all trials, the normal load was measured at 6.5±0.4. To calculate friction coefficient, transverse and normal forces were recorded simultaneously and divided by one another, yielding an instantaneous friction coefficient curve for each swipe. Like the normal force curve, the friction coefficient swipes exhibited step function behavior, a drastic spike, plateau, and drop-off. Approximately 75-100 data points were averaged from each plateau, giving each swipe (9 total per unique combination) a single mean friction value. An example of a single trial is shown in Figure 18. These means were then analyzed using ANOVA and Tukey's post hoc analysis to determine how counterface, angle, and texture dimensions are related.

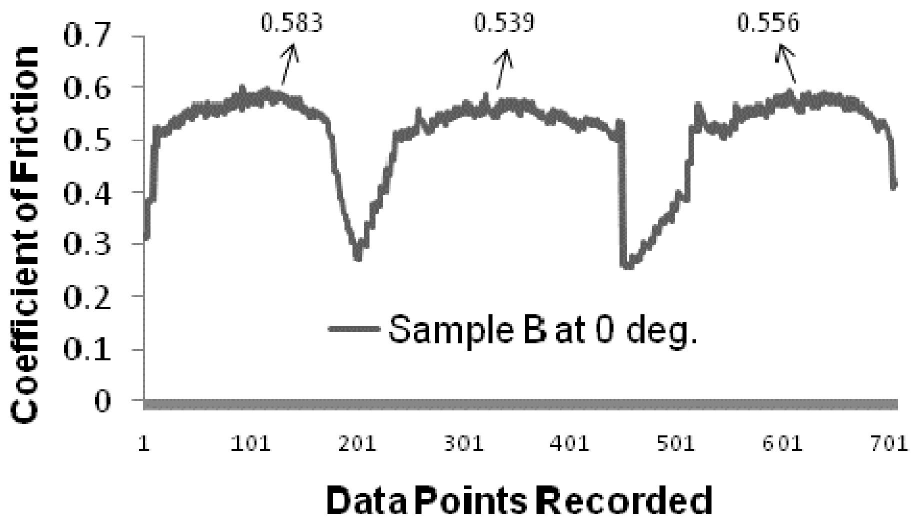

Figure 18. Example of coefficient of friction values from a single trial of three swipes.

3.3 RESULTS AND DISCUSSION

To determine how the counterface, angle of attack, and sample variation affected the coefficients of friction, an analysis of variance was performed across all 540 friction means. Table 4 displays the ANOVA output. The p-values clearly indicate that all three factors: counterface, sample type, and angle of attack, as well as each of their interactions show significant impact on the measured coefficients of friction.

Table 4. Analysis of variance comparing counterfaces, angle of attack, and sample geometry variation and each of their interaction components.

Source	DF	SS	F	p-Value
Counterface	1	2.8536	337.9182	< 0.001
Sample	9	3.1926	42.0061	< 0.001
Counterface*Sample	9	0.4137	5.4429	< 0.001
Angle	2	0.0768	4.5483	0.0111
Counterface*Angle	2	0.8464	50.1166	< 0.001
Sample*Angle	18	1.1283	7.4226	< 0.001
Counterface*Sample*Angle	18	0.8006	5.2668	< 0.001

Several observations can be made upon examination of the overall friction data per counterface (Figures 19 and 20). For both the finger and silicone measurements, sample J exhibits the greatest coefficient of friction. The fact that the smooth sample without texture has the greatest coefficient is to be expected, because according to adhesion contact theory, coefficient of friction increases as contact area increases.

For finger measurements, a Tukey's post hoc analysis determined that for the three different angles of attack across all samples, forces in the 0° direction, or parallel to the ridges, yielded the least coefficient of friction. When compared to 45° and 90°, the parallel direction is shown to be statistically different from each with a p-value of < 0.001. Additionally, 45° and 90° were deemed statistically identical to each other with $p < 0.7483$.

The silicone counterface, however, behaved in an opposite manner, where 0° forces yield the greatest coefficients, followed by 45° and 90° respectively. Comparing 0° versus 45° and 90° yielded $p < 0.001$ and $p = 0.0013$, and 45° versus 90° yielded $p = 0.0088$. Although they are slightly more similar to each other, their friction measurements remain statistically different from each other.

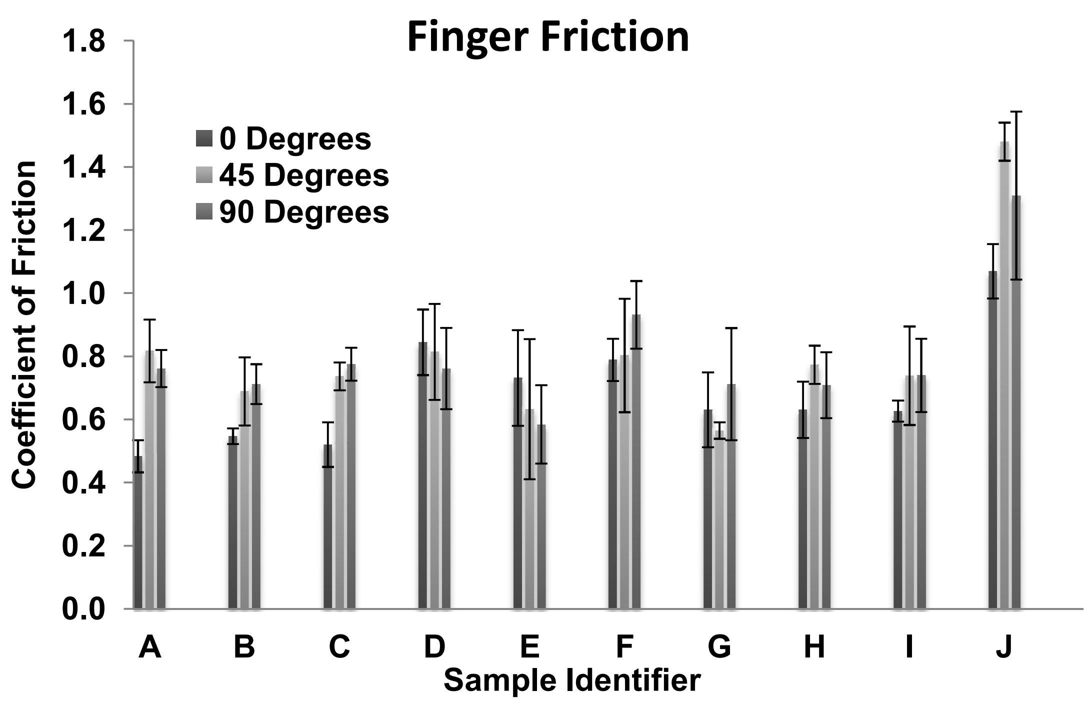

Figure 19. Finger coefficients of friction with standard deviations for each angle and sample.

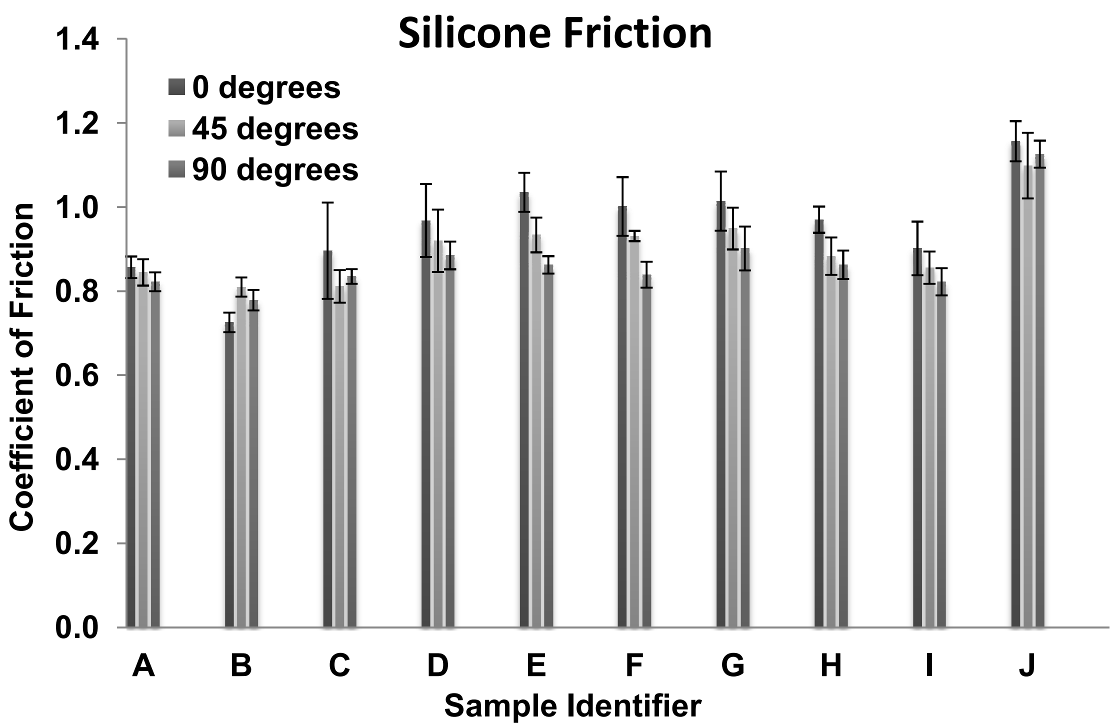

Figure 20. Silicone coefficients of friction with standard deviations for each angle and sample.

To more effectively determine the frictional trends with respect to surface geometry, the previously mentioned attribute categories for groove width and percent groove area were analyzed with angle of attack for both the finger and silicone tests. Figures 21a-d were all generated as visual representations of Tukey analysis, further separating the examined parameters into statistically unique classes.

The most defining feature of Figure 21a shows that when the finger travels in the longitudinal direction, friction drastically decreases as groove width increases, and when the grooves are sufficiently small, the behavior switches to a high friction mode. When in the transverse or 45° direction, finger friction is relatively unaffected by groove spacing. For silicone contact, the groove effects are reversed. There does not appear to be much of a longitudinal spacing trend, but as spacing increases transversely, friction decreases. For the percent groove plots (Figure 21c,d), friction is being compared to the groove to pitch ratio, and the same trends discussed above are evident in this case as well.

If the counterface stiffness is sufficiently high, as in silicone's case, grazing does not occur in the transverse direction because the material never has the opportunity to deform and enter the groove. The apparent contributor to silicone's frictional directionality trends is varying contact area. To a certain degree, human skin on the fingertip does in fact exhibit grazing. Prior to experimentation, it was expected that friction would increase as angle of attack increases, where 45° forces would yield a coefficient of friction between 0° and 90°, but it was determined that for these samples, the two transverse forces are not statistically different. From these observations, the grazing component in friction can be assumed to be, $\mu_g = f(b, p, \theta, E, N)$, where b is the groove dimension, p is the pitch, θ is the angle of attack, E is Young's modulus, and N is normal load. Additional testing is necessary to determine the specific relationships between these terms, but for the case of skin, it is evident that μ_g had some form of impact.

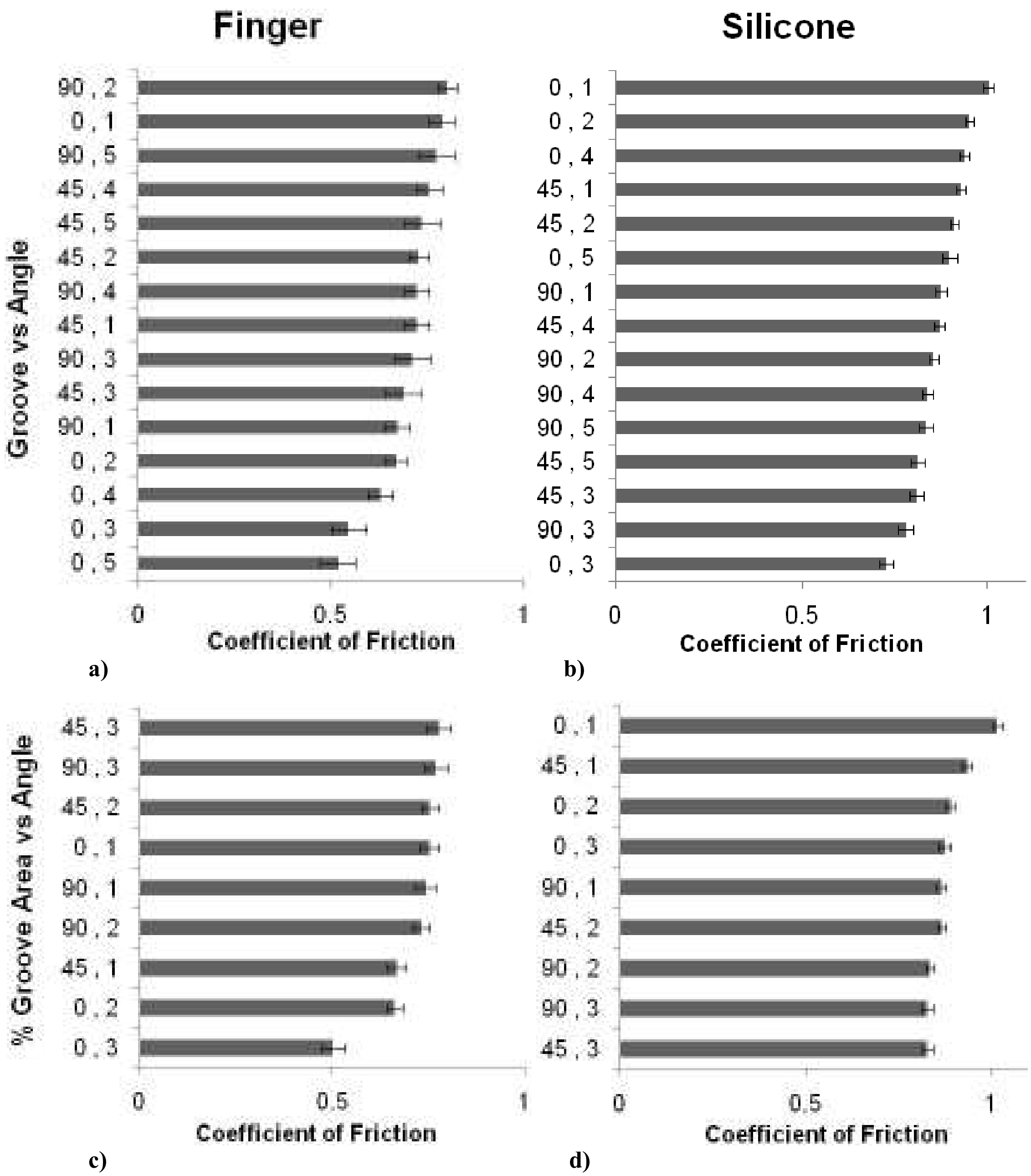

Figure 21. Categorized plots for each counterface, examining groove (a, b) and % groove area (c, d) effects on friction coefficients.

An interesting observation to note occurred fairly frequently throughout the finger testing. During the swiping process, it was ensured that the normal loading remained relatively constant, which should in turn yield a fairly constant friction coefficient. Periodically, the output friction for certain samples showed a positive slope deriving from a linearly changing resultant force. System noise and drift were considered to cause the anomalies, but the recorded slopes were approximately 80 to 100 times the degree of noise drift. Further investigation showed that compared to the rest, a portion of samples B, C, D, and I were unaffected by this anomaly. Although they all have different ridge and groove dimensions, these samples share similar ridge to pitch ratios of approximately 0.50, or 50% ridge area. It is highly possible that there are more complex interactions taking place at the skin-texture interface, such as non-uniform sliding across the samples with higher percent ridge area. With greater contact area, there is a greater chance that finger asperities may temporarily adhere to a given location and fail to slide at the same rate as the bulk of the finger translates across the texture; and the smaller grooves may interfere with the skin interface and prevent it from ever reaching a steady sliding mechanism.

Oddly, the slope anomaly is not an issue for the friction measurements with the silicone wand. The differences in counterface stiffness may explain this, assuming unsteady sliding is the cause. Because the silicone rubber is significantly stiffer than the pad of a finger, it does not deform across the texture geometries as much as human skin would and can more easily achieve uniform sliding.

3.4 CONCLUSIONS

Coefficient of friction is highly dependent on both the counterface, as well as geometry of the surface it comes into contact with. Directionality does play a factor in affecting friction behavior, but the trend it follows depends on the specific counterface. Maintaining a constant material for varied textured surfaces more easily allows comparisons of the separate friction components. High stiffness prevents macroscopic deformation, and is more affected by variable contact area, decreasing the coefficient of friction in the transverse direction. Low stiffness materials deform to the surface topography, and exhibit trends that follow the proposed grazing friction coefficient, μ_g, where friction decreases with longitudinal forces and increases transversely.

CHAPTER IV

GENERAL CONCLUSIONS

Contact mechanics, especially in the field of skin tribology, is extremely important due to its prevalence in the physical world. Although still in stages of infancy, skin tribology is becoming much more prominent in scientific research. These have included coefficient of friction and surface roughness investigations.

A friction coefficient between surfaces is highly dependent on material properties, directionality, microscopic and macroscopic texture geometry, and in certain cases, loading. Counterface stiffness is also key to predicting frictional behavior across textured surfaces. In addition to mathematically defining tribological interactions, there is also a subjective aspect to tactility that is highly dependent on the user. While subjectivity may vary, properly trained evaluators have been proven to be able to consistently grade materials based on predefined attributes. It has been discovered that friction does not play a significant role in determining certain surface perceptions and tactile attributes such as abrasiveness, fuzziness, slipperiness, and sensible texture. To more specifically investigate skin interaction in tribological applications, it would be highly beneficial to observe skin-surface interactions at the interface during motion across the surface.

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