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Tactile Perception of Vellum Quantified by Friction and Surface Roughness

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Abstract

Books throughout the Middle Ages were written on vellum, the prepared skins of animals, and it has been proposed that medieval readers navigated manuscripts in part by touch, by perceiving and recognizing the different textures of pages. However, scholars today often read these same books in printed or digital form, likely having a very different experience from that had with the physical pages. Here, we attempted to understand this difference by quantifying the tactile experience of interacting with vellum as sliding friction. Friction was measured on fourteen vellum samples from different animal sources and preparation methods on the hair and flesh sides of the page. Results were correlated to the sensory perception of an untrained panel and explained in terms of statistical surface roughness parameters. Data demonstrates divergence between optical and tactile perception of surface features and physical measurements, calling into question statements about vellum type and quality based on digital images alone. The results are the first step towards understanding the tactile experience of interacting with medieval vellum such that the experience might be approximated by scholars today.

Keywords: paper friction, tactile perception, consumer tribology, surface roughness

Statements and Declarations The authors have no conflicts of interest to declare that are relevant to the content of this article.

1 Introduction

In the Middle Ages, books were written on the prepared skins of animals, primarily calves, goats, and sheep. The material of these skins is called vellum or parchment, terms that are interchangeable in most current usages, [1]. Although the preparation can be extensive, the materials retain characteristics of skin, with noticeable differences between the outer (hair) side and the inner (flesh) side of the vellum. The hair side tends to be darker or yellower than the flesh side, and, especially in highly prepared vellum, it could have a markedly different texture [1]. Binding practices after the late tenth century reflected recognition of the differences in hair and flesh sides of the vellum: sheets were arranged so that hair sides faced hair sides and flesh sides faced flesh sides [2].

It has been proposed that medieval readers might navigate a manuscript in part by touch, by perceiving and recognizing the different textures of pages [3]. In that study, it was argued that recognition of such tactile apprehension of the page might challenge models of literacy and even developing science that increasingly relied on the visual at the expense of other modes of perception. Further, many of the evaluative parameters for describing the differences between vellum from different sources or preparation methods, as well as between the hair and flesh sides, involve both visual and tactile cues. Today, scholars often read early manuscripts as printed or digital versions of the physical documents. However, given the importance of the tactile experience of reading manuscripts in the Middle Ages, something is likely to be lost with a printed or digital alternative [1]. An approach to addressing this limitation is to understand what produces the tactile experience of interacting with medieval vellum such that the experience might be approximated.

Tactile perception of various products and materials has been quantified by friction [4, 5]. Friction is often related to perceptions of "slippery", "smooth", "soft" or "coarse" of consumer products [6, 7], and "mealiness" or "crispness" of food [8]. In such studies, friction is measured using instruments that measure lateral force during sliding between samples and either a human body part, usually a finger, or an artificial probe. Both approaches have advantages and disadvantages.

Studies with human subjects involve measuring friction during relative motion between a finger (or another part of the hand) and a sample. Then, either during the friction test or a separate perception evaluation, the subjects are asked to evaluate the feeling of the samples such that correlations between friction and perception can be identified. For example, a study of various materials, including glass, metal, and plastic, showed that friction was correlated to the perception of sticky vs. slippery [4]. Studies of friction between textile fabrics and fingers revealed that friction is not affected much by the sliding direction of finger [9] but the finger contact angle with the surface plays an important role [10]. However, the challenge with using human fingers is that friction results can vary significantly from person to person and depend strongly on the environment. For example, friction measured using human subjects has been reported to depend on gender, age, and the part of the body tested [7, 11, 12]. Skin moisture also plays a significant role in both friction and perception since it affects the physical and surface properties of skin [13, 14].

Temperature contributes as well due to its effect on the viscoelasticity and moisture level of human skin [11, 15].

The alternative to experiments with human skin is to measure friction using a probe made of an artificial material that mimics the finger [16]. A range of different probe materials and geometries have been used in such studies, but skin mimics are usually elastomers, often silicone, because of their skin-like elasticity. A few studies compared friction measured with a human finger vs. a silicone probe and reported that, while friction magnitudes differ, some friction trends can be captured using an artificial probe [17, 18]. The degree of similarity between artificial and physical fingers has been improved using various approaches including multi-layered materials [19] and liquid-filled samples [20]. Correlating friction measured using an artificial material with human perception is challenging because perception is necessarily evaluated using a human finger. However, the lack of subject- and environment-dependence of artificial samples is useful for minimizing variability in measured result.

There have been no previous tribological studies on vellum, but there are examples of friction measurements for printing paper. Most such studies focused on sliding between two sheets of paper or between paper and materials used to produce or process paper. However, paper friction studies focused on human perception have been limited. Some studies have included paper as one of multiple samples on which friction was measured using either artificial or human fingers [21, 22]. A study comparing different printing papers showed that friction measured with a human finger can be used to differentiate between paper samples and that rougher paper had lower friction than smoother paper [23]. In a follow up study that involved sensory perception of smoothness vs. coarseness, it was found that paper perceived as coarser had greater surface roughness and lower friction. The inverse relationship between coarseness and friction was attributed to the human subjects unintentionally reducing their applied load for smoother surfaces [24]. However, these previous studies used plant-based paper so the observed trends may not be extensible to the animal-based vellum.

Here, we used an artificial probe to measure friction on the hair and flesh sides of fourteen vellum samples from four different animal sources and subject to different processing methods. Friction was measured from linear reciprocating sliding of a silicon probe on each sample, approximating finger-vellum contact while reading. Friction results were correlated to human perception of coarseness as ranked by an untrained panel. Finally, trends in both friction and perception were analyzed in terms of surface topography and statistical roughness parameters.

2 Methods

2.1 Vellum Samples and Tactile Perception

Fourteen vellum samples, summarized in Table 1, were procured from Pergamena, a specialist producer of artisanal vellum. The animal sources of the vellum were either calf, sheep, goat, or deer, the first three of which were the most common sources of vellum in medieval Europe. All samples underwent the same initial processing, done by Pergamena. First, the flesh and hair were removed from the animal skin using mechanical as well as chemical treatments. Then, the samples were soaked to re-hydrate and remove contamination, and then stretched and dried. Finally, the material was subject to manual processing, including scraping, sanding, and rubbing with brick or pumice. The specifics of this last processing step differed depending on the expected use of the material. For example, vellum intended for calligraphy was prepared only the flesh side and subject to more abrasion that other samples, while manuscript vellum was prepared on both the sides of the skin. There was also one sample prepared for used in furniture that was stretched between two sheets of plexiglass to minimize the penetration of air into the skin.

Table 1: Vellum naming convention and intended use for each sample; no use-specific processing is indicated as “-”. The samples are subsequently referred to by these abbreviations followed by either H or F, for the hair and flesh side, respectively.

Animal Source	Intended Use	Abbreviation
Calf	Manuscript	C1
Calf	Calligraphy	C2
Calf	Calligraphy	C3
Deer	-	D1
Deer	Manuscript	D2
Deer	Calligraphy	D3
Goat	-	G1
Goat	-	G2
Goat	Furniture	G3
Goat	Manuscript	G4
Goat	Calligraphy	G5
Sheep	-	S1
Sheep	-	S2
Sheep	-	S3

Each sample was cut to approximately 30mm×100mm in preparation for friction testing. Photos of the samples, on both the hair and flesh sides, are shown in Fig. 1. Close-up images of the samples obtained using an optical microscope with darkfield illumination to improve the contrast are shown in Fig. 2. The texture and porous nature of the samples is clearly evident. There are also some visual differences between the hair and flesh sides of the samples, which will be discussed later in the context of the friction results.

An untrained sensory panel of eleven individuals (seven male and four female) evaluated the samples in terms of softness vs coarseness. Panelist age was not recorded, although it is known that both age and gender affect tactile perception [12]. Two of the participants had experience reading from vellum, both with original manuscripts and on printed or digital copies; qualitative

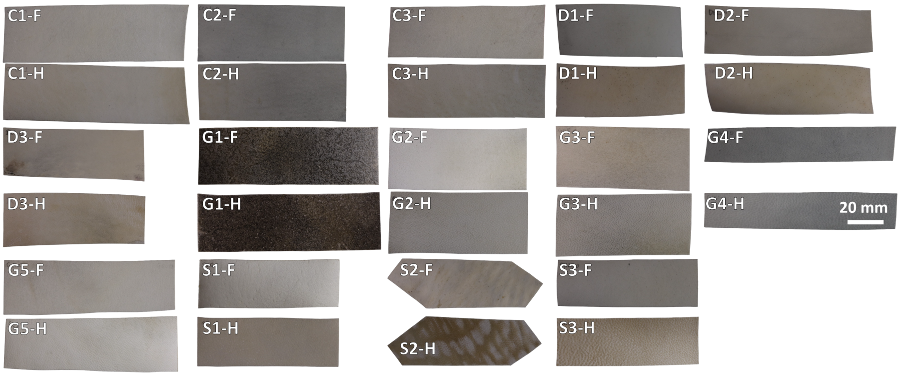


Fig. 1: Photos of the hair (H) and flesh (F) sides of the vellum samples prior to testing.

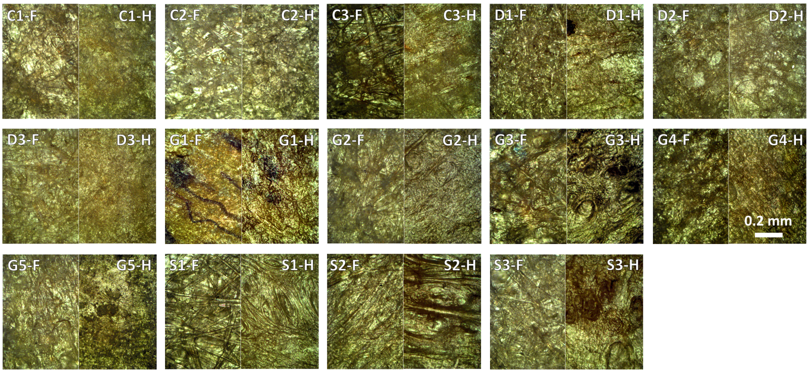


Fig. 2: Optical microscope images of the vellum samples showing close-up views of representative visible features.

descriptions from these two are referred to subsequently as expert opinions. Nine of the participants had no previous experience with vellum. All participants were instructed to run their index finger across the vellum sample, with no specific guidance for how hard to press (load) or how fast and in which direction to move their finger relative to the sample. They then gave each sample a coarseness rating on a scale of 1 to 5, with 5 being the coarsest. Participants were allowed to revisit previous choices and adjust their ranking until they felt confident in their determination. Participants were not informed of the vellum type or origin prior to testing. The trends in perceived coarseness were consistent for the two expert panelists and the other panelists, so quantitative analyses were performed using all panelist data.

2.2 Tribological Testing

Friction tests were performed using a custom-designed sample holder consisting of a base plate with adjustable clamps to hold vellum samples with different sizes and shapes. The hemispherical probe with 14 mm radius, approximating the size of a thumb pad, was made of a silicone-based elastomer (Ecoflex 00-30) having an elastic modulus of around 30 kPa. A load of 3 N was used, corresponding to a contact pressure of approximately 20 kPa. This pressure mimics the contact pressure of the human finger moving across paper and is consistent with the range used in previous paper friction studies of 0.2 kPa - 22 kPa [23–25]. The reciprocation tests were conducted in ambient conditions with temperature between 20 and 22°C. Each test consisted of nine sliding cycles with a speed of 0.6 mm/s and a stroke length of 20 mm.

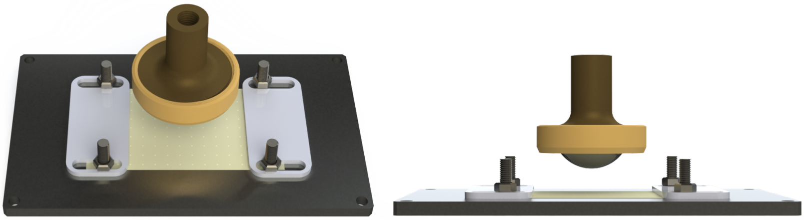


Fig. 3: Perspective and side view schematics of the custom test set up for measuring linear reciprocating friction between vellum samples and a silicone hemisphere, mimicking the tactile interaction between a finger and the page of a medieval manuscript.

Each experiment was conducted three times, one along the approximate centerline of the sample and two offset ±5 mm from the center. Friction data from the last 40% of each cycle was averaged over the nine cycles and three independent tests. This was repeated on the hair and flesh sides of the samples. A new silicone hemisphere was used for each sample. There was also no visible wear on either the silicone probe or the vellum samples. To confirm this, longer tests of one hundred cycles were conducted after the initial testing for select samples. The coefficient of friction varied less than 5% over the extended testing period and did not monotonically increase or decrease, indicating negligible surface change due to wear. This is in contrast with a study of plant-based paper that found friction decreased with stroke when measured using human fingers [23]. However, the observation in the previous study was attributed to chemical change of the paper due to interaction with the finger, which was not possible in our study that used artificial probes. In addition to confirming the samples did not change during the tests, that there was no wear also suggests such tests could be safely performed on medieval manuscripts in the future.

3 Results

Qualitative descriptions of both the visual and tactile perception from the two expert evaluators were collected first. Their descriptions are summarized as follows.

Only small differences between hair and flesh sides were observed for the calf samples. Sample C1 was described as being velvety on both sides with the flesh side being whiter and the hair side having light brown streaks. For both samples C2 and C3, the hair side had slightly more visible texture and spots of color that were not felt.

The flesh side of sample D1 was pale with small burrs and differed significantly from the hair side that was yellowish with dark follicles and consistent grain in one direction. The flesh side of the D2 sample was perceived to be velvety and the hair side as plastic-like with yellow color and visible follicles. Sample D3 was described as having a white, velvety flesh side and the hair side being slicker and plastic-like; the visual difference between hair and flesh was small, though the hair side had visible pores throughout. However, the hair side felt smoother.

There were five goat samples, with various intended applications. Sample G1 was described as gray-brown with clear markings, follicles, and looking like sandpaper, with significant visual difference between the hair and flesh sides. The opposite was observed on sample G2 for which the hair side was slightly rougher with visible follicles. For sample G3, there was little difference between the hair and flesh, although there were pores clearly visible on the hair side and the flesh side was slightly rougher. Sample G4 was described as having velvety hair side with patterning on both sides and gray pores clearly visible on the hair side. The flesh side of sample G5 was described as very rough and worn, while the hair was extremely smooth, almost waxy, with visible hair and light brown streaks.

For the sheep vellum, sample S1 was described as having pale wrinkles and quite different visually from the hair side which was very coarse and knobbly, with clearly visible hair, though there was only a slight tactile difference between the sides. The flesh side of sample S2 was described as creamy with puckering and discoloration while the hair side was brown mottled with cream spots and slightly rougher than the flesh side. Sample S3 was the perceived and the softest and smoothest of the sheep samples, while the hair side was notably stippled with follicles.

The quantitative evaluation of coarseness from all panelists is shown in Fig. 4. There was significant variation between the ratings, as expected for an untrained sensory panel with a wide range of ages and genders and no guidance for load, speed, or direction of sliding, so only a few of the differences between samples were statistically significant. The calf samples were consistently perceived as smooth. The deer samples were also perceived as smooth, with the exception of sample D1, particularly on the hair side. The sheep vellum samples were generally the coarsest, with the S2 sample being the coarsest of all samples evaluated. There was significant variation among the goat samples and between the hair and flesh sides of some goat samples. For the G1 sample, the hair side was much coarser than the flesh side, while the opposite was true for the G5 sample. Of all goat samples, G3 was perceived as the coarsest.

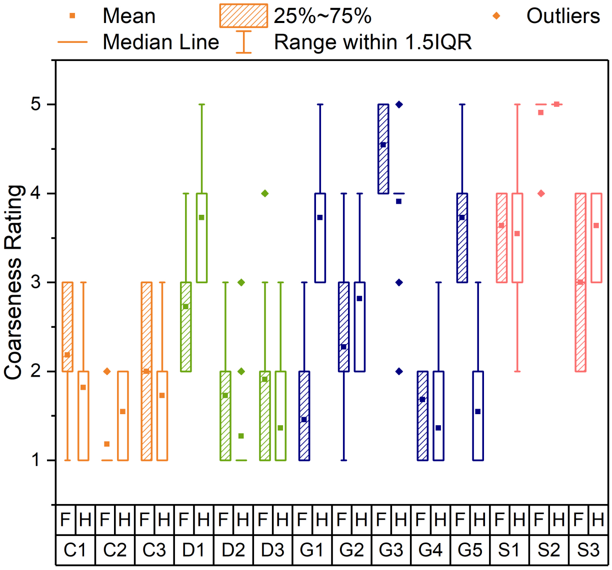
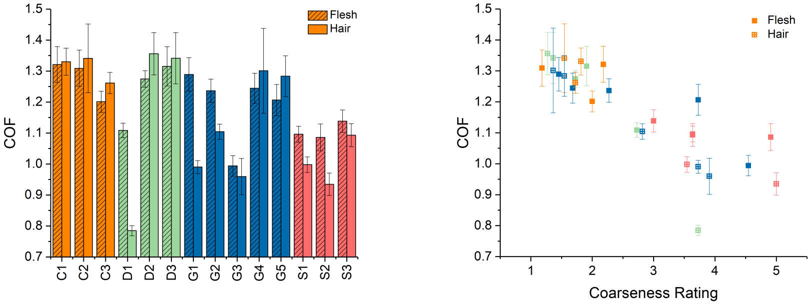


Fig. 4: Results from sensory evaluations of coarseness, where 5 indicates coarsest, for the flesh (F) and hair (H) sides of each vellum sample. Different colors are used to distinguish between calf (orange), deer (green), goat (blue) and sheep (red) samples. The mean value is shown as a solid squares, the median as a horizontal line, statistical outliers as diamonds, 25 to 75% range as boxes, and the 1.5 interquartile range as vertical lines.

The results from the friction tests are shown in Fig. 5(a). Most friction coefficients were between 0.8 and 1.4, with an overall average of 1.2. This is higher than values between 0.3 and 0.6 measured on plant-based paper with human fingers [22–24]. However, moisture has been shown to affect friction measured with human fingers. For example, friction measured on the same sample with a finger covered by a kitchen glove (i.e., without the natural moisture of human skin) was twice as large as that with an uncovered finger, which was attributed to the slightly wet conditions of the contact in the latter case [22]. There is no moisture on the silicon probe, so the higher friction observed here is reasonable.

Comparing the different animal sources, the only statistically significant trend was lower friction averaged over the sheep samples compared to the other three animal sources. There was no consistently observed difference between the hair and flesh sides of the samples. However, for cases where there was a statistically significant difference between hair and flesh (D1, S1, S2, G1, and G2), the hair side had lower friction. The lowest friction overall was observed for the hair side of sample D1.

The relationship between measured friction data and the perceived coarseness is shown in Fig. 5(b). There is a clearly evident trend of decreasing friction with increasing coarseness. This trend was quantified by the Pearson correlation coefficient that ranges from -1, for strong inverse linear relationships, to 1, for strong direct linear relationships. The correlation coefficient for friction and coarseness was -0.85. The correlation was slightly stronger for the hair sides of the vellum (-0.91 for the hair sides and -0.84 for the flesh sides). To understand the inverse trend, the surfaces were evaluated in terms of measured topography, i.e., roughness.



(a) (b)

Fig. 5: (a) Coefficient of friction for flesh (patterned bars) and hair (solid bars) sides of the vellum samples. (b) Friction coefficient vs. average coarseness rating. Animal source is differentiated by color: calf (orange), deer (green), goat (blue), and sheep (red). Friction coefficient error bars are standard deviations over three independent tests for each sample.

Each sample surface was characterized using interferometry. The corresponding topography images are shown in Fig. 6. Qualitative comparison of these images indicated that, with the exception of the sheep samples S1 and S2, the surfaces were slightly rougher, i.e., more variation in color on the contour plots, for the flesh side of the samples. This was attributed to the more intensive scraping required to remove the subcutaneous tissue, fat, and muscle, as compared with the hair side, where only hair follicles and surface irregularities must be removed. There also appeared to be higher spatial frequency of features on the flesh sides of some of the samples.

The surface height data in Fig. 6 was used to calculate statistical roughness parameters to identify the origin of the friction and smoothness perception trends. First, the shape of the probability distribution functions of surface heights for each sample was quantified as their skewness and kurtosis.

Kurtosis S_{ku} reflects the roundness of peaks and valleys. A kurtosis value greater than three indicates sharp surface features while a kurtosis value less then three indicate rounder features. The results are shown in Fig. 7(a). For

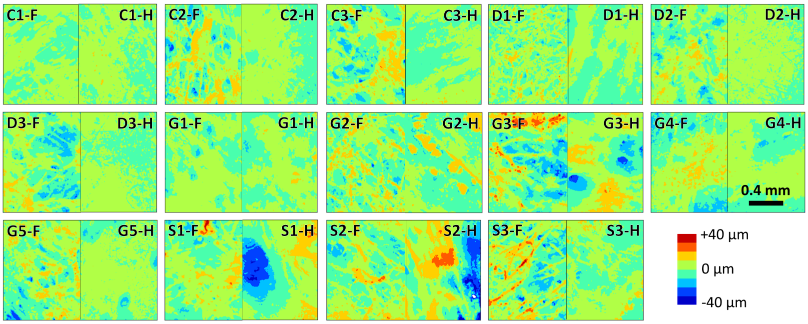
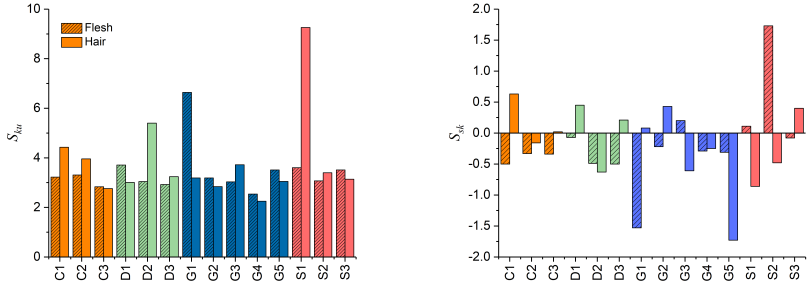


Fig. 6: Surface topography of the samples measured using interferometry where color indicates height from dark blue valleys to dark red peaks.

most surfaces, $S_{ku} \approx 3$, indicating a symmetric distribution of surface features. However, there are a few cases where the kurtosis was large (> 4), specifically C1-H, D2-H, G1-F, and S1-H, which points to their roughness being dominated by sharp peaks and valleys.



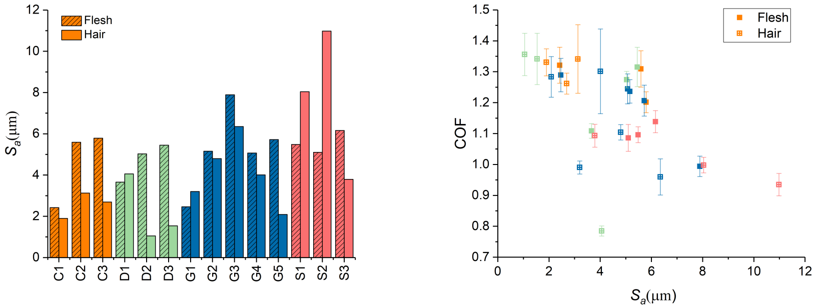
(a) (b)

Fig. 7: (a) Kurtosis S_{ku} and (b) skewness S_{sk} of the surface height probability distribution functions for the flesh (patterned bars) and hair (solid bars) sides of the vellum samples. Animal source is differentiated by color: calf (orange), deer (green), goat (blue), and sheep (red).

Skewness S_{sk} captures the distribution of peaks and valleys on the surface, where a negative skewness indicates more valley than peaks and a positive skewness means the surface is mostly comprised of peaks. The skewness results shown in Fig. 7(b) show that, for most samples, $-0.5 < S_{sk} < 0.5$, indicating similar distributions of peaks and valleys. Notable exceptions are the flesh side of S2 that had a very large positive skewness, meaning tall surface peaks. Also, the flesh side of G1, hair side of G5, and hair side of S1 had large negative skewness. Generally, there were more surfaces with negative skewness, indicating that valleys dominated the surface roughness, perhaps corresponding, in the hair side samples, to the pores observed in the qualitative visual analysis and seen in the microscope (Fig. 2) and interferometer images (Fig. 6).

We also quantified the lateral distribution of surface features in the sliding direction as the correlation length, i.e., the distance at which the autocorrelation function of surface heights decays to 0.15. For most samples, the correlation length β was between 0.05 and 0.35 mm. However, correlation lengths larger than 0.50 mm were calculated for samples G3-F, G4-F, and C3-H. On average, the correlation lengths on the hair sides of the samples were larger than those on the flesh sides ($\beta_{hair} = 0.26$ mm and $\beta_{flesh} = 0.21$ mm), indicating a higher degree of order of surface features on the flesh sides of the sample. However, no statistically significant trends were identified between friction and either skewness, kurtosis, or correlation length.

Lastly, the average roughness S_a of each sample was calculated and the results are shown in Fig. 8(a). The lowest average roughness was observed for the hair sides of samples C1, D2, D3, and G5. The highest roughness was measured for the hair sides of samples S1 and S2, and the flesh side of sample G3. For many of the samples, there was a significant difference between the hair and flesh sides of the samples. Notably, for samples C2, C3, D2, D3, and G5, the flesh side was at least twice as rough as the hair side; all these samples except D2 were prepared for calligraphy, meaning their flesh sides underwent additional abrasive processing steps. In fact, the flesh side was rougher for all samples except D1, S1, S2, and G1, with the two sheep samples exhibiting the most significant difference.



(a) (b)

Fig. 8: (a) Average roughness S_a of the flesh (patterned bars) and hair (solid bars) sides of the vellum samples. (b) Surface roughness vs. average coarseness rating. Animal source is differentiated by color: calf (orange), deer (green), goat (blue), and sheep (red).

The average surface roughness results are plotted against friction coefficient in Fig. 8(b). Friction generally decreased with increasing roughness. This trend is consistent with friction of skin and skin mimics measured on various materials, including hard plastics, metals, and glass, [26–28] as well as on printing paper [23, 24]. The inverse relationship between friction and roughness has been explained by adhesion-dominated friction that is lower on rougher surfaces because of their smaller real contact area [27]. However, a power law relationship between friction and average roughness has been proposed, where a power law exponent between -0.66 and -1 would indicate adhesion-dominated friction [14, 28]. Previous studies of friction on skin reported power law exponents of -0.4 [26] and -0.135 [28]. A power law fit to the vellum data here gave an exponent of -0.14 for the silicon skin mimic sliding on vellum. This indicates that both adhesion and deformation contributed to the observed friction trend.

The negative correlation between friction and coarseness in Fig. 5(b) combined with the negative correlation between friction and roughness in Fig. 8(b) suggests a positive correlation between perceived coarseness and surface roughness. However, the correlation coefficient between roughness and coarseness was 0.64, lower than the correlation coefficient between friction and coarseness of -0.85. This indicates that, while roughness strongly affects tactile perception of vellum, there are other contributing factors. In our study, the artificial probe is the same for all tests, so any differences must be due to the vellum itself. Previous studies of skin-fabric friction have shown that textile microstructure is an important parameter [27]. For example, natural yarn has higher friction that synthetic yarn due to the hairiness and other features of the natural fibers. Therefore, it is possible that the natural features of the animal-based vellum samples, such as the pores observed in Fig. 2, contribute to friction more than roughness and so affect tactile perception.

4 Conclusions

This study combined approaches from the humanities and the scientific community to understand how the perception of vellum might influence the experience of reading a medieval manuscript. Qualitative and quantitative analyses were performed on the hair and flesh sides of vellum samples sourced from various animals and processed using a range of techniques. An inverse relationship between friction and perceived coarseness was identified and explained in terms of the inverse relationship between friction and surface roughness for wearless sliding with adhesive and deformation contributions.

Samples from all animals were perceived to have a wide range of surface features and visual appearances, indicating that preparation methods are perhaps more significant than species in the final feel and appearance. This complicates the common assumption that scholars can distinguish species based on such observations. Evaluative parameters for describing differences between hair and flesh sides of vellum have traditionally involved visual cues (e.g., color) and subjective judgements (e.g., "fineness"). Many extant applications of physical science to manuscript materials involve the visual exclusively (e.g., ultraviolet illumination) or a combination of visual and chemical analysis (e.g., spectroscopy). Tribological study enables testing that focuses on tactile perception. This enables scholars of early manuscripts to consider what might be apprehended, not with amplified vision, but by touch alone.

Quantifying differences in the surfaces of vellum samples contributes to current research on medieval reading practices and medieval understandings of relationships between readers and texts. Literary and art historical studies have suggested that readers of manuscripts in the early Middle Ages recognized the vellum of a manuscript page as skin, like their own. For example, it was argued that some scribes self-consciously emphasized the similarity between the vellum on which the manuscript is written and representations of animal or human skin within its literary texts: medieval bestiaries consistently feature episodes representing wounded skin on manuscript pages in which the vellum itself was torn in its production [29]. If medieval reading involved a process recognized as skin-to-skin contact, not simply visual apprehension, attention to what might have been perceived in that contact is essential to understanding that process. There exist very fine-grained differences in tactile perceptions based on the individual properties of a reader's fingers, including dryness, calluses, oiliness, and even fingerprint shape and depth. These same factors have been shown to affect friction[9, 10], and could be captured in future work by design of an artificial probe with features that mimic real fingertips [18].

Further, comparison of visual and tactile impressions indicates strong inconsistencies between visually perceived texture and tactile perception of texture, suggesting that statements regarding vellum texture and quality based on viewing reproductions of manuscripts should be avoided. More detailed examination of these inconsistencies will be the subject of future study. Nonetheless, preliminary findings here suggest that, to assess the surface texture of vellum, which is often correlated with statements regarding quality and expense, objects must be handled or otherwise evaluated alongside study of visual cues. Without question, visual factors can shape tactile perception. The history of manuscript studies suggests that some evaluation of vellum that purports to be exclusively about texture has been largely influenced by visual factors, such as color, stippling patterns, and other exclusively visual phenomena. Terms such as "smoothness" and "roughness" conflate the visual and the textural, as this study demonstrates. This study provides a starting point for reevaluation of qualitative analyses of manuscript materials, decoupling the visual and the textural. The disjunction between optically perceived textures and measured tactile data should cause us to reevaluate prior claims regarding vellum properties such as "fineness", "quality", and "value".

Lastly, it is significant that the friction tests in this study did not result in wear of the samples. Vellum, unlike paper, is a durable material that responds well to human touch, hence the survival of manuscripts after hundreds of years of use. The absence of evidence of wear in this study suggests that these methods might be developed for further testing of actual medieval manuscripts.

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