"Soft Tribology and Tactile Sensing for Biomimetic Skin Applications"

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Abstract:

Tribology is key to understanding cosmetic feel, impacting product-skin interaction and perceived sensory experience. Skin friction, influenced by both product properties and skin physiology (age, body part, hydration, sebum), were studied for two skincare products with distinct sensory profiles. Two skincare formulations (1 with superior tactile perception, and 2) were tribologically tested using a rheometer and a custom three-ball-on-plate system. Five substrates representing a range of surface topographical textures –2 soft (Polyurethane and Silicone) and 3 relatively rough (Collagen Fiber, Cellulose Nitrate, and Polycarbonate)– ; were used to assess their effectiveness in predicting consumer perception of product formulas when performing tribological test in vitro. Friction coefficients (COF) were measured on the five formula -coated substrates, and plotted against sliding speed to generate Stribeck curves. All tests were performed in triplicates. Friction tests confirmed Formulation A's better lubrication compared to Formulation B across five different materials, mirroring expert panel assessments. However, the degree of difference depended on the material's properties. At a constant speed of 10 mm/s, two distinct friction coefficient (COF) groups emerged. Softer materials (polyurethane and silicone) showed lower and identical COFs for both formulations. Rougher materials (collagen, cellulose nitrate, and polycarbonate) exhibited higher and identical COFs. This material-dependent COF variation aligns with existing research showing that surface texture (like wrinkles) and thicker skin layers increase friction. The higher COF observed with collagen, cellulose nitrate, and polycarbonate may stem from their roughness or adhesive characteristics. Importantly, the difference in COF between Formulation A and B was much smaller on softer materials (around 0.025 to 0.04) compared to rougher materials (~1). While further investigation with a wider range of products is warranted, this observation strongly suggests that substrate hardness plays a crucial role in frictional properties. Incorporating this understanding of substrate interactions into tribological measurements could significantly improve the accuracy and reliability of predictive models for sensory perception, particularly tactile feel.

Key Words: Tribology, Coefficient of friction, Cosmetics, Sensory, Soft substrates

1. Introduction

The global cosmetics industry has evolved into a fast-paced and booming market with a valuation of US$ 700 billion each year, which requires constant innovation and understanding of sensory science involving skin [1]. The study of skin sensory perception and its link to tribology measurements is a burgeoning field that combines insights from dermatology, material science, and engineering. Tribology, the study of friction, wear, and lubrication, plays a crucial role in understanding how skin interacts with various surfaces, which in turn affects sensory experiences such as touch and comfort. The complexity of human skin, with its variability in structure and properties, presents unique challenges and opportunities for research in this domain [2].

The frictional behavior of skin is influenced by its hydration level, age, anatomical site, and health conditions. For instance, dry skin tends to have a lower friction coefficient compared to moisturized skin, which can affect sensory perception and comfort [3]. Skin tribology is affected by environmental conditions such as humidity and temperature, as well as personal factors like ethnicity, gender, and diet [4]. The presence of sweat acts as a natural lubricant, affecting the frictional interaction between skin and other surfaces. The non-Newtonian properties of sweat can influence the dynamic viscosity and load-carrying capacity of the skin, impacting sensory experiences [5]. Research has shown that the frictional behavior of skin is affected by both adhesion and deformation components, which vary with different skin conditions and contact scenarios [6]. Hydration is known to modify the properties of the stratum corneum [7] and in part is responsible for a softening thereof. Elderly individuals often exhibit lower finger friction coefficients, moisture, and elasticity, which are linked to reduced tactile discrimination [8].
Various instruments, such as tribometers, are used to measure the coefficient of friction and other tribological parameters of skin. These measurements can be correlated with physiological signals like skin conductance and temperature to assess comfort sensations [9]. Both in vivo (on living skin) and ex vivo (on skin models) studies are conducted to understand skin tribology. These studies help in developing biofidelic skin models that replicate human skin properties for more accurate measurements [10]. Combining tribological measurements with electrical impedance and other sensor data allows for a comprehensive evaluation of skin

conditions, aiding in the development of skincare products and early diagnosis of skin diseases [11].

While the study of skin tribology offers valuable insights into sensory perception and product design, it also presents challenges due to the inherent variability of human skin. Factors such as individual differences and environmental conditions make it difficult to standardize measurements and predictions. Moreover, the living nature of skin limits the applicability of conventional tribological models, necessitating the development of specialized methods and models for accurate assessments [12]. Despite these challenges, ongoing research continues to enhance our understanding of skin tribology, paving the way for innovative solutions across various industries. However, despite its importance, comparative studies of cosmetic formulations based on tribological profiles remain limited [13]. Therefore, this study intends to bridge this critical research gap and eventually help in improving the consumer experience. The purpose of this study involves studying coefficient of friction in two skincare products measured on five different types of substrates. These substrates represent a range of surface textures (two soft types and three coarser types) and were used to assess their effectiveness in predicting consumer tactile perception of these products.

2. Materials and Methods

2.1 Rheological characterization

The profile testing was performed on a research rheometer (HR10, TA Instruments) fitted with a custom “three balls on a plate” measuring system. In this test type, flow, squeezing, and bulk shearing methods were followed. The process involves bringing those surfaces into contact under a defined pressure and sliding one against the other, measuring the frictional drag over a range of sliding speeds. The surfaces and/or any applied lubricating liquid form the test sample. The formulations are brought into contact with a compliant surface and customer-supplied substrates onto which 0.5 mL of the sample has been spread to an even layer.

2.2 Sample preparation

Two formulations were evaluated for their tribological properties. A consistent axial load of 1N was applied, and the angular velocity was varied from 0.05 rad/s to 20 rad/s. The tribological evaluation employed a comparative approach, assessing two formulations across a range of substrate materials with varying properties. Five substrates were selected, encompassing both soft (polyurethane and silicone) and relatively rough (collagen fiber, cellulose nitrate, and polycarbonate) surfaces. This approach allows for a more comprehensive understanding of how the formulations behave under different contact conditions, mimicking a wider variety of realworld applications. Stribeck curves were generated by plotting COF against sliding speed. Each test was performed three times to ensure reliability.

2.3 Data collection and analysis

Friction, crucial for the sensory experience of cosmetic products, was evaluated by generating Stribeck curves. These curves plot the coefficient of friction (calculated as the ratio of sliding force to normal force) against sliding speed, providing a comprehensive picture of lubrication behavior and regimes across a range of application speeds. All measurements were performed in triplicate at a biologically relevant temperature of 34°C, mimicking skin temperature during product application.

Analyzing key aspects of the Stribeck curve, such as the transition points between regimes and the minimum coefficient of friction, allows for a quantitative comparison of the lubricating properties of different formulations. This information is directly relevant to the perceived "slip" and "spreadability" of cosmetic products. The study acknowledges the interplay between rheology (bulk flow properties) and tribology (surface interactions) in cosmetic application. Rheology dominates in the initial stages, where the product is applied as a thick film. As the film thins during spreading, tribological interactions become increasingly important, influencing the final sensory experience. This shift from rheological to tribological dominance is analogous to the application of topical skincare products or the oral processing of food and beverages, highlighting the study's broad relevance to consumer product development. By considering both rheological and tribological data, a more complete understanding of product performance and consumer perception can be achieved, facilitating the development of optimized formulations with enhanced sensory properties.

3. Results

The frictional properties of two cosmetic formulations were evaluated in relation to their perceived smoothness and spreadability during application. The coefficient of friction (COF), a measure of shearing resistance, was determined for each formulation across five substrates, including soft materials mimicking skin (polyurethane, Bioskin from *Beaulax,Co.Ltd.* and silicone) and rougher materials representing skin with textural variations (collagen fiber film, cellulose nitrate filter, and a Millipore^{TM} Isopore polycarbonate filter). Measurements were performed in triplicate at a constant sliding speed of 10 mm/s, reflecting typical cosmetic application speeds. Table 1 presents the COF (μ) values, and Figure 1 visually compares the average μ values for each formulation across the substrates.

Formulation 1 consistently exhibited a lower COF than Formulation 2 across all substrates, indicating smoother spreading and glide. This objective finding corroborates subjective assessments from expert panel evaluations. The magnitude of the μ difference between formulations varied depending on the substrate. On softer, skin-like materials (polyurethane and silicone), the COF difference was relatively small. This minimal differentiation suggests that these substrates are less sensitive to the variations between the formulations, making them less suitable for discerning subtle differences in frictional properties. Consequently, collagen fiber, cellulose nitrate, and Millipore^{TM} Isopore polycarbonate are preferred substrates for evaluating these formulations, as they exhibited clearer differentiation in COF values. On these rougher substrates, the difference in COF was substantially larger (~1), implying that Formulation 1's superior glide would be more perceptible on skin with texture or imperfections. The higher COF observed on rougher substrates aligns with the well known tendency of skin texture, such as wrinkles and thicker skin layers, to increase friction [14] The increased friction observed with Formulation 2 on the silicone substrate, which mimics skin's oiliness and hydrophobicity, might be attributed to a higher concentration of particulates or a thicker base.

Regarding substrate performance, cellulose nitrate filters demonstrated the highest repeatability at low speeds, while silicone showed the best repeatability at higher speeds. All substrates yielded consistent results at the chosen quantification speed of 10 mm/s. While silicone and Bioskin showed less differentiation between formulations, the Millipore Isopore polycarbonate filter presented a unique challenge: Formulation 1 caused rapid substrate deterioration, necessitating the use of a fresh substrate for each measurement. For consistency, a fresh Millipore Isopore substrate was also used for each measurement with Formulation 2, although it did not exhibit the same deterioration. Additionally, both formulations caused noticeable adhesion to the lower testing pad when used with the cellulose nitrate filter, requiring significant effort to remove. These observations highlight the importance of careful substrate selection in tribological studies of cosmetic formulations.

Table 1. *Coefficient of Friction Metrics for Formulation 1 and Formulation 2 across five substrate types in triplicate*

Substrate	Coefficient of Friction at 10mm/s							
	Formulation 1				Formulation 2			
	Run 1	Run 2	Run 3	Mean	Run 1	Run 2	Run 3	Mean
Bioskin Substrate	0.0682	0.0552	0.0729	0.0654	0.1060	0.0888	0.0763	0.0905
Collagen Fiber Film	0.1280	0.1440	0.1500	0.1410	0.2550	0.2650	0.2020	0.2410
Cellulose Nitrate Filter	0.1390	0.1560	0.1120	0.1360	0.2310	0.2570	0.2390	0.2420
Millipore Isopore Polycarbonate Filter	0.1570	0.1370	0.1300	0.1410	0.2630	0.2580	0.2230	0.2480
Silicone Substrate	0.0801	0.0693	0.0649	0.0714	0.1190	0.1110	0.1080	0.1130

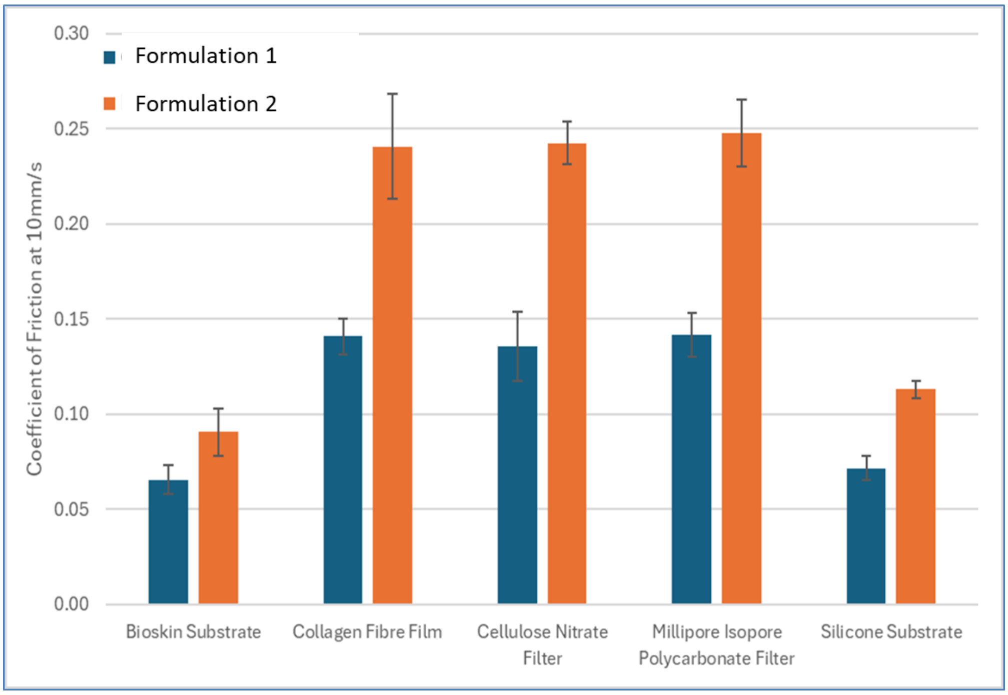
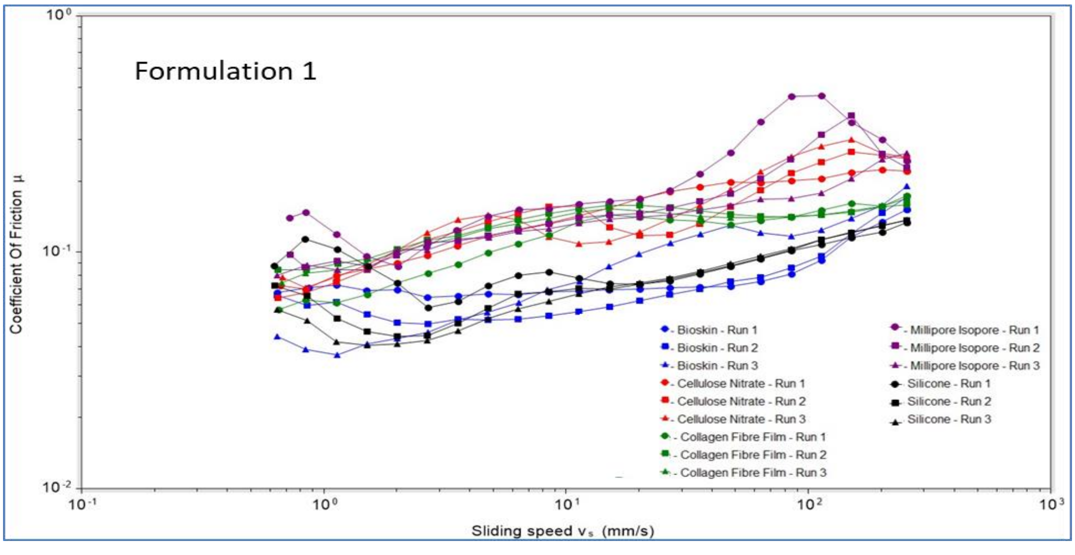
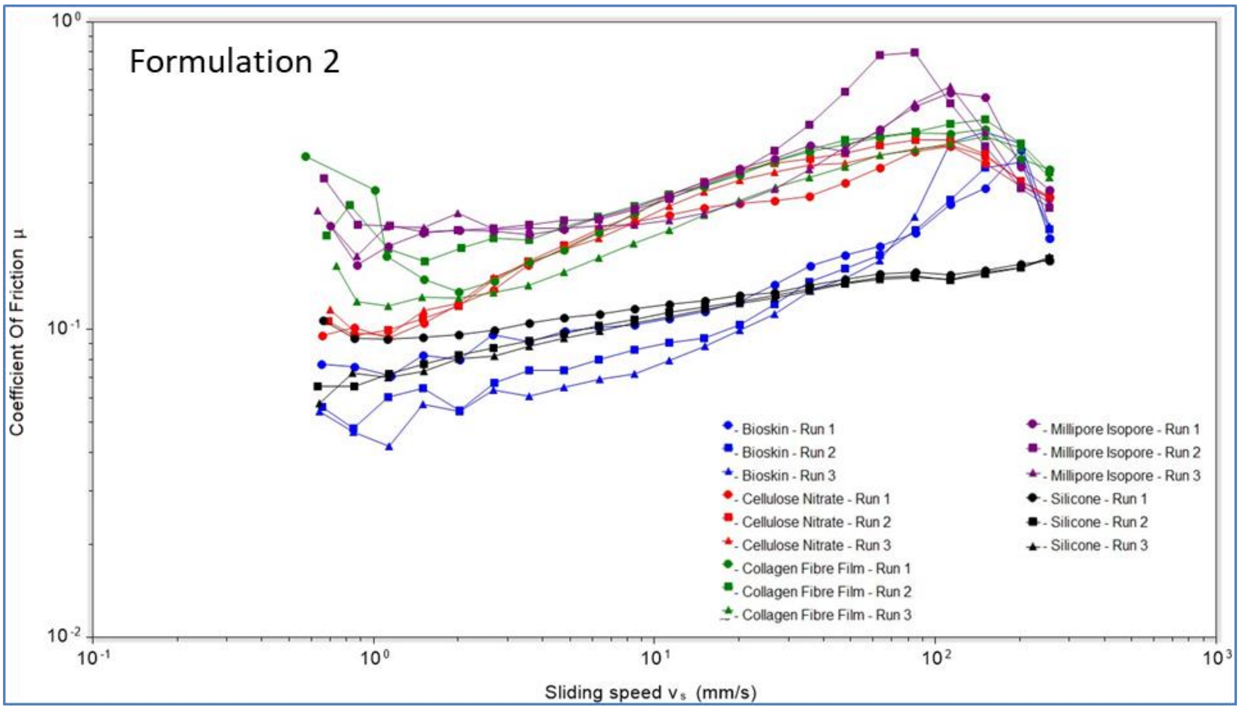


Figure 1. *Tribological measurements of the two formulations, Formulation 1 and Formulation 2, on different substrates*

Figure 2 presents the Stribeck curves comparing the five substrates within each formulation. Within Formulation 1 (Figure 2a), the Milipore Isopore polycarbonate filter peaked in terms of COF, while Bioskin and silicone showed lesser friction, implying that Formulation 1 could spread more smoothly across these surfaces than others. Similar results were also observed for Formulation 2, where the Milipore Isopore polycarbonate also displayed facing a lot of friction compared to the others (Figure 2b).



(a) Coefficient of Friction vs sliding speed (mm/s) for Formulation 1



(b) Coefficient of Friction vs sliding speed (mm/s) for Formulation 2

Figure 2. *Coefficient of friction vs Sliding speed of the two formulations, Formulation 1 and Formulation 2, on different substrates*

4. Discussion

This study investigated the tribological behavior and tactile responses of two popular cosmetic skin formulations using five different biomimetic substrates, providing insights into how formulation and substrate properties interact to influence perceived skin-feel. Formulation 1 consistently demonstrated lower COF values, indicating superior lubricity and smoother glide compared to Formulation 2. This aligns with sensory evaluations, where Formulation 1 was described as smoother, thicker, and creating a more slippery sensation during and after application (Figure 3). Conversely, Formulation 2, while less slippery, penetrated the skin more rapidly, suggesting a different formulation viscosity or composition.

The observed discrepancies in frictional and tactile properties likely arise from the inherent physical disparities between the formulations. Formulation 1's thicker consistency, opacity, and film-forming properties contribute to its enhanced lubricity and "soaping" effect. Formulation 2's quicker absorption points towards a thinner consistency, potentially with different emollient or humectant components.

While direct comparisons with existing research are constrained by the limited number of studies employing identical formulations and methodologies, our findings resonate with broader themes in skin tribology. The significance of substrate properties in tribological measurements is well-documented [2, 3, 13]. The observation of similar or lower COFs on softer substrates (Bioskin and silicone) is consistent with the understanding that substrate compliance impacts frictional behavior [3]. Bioskin's hydrophilic nature, facilitating the formation of a lubricating layer, has been previously reported [1], though direct comparison is limited by variations in experimental gels. While silicone substrates have been associated with higher friction in some studies [1], the lower friction observed here could be attributed to silicone's inherent lubricating properties, potentially overshadowing formulation-specific effects.

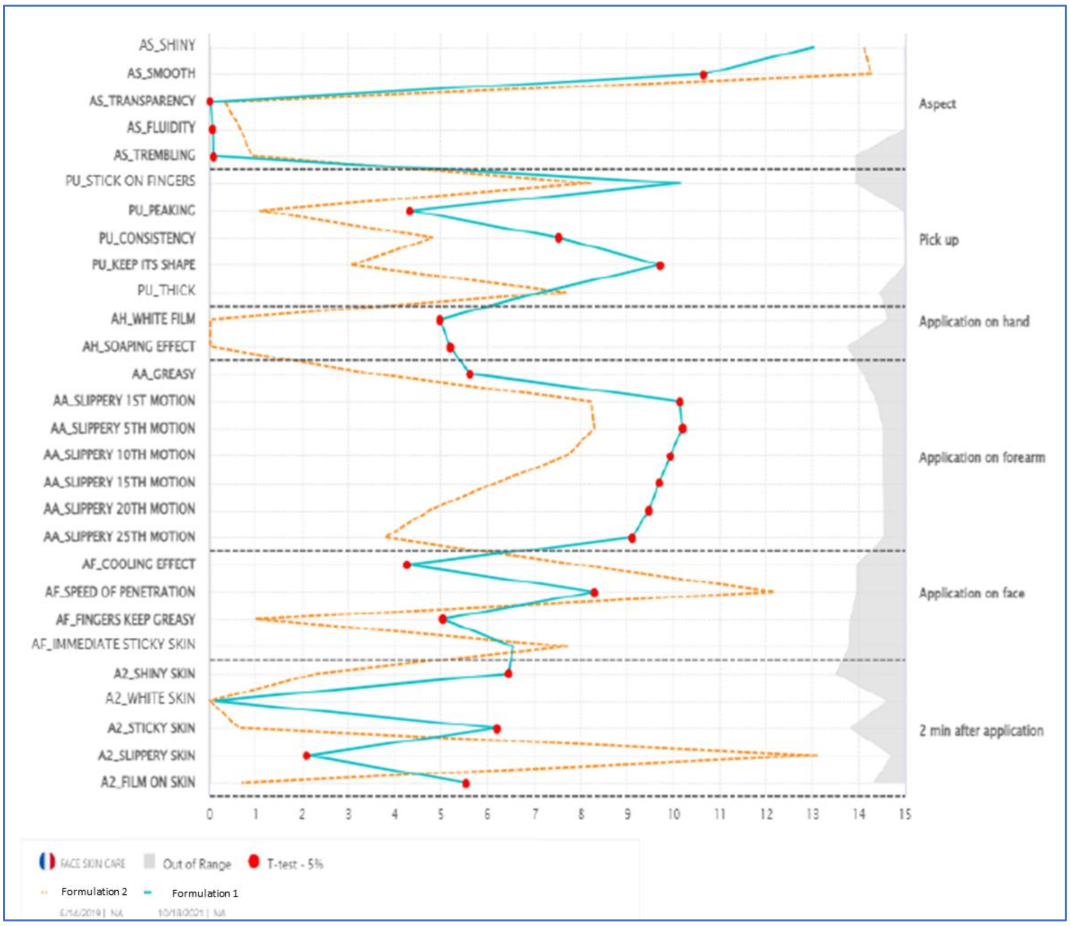


Figure 3. *Moments of evaluation between Formulation 1 and Formulation 2*

This study's findings have important implications for cosmetic formulation design. The observed substrate-dependent variation in COF underscores the critical role of substrate properties in accurately assessing frictional behavior and predicting tactile perception. As emphasized by [5, 12], a comprehensive understanding of skin lubrication mechanisms is essential for developing cosmetic products with optimized sensory attributes. By considering substrate interactions, tribological measurements can become more robust and reliable predictors of in-vivo tactile feel. This knowledge can guide product development by ensuring compatibility with both skin chemistry and topography, ultimately enhancing consumer experience and potentially influencing product marketing and consumer engagement. The use of five distinct substrates in this study reinforces the importance of carefully considering surface properties when simulating human skin in vitro. This approach allows for a more nuanced understanding of how formulations interact with different skin types and textures.

Furthermore, this research highlights the potential of tribology as a tool for rapid screening and refinement of cosmetic formulations, minimizing reformulation cycles, reducing raw material waste, and streamlining research processes. However, it is important to acknowledge the study's limitations, including the limited number of formulations tested, the absence of a natural substract (i.e. stratum corneum) for compariuson, the absence of statistical analysis, and the lack of focus on wear and lubrication quantification. Future research should incorporate sensory evaluations with human participants, explore a wider array of substrates, include statistical analysis, and investigate wear and lubrication phenomena. Complementing tribological data with rheological profiling could offer a more holistic understanding of formulation behavior and its impact on sensory perception [13]. Incorporating these recommendations will strengthen the link between in vitro tribological measurements and in vivo sensory experiences, leading to more effective and consumer-centric cosmetic product development.

5. Conclusion

This study demonstrates that Formulation 1 exhibits superior lubricity, potentially leading to a smoother, more desirable user experience. Its improved performance on rougher substrates suggests enhanced efficacy on skin with textural irregularities. While Formulation 2's tactile properties remain within an acceptable range, its higher friction might be perceived as a thicker or more resistant feel during application. Notably, the Bioskin substrate proved most effective in simulating normal or moisturized skin, with both formulations demonstrating favorable performance on this material. These findings highlight the potential of soft tribology as a valuable predictive tool for in vivo sensory performance, offering the possibility of reducing reliance on panel testing during early cosmetic development stages. This approach can streamline the development process, accelerating the creation of formulations optimized for desired tactile attributes.

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