

Investigation on the Friction Coefficient of Indian-Origin Human Hair

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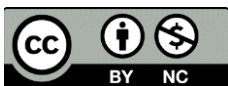
ABSTRACT

Human hair often interacts with polymer grooming tools and fails due to sliding contact and friction. The friction characteristics of human hair under dry and wet conditions at different applied loads are studied using an in-house developed capstan tribometer. Tests were conducted using a healthy Indian-origin female's hair to avoid the effect of various treatments, followed in different individuals. Wet conditions were simulated by spraying water on the cylinder surface in a controlled manner. Compared to dry conditions, the measured friction coefficients showed a greater friction coefficient in wet conditions. In both dry and wet conditions, it was found that the friction coefficient for human hair decreased as the load increased. The contact area under wet conditions differs from dry conditions due to the presence of water and meniscus formation at the interface, contributing to the difference in the friction coefficient.

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1. INTRODUCTION

Hair friction is a critical factor in the grooming, styling, and overall manageability of hair. The interaction between hair and grooming tools, such as combs and brushes, involves significant frictional forces that can influence hair quality. Excessive friction can lead to hair damage. This damage can be minimized by using hair care products such as shampoo, conditioner, serum, etc., which will affect the coefficient of friction. Additionally, suitable materials usage and grooming tool design will minimize friction and protect against hair damage.

Human hair is a complex hierarchical structure with a diameter typically ranging from 50 to 100 μm [1]. It mainly consists of three layers: medulla, cortex, and cuticle as shown in Fig. 1 [2]. The medulla is the innermost layer of hair, surrounded by the thickest layer, the cortex. The cortex is the primary structural part of hair, containing cortical cells which consist of microfibrils. The cortex plays a role in determining mechanical stability, strength, color, texture, and overall hair health [3]. The cuticle covers the cortex and consists of layers of thin scales. Each scale is about 0.5 μm thick

and approximately 60 μm in length. Five to ten scales overlap to produce the cuticle, which has a total thickness of about 5 μm [4]. The structure of the cuticle is affected by the environment and various hair-styling processes such as combing, brushing, coloring, etc. These styling processes can damage the cuticle, particularly if done harshly or with inappropriate tools. Hair damage tends to be more severe in the case of long hairs having lengths more than 25 cm [5].

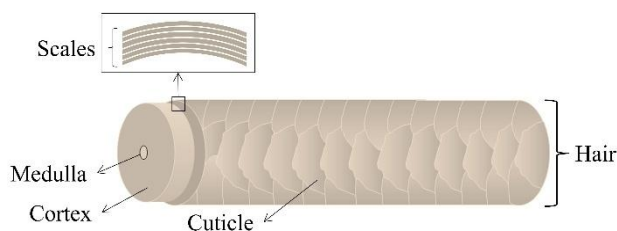


Fig. 1. Schematic of human hair.

Although research on hair friction is crucial, there aren't many published reports because it's hard to measure. Shampoo and conditioner industries are interested in understanding how their products affect friction behavior [6], for better product development. Lower friction between hair strands reduces tangles and knots, making hair easier to comb. Minimizing friction also prevents hair breakage and cuticle damage during combing and brushing. Therefore, understanding hair friction assists in optimizing the material and design of grooming tools. Additionally, the insights into hair friction are valuable for developing artificial synthetic hair that mimics the properties of natural hair.

Different types of experiments were conducted to understand the frictional behavior of hair. Robbins [5] followed the capstan method to evaluate hair friction. The authors used a tensile testing machine in which one end of the hair was connected to the tensile testing machine while attaching a load to the other end. The hair strand was partially wrapped around two mandrels. As the mandrels moved downward, the frictional tension was recorded, and the friction coefficient was calculated. Bhushan et al. [6] employed AFM (Atomic Force Microscopy) techniques to evaluate friction between hair strands and polyurethane film considered equivalent to human skin. AFM technique was also used to measure the

frictional force between the two hair strands [7]. The nano scratch technique was employed to investigate the nanotribological properties of human hair [8]. Friction Force Microscopy (FFM) was used to assess the frictional properties of hair [9]. The friction between the bundles of human hair and human fingers was evaluated using a tribo tester, which was also used to explore the friction dynamics of artificial hair [10]. Straight, curly, and wavy hair types were used [11]. A friction and wear study involving human hair under different surface treatments was conducted by rubbing two single strands together in a direction [12]. Furthermore, the static friction of human hair against human hair was assessed through a novel method of tying a knot [13]. Numerous experimental techniques demonstrated the intricacy and unpredictability of the frictional behavior of human hair.

In daily life, hair interacts with other hair strands during headshakes and entanglements, with human skin (such as fingertips), with grooming tools (like combs), with textiles and fabrics, and with hair accessories (such as pins and clips). Interaction of hair with grooming tools, mostly made of polymeric materials, is frequent and influences hair damage. The cuticle is affected by environmental conditions, such as humidity, temperature, and water exposure [14], and also based on the washing liquids and conditioners. Understanding all these factors is crucial as they can significantly impact the frictional properties of hair. Moreover, the frictional properties of hair can also exhibit variations due to ethnicity, with differences in hair shaft shape, texture, and cuticle structure [15]. The primary purpose of this work is to report the friction behavior of single human hair strands under different loads in both dry and wet conditions, using an in-house developed tribometer. To reduce inherent structural differences in hair from person to person and from individual hair care practices, hair samples were collected from a single healthy individual of Indian origin. Human hair frequently slides against polymeric grooming tools, and in the current study, the hair is made to slide against a capstan cylinder made up of polyamide (a common comb material). Friction characteristics of human hair under dry and wet conditions are reported.

2. MATERIALS AND METHOD

Hair strands were collected from a female individual of Indian ethnicity. The collected hair strands were not less than 45 cm and they have undergone normal washing, oiling, and other regular hair care processes. The considered hair samples did not undergo any kinds of processes such as hair straightening, curling, dyeing, or bleaching. The hair strands were washed to remove oil, dust, and other impurities, and then dried completely in the open environment.

Two types of samples were prepared: (i) dry hair, and (ii) wet hair. The dry hair samples were prepared by keeping the hair strands in the oven at 40°C for 1 h. While the wet hair samples were prepared by soaking the dry hair strands in distilled water for 1 h at ambient temperature (28-30°C). The tested samples were cut to a length of 15 cm from the middle region of a long hair. The hair samples were rubbed against a smooth polyamide cylinder. The polyamide material was chosen as the counter body because many hair grooming tools such as combs, brushes, etc. are made up of polyamide and similar polymers.

The hair surface was observed using a digital microscope (Olympus DSX1000) using DIC (Differential Interference Contrast) microscopy mode. This method improves contrast for detailed observation of samples, generally used for sample surfaces with minimal height differences. The same digital microscope was used to measure the diameter and roughness using non-contact methods. The digital microscope is capable of capturing high-resolution 3D images of a sample by acquiring multiple images at different focal planes and combining them using advanced algorithms. The embedded software is used to analyze these 3D images and determine the roughness of the surface. Measurements were taken at various locations of different hair strand samples, and the average diameter and roughness were estimated as shown in Fig. 2.

A tribometer was designed and developed to investigate the friction coefficient of single hair strands (Fig. 3). A single hair strand is wrapped around the capstan cylinder; one end of the hair strand is connected to a high-accuracy load cell, and the other end is connected to a known deadweight load with the help of two grippers.

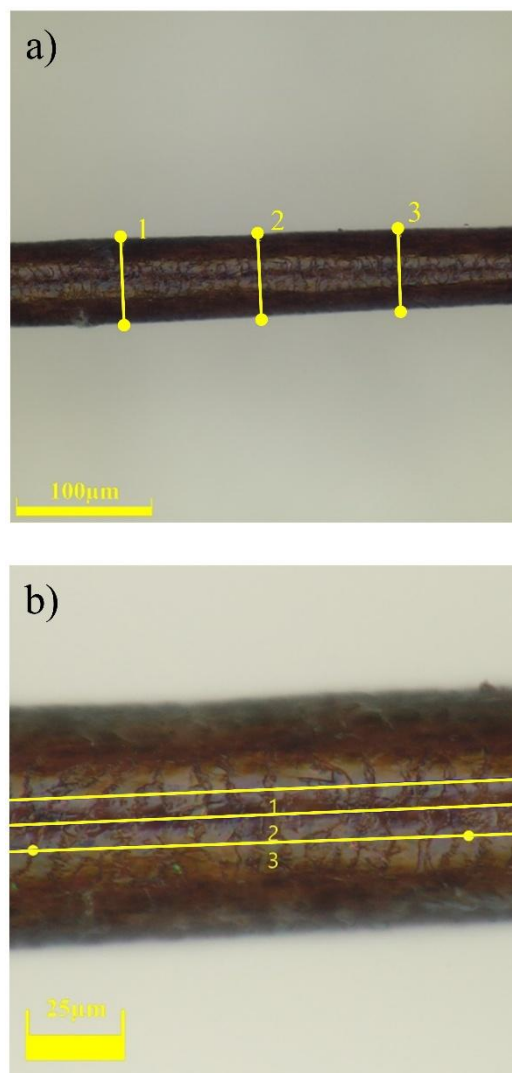


Fig. 2. Optical images of human hair: a) diameter measurement locations and b) roughness measurement paths.

When the capstan cylinder starts rotating, the variations in tension are recorded with time by the load cell. The coefficient of friction (μ) between a hair strand and the counter body surface is estimated using equation 1.

$$\frac{T_2}{T_1} = e^{\mu\theta} \quad (1)$$

Here, T_1 is the known applied load, T_2 is the load cell reading and θ is the wrapped angle in radians. In the current study, the wrapped angle is kept constant, which is π radian (180°).

The cylindrical counter body was prepared by machining an extruded polyamide rod. The diameter and roughness (R_a) of the counter body capstan cylinder are 50 mm and $0.49 \mu\text{m}$, respectively. The friction test conditions employed are given in Table 1.

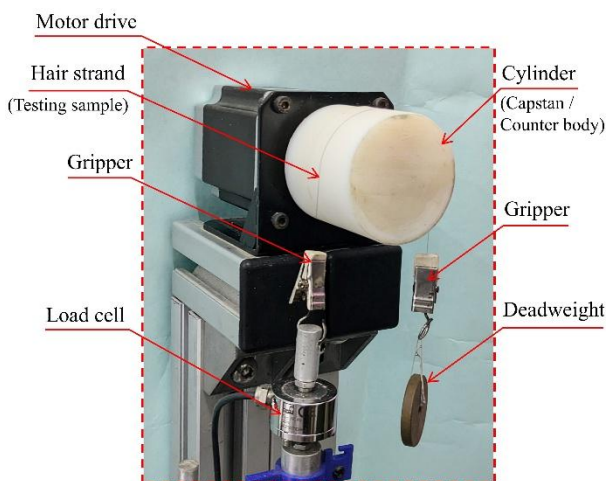


Fig. 3. In-house developed tribometer used for single hair strand test.

Table 1. Hair friction test parameters employed.

Parameter	Value
Cylinder diameter	50 mm
Rotational speed	1 rpm
Sliding speed	157 mm/min
Contact length	78.54 mm
Deadweight load	15 g, 25 g, and 50 g
Test duration	200 s
Test conditions	Room temperature 1. Dry counter surface 2. Wet counter surface

All the friction tests were performed in the laboratory atmosphere (28-30°C, 50-60% RH). In the case of wet hair friction testing, the capstan cylinder surface was mist-sprayed with distilled water as illustrated in Fig. 4. While running an experiment, the mist spray was used in regular intervals to keep the counter body surface wet throughout the experiment. The friction force varies depending on the direction of the cuticle and the sliding motion [16–18]. In the experimental setup, the root end of the hair strands was connected to the load cell, while the hair tip end was connected to the deadweight load. The hair samples were slid over the polyamide counter body for 200 s under dry and wet conditions. A 25 g deadweight load was connected to the end of a hair strand sample. This configuration resulted in the sliding direction of the capstan cylinder ‘along the cuticle’ direction, from root to tip direction, as illustrated in Fig. 5. The sliding direction normally followed while grooming (‘along the cuticle’ direction,) is duplicated in

tests [17]. In this paper, the values following the ‘±’ symbol represent the standard deviation from the mean.

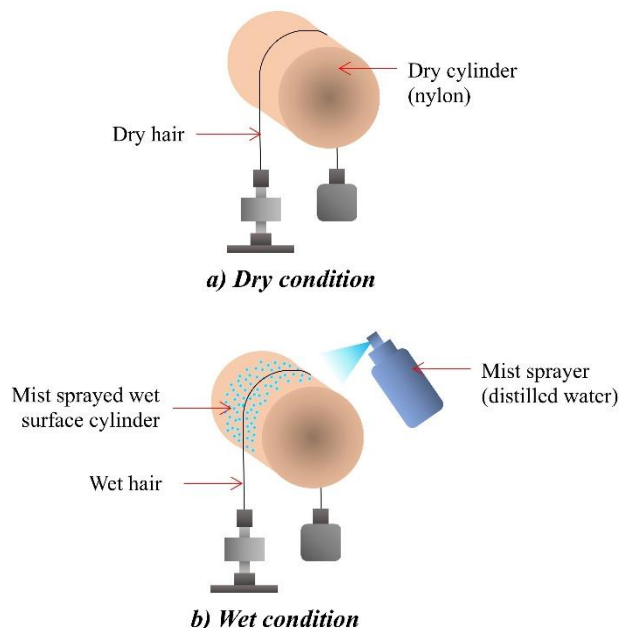


Fig. 4. Schematic of hair-capstan contact under (a) dry condition and (b) wet condition tests.

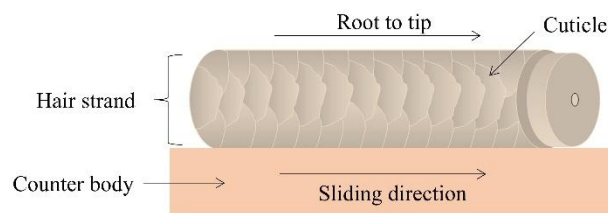


Fig. 5. Schematic of hair cuticle direction and sliding direction

3. RESULTS AND DISCUSSION

The DIC microscopy images of hair surfaces are shown in Fig. 6. The cuticle scales are found closely aligned, indicating smooth and healthy hair. Better moisture retention, increased strength and durability, and protection from environmental harm are just a few benefits that come with having tight cuticles.

The diameter of the hair samples ranged between 60 and 90 μm. The hair samples’ measured average roughness (R_a) along the length is $0.102 \pm 0.029 \mu\text{m}$. This roughness value was the average of a minimum of 30 readings.

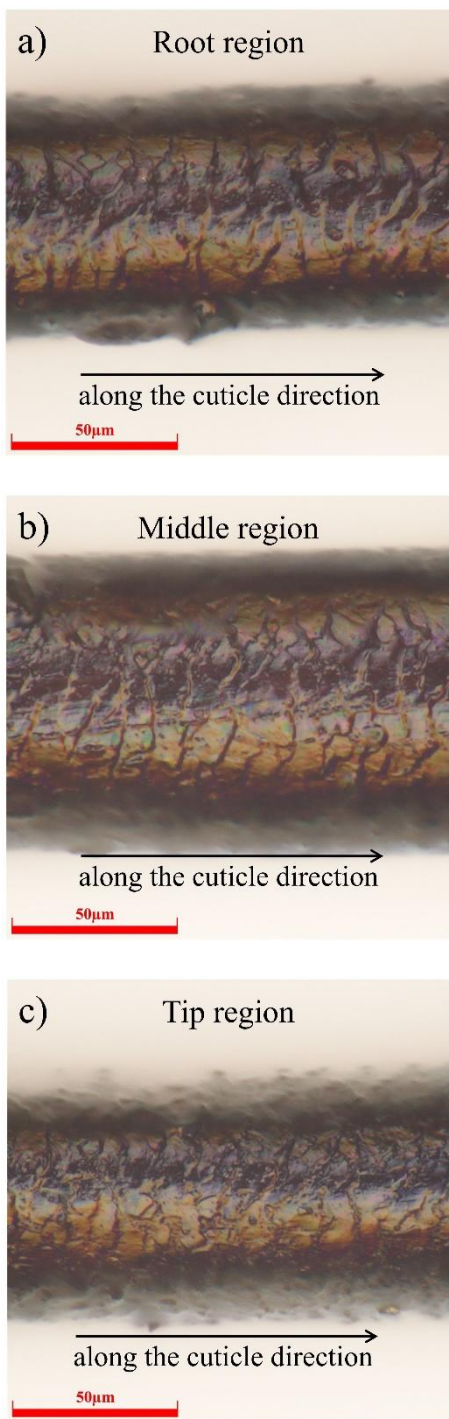


Fig. 6. Surface of a human hair in three regions observed under microscopy (a) root (b) middle and (c) tip region.

The typical friction coefficient variation vs sliding time is shown in Fig. 7. The instantaneous coefficient of friction was calculated with the help of Equation 1 and the steady-state coefficient of friction was calculated by averaging the values of the instantaneous coefficient of friction from the steady-state friction period. The steady-state

friction represents the period during which the sliding surfaces reach a relatively stable sliding condition. When the successive values of the friction coefficients are less than 10%, it is considered that the steady state is reached. For uniformity in both types, the steady state is estimated from 60 s to 200 s.

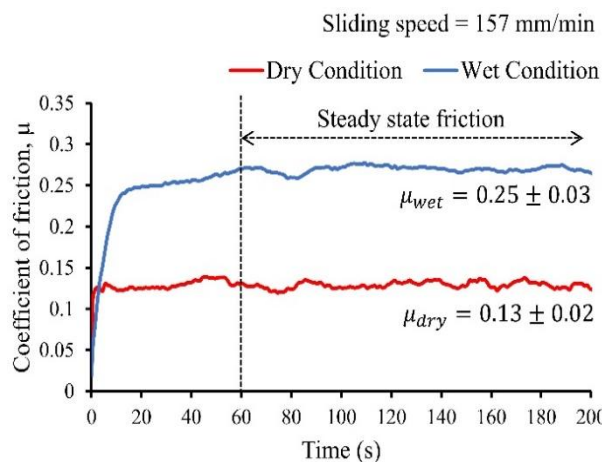


Fig. 7. Coefficient of friction vs time plots for human hair sliding against polyamide in dry and wet conditions.

The results showed distinct variations in the frictional behavior of human hair in dry and wet conditions. The steady-state coefficient of friction for human hair is 0.13 ± 0.02 in dry conditions and 0.25 ± 0.03 in wet conditions. With a high friction coefficient, the susceptibility of hair damage under wet conditions is high compared to dry conditions. Robbins [5] reported a similar range of friction coefficient values for both dry and wet hair when tested against polyamide in a different type of test configuration.

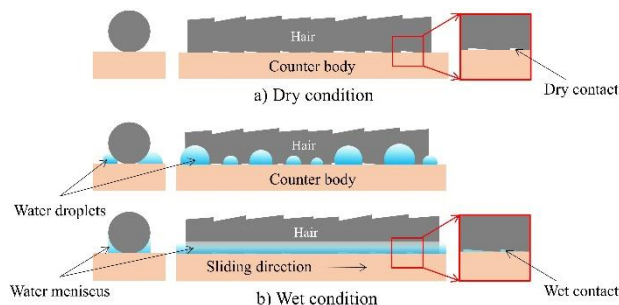


Fig. 8. Interaction of hair and counter body surfaces in (a) dry and (b) wet conditions.

The meniscus formation was observed around the contact in wet conditions, as illustrated in Fig. 8. The presence of water near the interfaces due to meniscus formation increases the

adhesion between the hair and the cylinder surface. In dry conditions, the edges of the cuticle can form small voids at the interface due to the undulations of the hair surface. Under wet conditions, water particles present in the wet hair get entrapped and increase the real contact area. This increased contact area results in higher friction of human hair in moist or wet conditions.

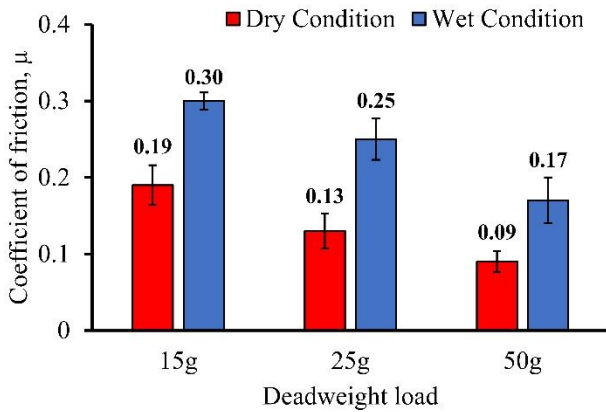


Fig. 9. Comparison of the steady state friction coefficients under different loads in dry and wet conditions.

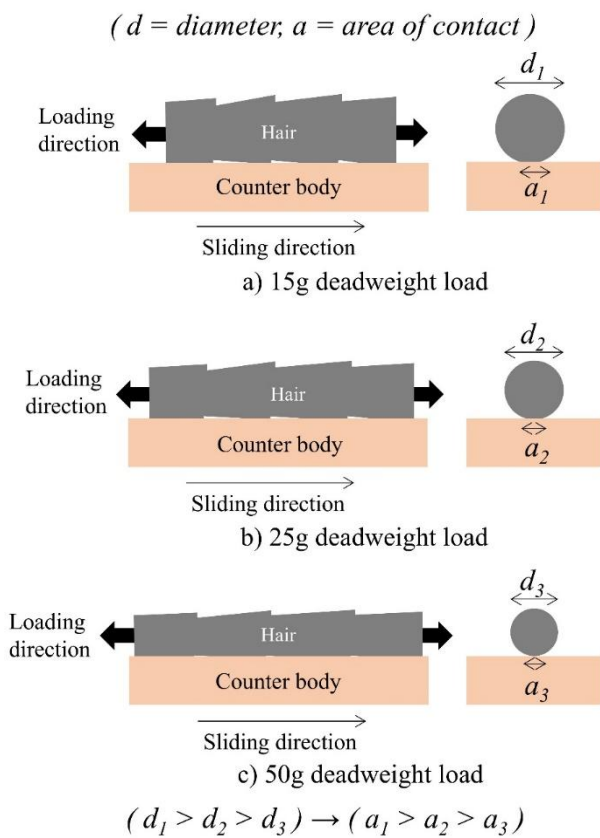


Fig. 10. Comparison of the steady state friction coefficients under different loads in dry and wet conditions.

The dependency of the coefficient of friction with load was studied in both dry and wet conditions. The steady-state friction coefficient values are plotted in Figure 9. The coefficient of friction for wet hair was higher than that of dry hair in all the loads investigated. With an increase in normal load, which corresponds to intensive combing or use of grooming tools, the friction coefficient was reduced in both the test conditions, dry and wet. This decrease in friction can also be related to the area of contact between the hair and the counter body surface. Lee and Kwon [19] reported that the engineering strain for human hair can reach up to 0.52 until failure occurs, and Poisson's ratio of human hair is 0.37 ± 0.05 . Such high breaking strain and Poisson's ratio indicate a large decrease in the cross-sectional area of the hair strand due to the increase in length at high loads. This reduction in hair diameter affects the contact area as shown in Fig. 10 and leads to a disproportionate increase in the frictional force relative to the normal force, resulting in a decrease in the coefficient of friction.

4. CONCLUSION

The friction characteristics of dry and wet hair at different normal loads were investigated using an in-house developed capstan-based test device and the following conclusions were drawn:

1. The in-house developed tribometer proved effective for testing single hair strands in dry and wet conditions.
2. Hair strands exhibit higher values of friction coefficients in water-soaked wet conditions compared to dry conditions, attributed to increased real contact area and meniscus formation at the hair-counter body interface.
3. High applied load results in reduced friction coefficients for a single hair strand due to the elongation and decrease in diameter under load.

However, this study has some limitations. The research focused on hair samples from a single individual of one origin to minimize variability. Different hair types can affect friction, but this study focused only on straight hair. Despite these limitations, this study provided an understanding of the effect of water and loads on hair friction, contributing to further research in the field of hair tribology.

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