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Short Communication

Hair-on-hair static friction coefficient can be determined by tying a knot

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A B S T R A C T

Characterizing the tribological properties of the hair–hair interface is important to quantify the manageability of hair and to assess the performance of hair care products. Audoly et al. (Phys. Rev. Lett. 99, 164301, 2007) derived an equation relating the self-friction coefficient of an elastic fiber to the dimensions of a simple, relaxed overhand knot made from this fiber. I experimentally tested and validated their equation using nylon thread and an independent measurement of its self-friction coefficient. I show that this methodology can be applied to provide high-throughput data on the static self-friction coefficient of single hair fibers in various conditions and to quantitatively assess how hair care treatments (conditioner, relaxant) alter frictional properties. I find that treatment of hair with 1 M sodium hydroxide leads to a quick, irreversible self-friction coefficient increase; the resulting fine frictional fibers can be used to form very small knots for microsurgical vessel and organ ligature in medicine or embryology. The relaxed overhand knot method can more generally be used to measure the self-friction coefficients of a wide range of elastic fibers from the nano- (e.g. proteins, nanotubes) to the macro-scale (e.g. textile fiber, fiberglass).

1. Introduction

The frictional properties of hair are, along with its elastic properties, among the most important parameters governing hair manageability. Central to the tribological properties of hair is the outer cuticle layer made of keratin scales and covered with a layer of a saturated fatty acid, 18-methyleicosanoic acid. The tendency of hair to form knots, the ease with which hair is combed, and the "softness" of hair, as judged by touching it, are all directly linked to the friction of hair, either on itself or on other materials. Assessing the frictional properties of different hair types and how they are modified by hair-care products are therefore important challenges for cosmetic scientists and biophysicists.

1.1. Methods to measure hair-on-hair friction

The first methods developed to measure hair friction usually involved hair bundles, such as the Roeder method [1,2]. The apparatus developed by Roeder (Fig. 1a) consists of a pulley with a mandrel surface covered with hair. A single hair is then passed around the pulley to which two weights are fastened, one on each side of the pulley. The friction of the hair on itself is then measured by means of a torsion balance as the difference of force required to bring the single hair fiber in motion on this hair-covered mandrel. More recently, a fully automatic tribometer has been developed [3] to measure the friction of a surface pressed against a bundle of parallel hair (Fig. 1b). Concerning single hair measurements, Dussaud et al. introduced an "inclined plane" method [4] in which a loop of hair is deposited on two parallel hair fibers (Fig. 1c); the whole setup is gradually inclined until the hair loop slides, the static friction coefficient μ_s is deduced from the sliding angle θ as $\mu_s = \tan\left(\theta\right)$. Although this method is straightforward, it is slow and not suited to test friction in a medium other than in air. By gluing hair on atomic force microscopy (AFM) cantilevers (Fig. 1d), Luengo et al. [5] have recently measured the contact and non-contact normal force between two hair strands and the dynamic friction when the two are rubbed against each other. La Torre et al. [6] used silicon nitride AFM cantilevers to measure the roughness, adhesion and frictional properties of hair and the modification induced by different ingredients used in conditioner. Although providing detail at a nanometric scale and with a sensitivity high enough to probe molecular forces, the AFM has a low sample throughput (typical measurement time for a pair of hair fibers ~ half-a-day) and requires specialized equipment.

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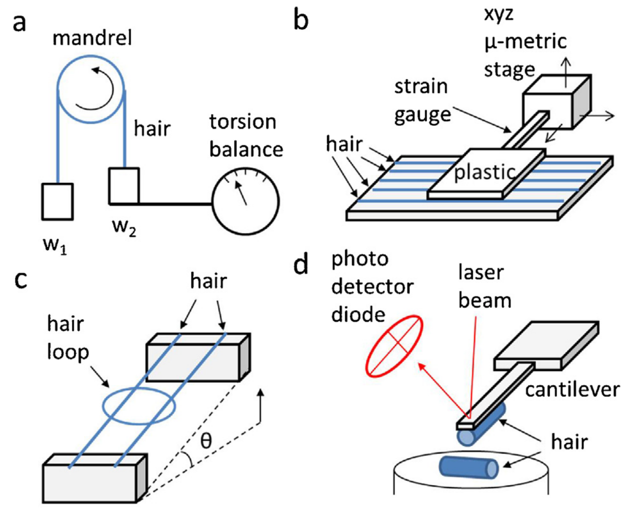

Fig. 1. Different methods to measure the frictional properties of hair. (a) The Roeder [1,2] method, the mandrel surface is covered with hair. (b) Apparatus devised by Bhushan et al. [3] to measure the frictional properties of a hair bed on another material (here plastic). (c) Inclined (θ) plane method [4] with three hairs (one hair loop and two tensed hairs that support the hair loop). (d) Friction, topology and adhesion can be measured with an Atomic Force Microscope with a cantilever on which a piece of hair has been glued [5]. The two hair samples are here at a 90° angle.

1.2. Principle of the relaxed overhand knot method

Here, I introduce a new and simple method to measure hair-on-hair friction based on tying an overhand knot with a single hair strand (Fig. 2a). The knot is tightened to a loop radius of a few millimeters; when the tensile force is released, the elastic bending energy stored in the fiber causes the loop diameter to increase (Video S1). Fiber-on-fiber friction locks the loop at an equilibrium diameter D (Video S1, Fig. 2a,b). According to Amonton's law, this friction force f is proportional to the normal force N that presses the hair fiber against itself within the braid of the knot, i.e. $f = \mu_s N$ (Fig. 2a). This normal force is directly proportional to the elastic bending energy in the knot. Because both the driving force for loop opening and the friction force that halts loop opening are proportional to the elastic bending energy, it follows that the equilibriumdiameter of the loop will depend only on the self-friction coefficient of hair, and not on the elastic bending energy. The equilibrium diameter is therefore independent of fiber elastic properties. A similar situation is encountered in calculating the sliding angle of a mass on an inclined plane: it only depends on the friction coefficient and not on gravity because gravity drives both sliding of the mass and generation of the friction force via Amonton's law. The detailed calculation of the knot equilibrium shape has been worked out by Audoly et al. [7] who found that loop diameter D, fiber diameter d and the static fiber-on-fiber friction coefficient μ_s are related by

$$\mu_s = 1.02\sqrt{d/D} \tag{1}$$

In other words, *the self-friction coefficient of an elastic fiber of diameter d can be obtained by simply measuring the equilibrium diameter D of a relaxed overhand knot*. To the best of my knowledge, this most elegant and forceful result has been subject to only very limited experimental testing [7] and has not been used to perform tribological measurements on common fiber material.

I first experimentally tested Eq. (1) on a simple, homogeneous material (nylon) and compared the results with another, established and independent measurement method (inclined plane). I then applied this methodology to the industrially and biophysically relevant case of hair. I found static friction coefficients for dry and wet hair that are consistent with those reported in the literature and I could quantify the effect of applying conditioner and sodium hydroxide (hair straightener). I believe this simple method-

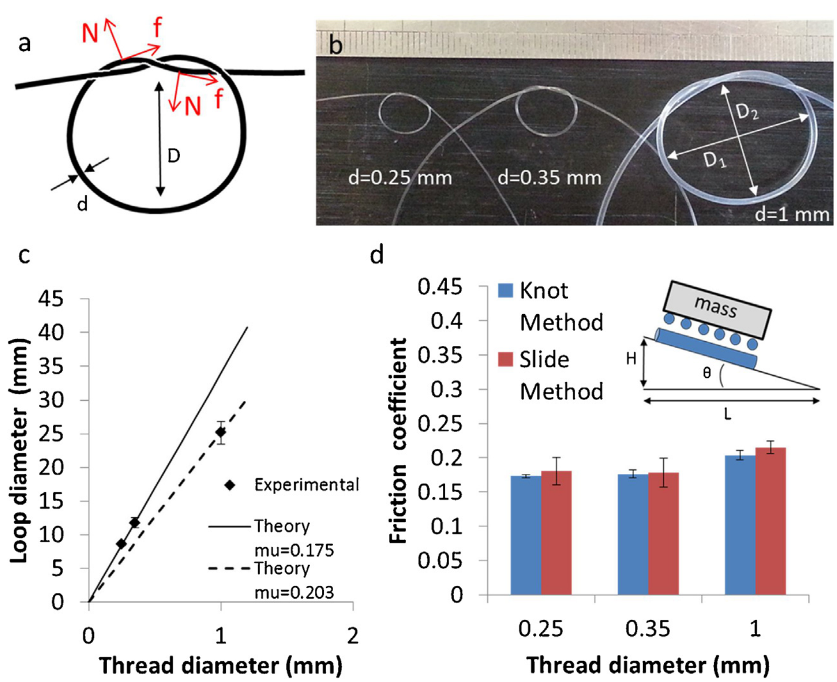

Fig. 2. Testing the knot method with nylon fibers. (a) Scheme of the relaxed overhand knot. One braid exerts a normal force N on the other, the local friction force that resists loop opening is $f = N\mu_s$. (b) Relaxed overhand knots obtained for three different nylon thread diameters, a millimeter scaled ruler is placed in the top part of the picture. The long (D_1) and short (D_2) axis of the ellipse formed are indicated for the 1 mm thread. (c) Experimental relaxed knot average diameter $D = (D_1 + D_2)/2$ versus thread diameter d, fitted by theoretical curves for two values of the friction coefficient $\mu_s = 0.175$ and $\mu_s = 0.203$. Total error bar length = SD, n = 5–10 measurements. (d) Comparison of static friction coefficients obtained by the knot (n = 5–10) and inclined plane method (n = 5). Total error bar length = SD. Inset: Scheme of the inclined plane method used to provide an independent measurement of μ_s. The fibers are attached to the mass and to the inclined plane, the two surfaces are shown slightly offset for visual clarity.

ology will allow for high throughput measurements of hair-on-hair friction at a single hair scale for both fundamental and applied tribological studies. Although the present study focuses on hair, I expect that the overhand knot will become a popular tool to investigate the frictional properties of other elastic fibers from the nano- (DNA, actin [8]), micro- (textile fibers) to the macro-scale (elastic wire).

2. Results

2.1. Testing the knot theory and methodology with a homogeneous material, nylon

I first resorted to a homogeneous material – nylon – to experimentally test the equation for the equilibrium shape of a relaxed overhand knot. I used threads of diameter 0.25 mm, 0.35 mm (Nylon Monofilament, Dhondt, Belgium), and 1 mm (Standers, France). The 1 mm wire was first straightened manually to make sure the intrinsic curvature (resulting from the fact that the wire is spun around a cylinder) was much lower than that of the relaxed overhand knot; the 0.25 and 0.35 mm wire had negligible intrinsic curvature. The threads were then wiped clean by rubbing them with paper cloth imbibed with 70% ethanol. This step was essential to warrantee that the threads had reproducible surface states and frictional properties; threads not wiped with ethanol systematically exhibited lower friction. I then tied a simple overhand knot, pulled it tight with tweezers to a loop diameter in the range 1–10 mm, released it until it reached a stationary state, and made a photograph with a binocular. The knot was not tightened beyond $d/D \gtrsim 0.2$ as it otherwise did not open up elastically any more. Knots usually relaxed very quickly (within 5 s); in some cases, some slow stick-slip motion was observed and the knot only became stationary after a more prolonged observation period (max:~30 s). Fig. 2b shows a representative picture of the relaxed knots for the three thread diameters. I found that the equilibrium shape of the fiber was an ellipse with long and short axis D_1 and D_2 respectively. The average flattening factor of the ellipse $(D_1 - D_2)/D_1$ was in the range 0.1–0.15, i.e. the deviation from a circle was small; I report here the average diameter $D = (D_1 + D_2)/2$ of the relaxed knot. The knot tying procedure was repeated 3–5 times on up to 3 different samples of each thread type (diameter) and I varied the knot position along the thread to probe different regions of the material; the results are shown in Fig. 2c. Whereas the 0.25 and 0.35 mm threads were well fitted by equation (1) with a friction coefficient $\mu = 0.175 \pm 0.005$, the 1 mm thread seemed to exhibit higher friction ($\mu = 0.203 \pm 0.007$). I next measured the friction coefficient for each thread type using another, independent method, the inclined plane technique (Fig. 2d inset). For each thread type, I secured ~8 pieces of thread with double sided scotch tape to the surface of a piece of metal (m = 20 g) and to the surface of an inclinable plane; threads on one surface made a 45° angle with those on the other surface. The threads had been wiped with ethanol before securing them to the surface. I put the mass in contact with the plane and gradually increased the inclination angle θ until the mass started to slide. I measured the gliding height H and deduced the friction coefficient $\mu_s = H/L$. The measurement was repeated 5 times for each thread type. Fig. 2d shows that the nylon-on-nylon static friction coefficients obtained by the knot and the inclined plane method are in good agreement (maximum difference: 5.4%); the values obtained are in the range 0.17–0.21, consistent with values reported in the literature (0.15–0.25 [9]). This shows that the knot method and Eq. (1) can be reliably used to measure the static friction coefficient of an elastic fiber on itself. The derivation of Eq. (1) assumes that the equilibrium loop diameter is small compared to the fiber diameter, i.e. $\sqrt{d/D} \ll 1$. As $d/D \to 1$, the knot enters a different regime in which friction dominates the elastic opening force: the knot no longer opens up after tension is released. This sets an upper limit on μ_s values that can be measured by the knot method; I experimentally found this limit to be $\mu_s \sim 0.45$ (see section on alkali treatment of hair).

2.2. Applying the knot method to measure hair friction

I next applied this methodology to determine the frictional properties of hair in different conditions. I picked hair from my own head (Caucasian type); they had been shampooed ~3–6 h before the measurements. I measured their diameter with a high-magnification binocular, tied overhand knots with the help of fine tweezers and placed the resulting loops on a low friction Teflon surface to ensure that knot opening was not impeded by friction of the hair with the supporting surface. For each hair, up to 5–8 different knots were tied and the knot position displaced to probe different regions along the hair strand. I repeated the same procedure with the same hair strand in distilled water (after waiting ~10 min for hydration) and in a commercial conditioner solution ("Zeste Pamplemousse", Le Petit Marseillais). Representative relaxed overhand knots are shown in Fig. 3a; I measured the average diameter $D = (D_1 + D_2)/2$. The static friction coefficients deduced from these measurements for three different hairs are presented in Fig. 3b. I found that the static friction coefficient of wet hair was significantly higher (by 35–60%) than that of dry hair. In the conditioner solution, static friction was significantly reduced (by 25–33%) compared to pure water. The static hair-on-hair friction coefficients I found were in the range 0.12–0.25; they are consistent with static (μ_s) or dynamic (μ_k) values reported in the literature (Schwartz et al. [2], $\mu_s = 0.16$–0.3 for wet hair; Sadaie et al. [10] $\mu_k = 0.1$ c–0.2 in air at 50% relative humidity (RH); Luengo et al. [5] $\mu_k = 0.05$–0.3 in air at 75% RH). The fact that wet hair is more frictional than dry hair is a well-known fact of hair science [2]. The surface of a hair fiber is made of keratin scales (Fig. 3c): when the hair is wet, the scales bulge outward and the hair surface becomes rougher, causing the friction coefficient to increase. Conditioner is slightly acidic (pH = 5 for the one I used) and contains cationic surfactants that neutralize the negative charges at the hair surface and cover it with a surfactant layer. Silicones in the conditioner formulation also contribute to hair lubrication [6]. Compared scanning electron microscopy micrographs (Fig. 3c) of untreated and conditioner-treated hair distinctly show that the conditioner smoothes out the gaps between scales. The knot method makes it straightforward to assess the macroscopic frictional effects resulting from these microscopic structural changes. Hair-on-hair friction coefficient vary depending on the relative orientation (root-to-tip or tip-to-root) of the scales on the two hair strands and on the direction in which they are pulled [2]. The knot method probes the friction coefficient of two parallel hair strands that are pulled in opposite directions (Fig. 3d, scheme). Hair cross section is elliptic (for Caucausian hair small axis/long axis ~0.75): ideally the small and long axis of the ellipse should be measured and their average computed to deduce an absolute μ_s from [1]. In my measurements, the error on the friction coefficient associated with not knowing whether the measured fiber diameter is the long or small axis is ±7%; this error does not affect conclusions on relative μ_s values measured on the same fiber in different physico-chemical conditions.

2.3. Treatment with alkali irreversibly increases hair self-friction coefficient

Hair relaxants (=hair straighteners) are used to straighten curly hair. The active ingredient of hair relaxants is sodium hydroxide, which chemically reacts with cystine and amid groups and cleaves peptide bonds of hair proteins [11]. I used the knot method to probe the effects of sodium hydroxide on hair friction. Immersing hair

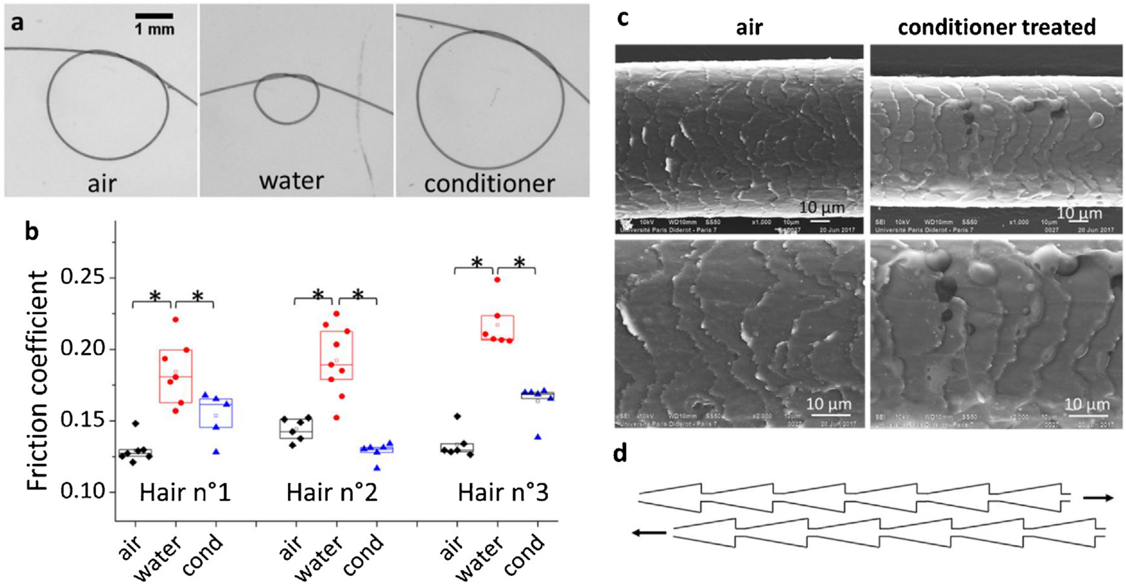

Fig. 3. Measurement of hair friction using the knot method. (a) Representative relaxed overhand knots obtained for hair in air, water and conditioner. (b) Deduced friction coefficients for 3 different hairs in air, distilled water and conditioner. Hair diameters d of hairs 1–3 were 72, 63 and 67 μm respectively; diameter changes induced by hydration over the time scale of these experiments (~15 min) were small (~10%). Each data point corresponds to a knot at different positions along the hair strand. A star indicates a statistically significant difference (Mann–Whitney two-tailed test, $p < 0.05$). (c) Scanning electron microscopy micrographs showing untreated and conditioner-treated hair at low (top) and high (bottom) magnification. d) Hair-on-hair friction coefficient depends on the relative orientation and pulling direction of the two hairs; the configuration probed by the knot method is depicted here.

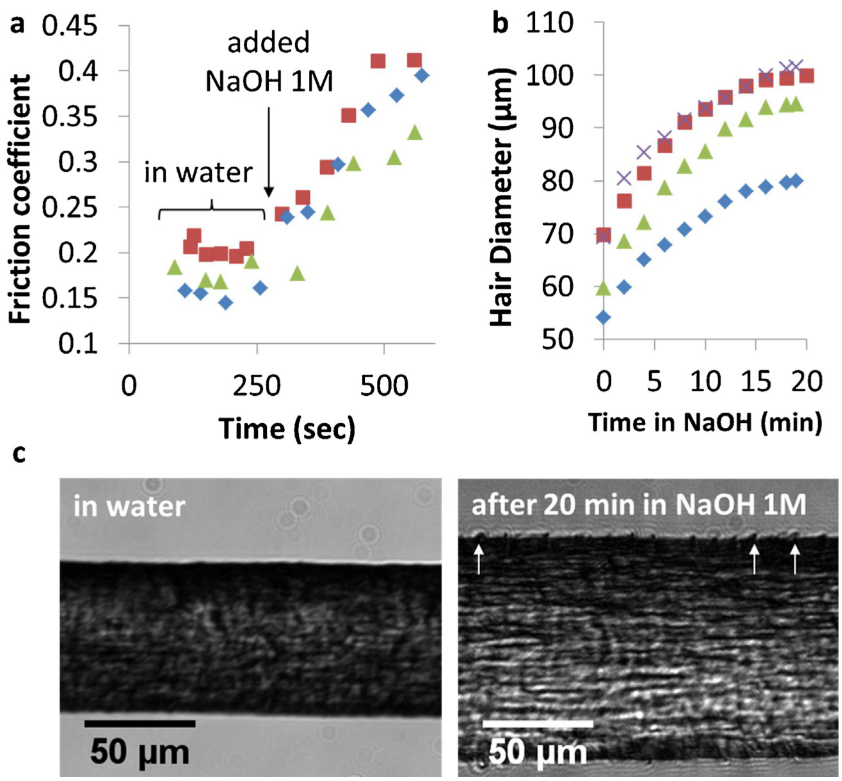

Fig. 4. Treatment of hair with sodium hydroxide (1 M NaOH) causes an irreversible friction increase. (a) Time evolution of the static self-friction coefficient of hair determined by the knot method, in water (up to 250 s), and after it is immersed in 1 M NaOH. The gradual increase of hair diameter during immersion in NaOH was taken into account to compute the friction coefficient with Eq. (1). Each data point is a separate measurement along the hair, the three symbol colors correspond to three different hairs. (b) Evolution of hair diameter in 1 M NaOH for 4 different hairs. (c) Microscope (×20) views of a hydrated hair (scales not visible at hair edge) and after 20 min treatment in NaOH: the hair diameter has increased and scales bulge outward (white arrows point at the most conspicuous ones).

in 1 M NaOH (pH 14) led to a rapid increase of μ_S (Fig. 4a). After 20 min in 1 M NaOH, the friction had increased to such an extent that the equilibrium loop size was comparable to the hair diameter. When $d/D \gtrsim 0.2$, knots did no longer elastically relax. This means that the maximum friction coefficient that can be measured by the knot method is $\mu_{s,max} \sim 1.02\sqrt{0.2} \sim 0.45$. I found that the friction increase induced by NaOH was irreversible: friction remained high (μ_s>0.45) for at least 2 h after the hair was immerged back in distilled water. Consistent with previous research [12], I observed that treatment with 1 M NaOH led within 20 min to a ~50% hair diameter increase (Fig. 4b). Individual hair scales at the hair edge could distinctly be seen to bulge out after treatment with NaOH (Fig. 4c): roughening of the hair surface is consistent with an increased self-friction coefficient.

Hair is a unique material: it is widely available, biocompatible, has a high ultimate tensile strength (~10 MPa) and micron-sized dimensions (~10 μm diameter for Vicuña hair). Because of these properties hair was used in the past as fine suture thread for surgery [13,14]. I demonstrated that NaOH treatment provides a straightforward way of increasing hair friction. Such high-friction fibers are an ideal material to form micron-sized knots for microsurgery applications in medicine [15] or experimental embryology [16], for example to ligature blood vessels or organs without completely tightening the knot (which would damage or cut the tissue).

3. Conclusion

I believe that the relaxed overhand knot will become a valuable method to probe the frictional properties of hair and elastic fibers for the following reasons:

- It allows for quick, repeated measurements at different locations along the same hair, providing statistics at a single hair scale. This makes it possible to compare the friction coefficient of different hair types (caucasian, asian etc.), in healthy or diseased condition (e.g. trichodonosis) or to perform comparisons between different animals.
- It is straightforward to measure the friction coefficient in different conditions of temperature, relative humidity, and to quantitatively assess the effects of different hair-care products, conditioners, bleach, relaxants etc.
- It requires very little equipment (binocular).
- It can be scaled up or down to probe the friction of fine textile fibers, fiberglass, nanotubes, proteins (F-actin, [8]), to list just a few examples.

Limitations include the fact that the knot method only probes the frictional coefficient in the configuration of two parallel hair strands pulled in opposite directions (Fig. 3d). It cannot measure friction coefficients above $\mu_{s,max} \sim 0.45$. It is also not applicable to very curly hair, i.e., which has an intrinsic curvature comparable to that of the relaxed overhand knot (for hair typically D ~ 1 cm). Using this method, I could quantify the lubricating effect of conditioner and I proved that 1 M NaOH induces a quick, irreversible self-friction coefficient increase. I suggest that such high-friction, micron-sized fibers can be used to form secure micron-sized knots to ligature vessels or organs in microsurgical applications in medicine [15] and embryology [16].

Conflict of interest

The author declares no conflict of interest. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.colsurfb.2017.08.048.

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