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A technique to determine friction at the finger tips

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Abstract

This paper proposes a technique to calculate the coefficient of friction for fingertip-object interface. Twelve subjects (6 males and 6 females) participated in two experiments. During the first experiment (the “imposed displacement” method) a 3D force sensor was moved horizontally while the subjects applied a specified normal force (4N, 8N, 12N) on the surface of a sensor covered with different materials (sandpaper, cotton, rayon, polyester, and silk). The *normal force* and the *tangential force* (i.e. the force due to the sensor motion) were recorded. The *coefficient of friction* (μ_d) was calculated as the ratio between the tangential force and the normal force. In the second experiment (the “beginning slip” method), a small instrumented object was gripped between the index finger and the thumb, held stationary in the air and then allowed to drop. The weight (200g, 500g and 1000g) and the surface (sandpaper, cotton, rayon, polyester and silk) in contact with the digits varied across trials. The same sensor as in the first experiment was used to record the *normal force* (in a horizontal direction) and the *tangential force* (in the vertical direction). The *slip force* (i.e. the minimal normal force or grip force necessary to prevent slipping) was estimated as the force at the moment when the object just began to slip. The coefficient of friction was calculated as the ratio between the tangential force and the slip force. The results show that: (1) the “imposed displacement” method is reliable; (2) except sandpaper, for all other materials the coefficient of friction did not depend of the normal force; (3) the *skin-sandpaper* coefficient of friction was the highest $\mu_d = 0.96 \pm 0.09$ (for 4N normal force) and the *skin-rayon* rayon coefficient of friction was the smallest $\mu_d = 0.36 \pm 0.10$; (4) no significant difference between the coefficients of friction determined with the “imposed displacement” method and the “beginning slip” method was observed. We view the “imposed displacement” technique as having an advantage as compared to the beginning slip method, which is more cumbersome (e.g. dropped object should be protected from impacts) and prone to subjective errors due to uncertainty in determining the instance of the slip initiation (i.e. impeding sliding).

Keywords

coefficient of friction; index finger; thumb; slip force

INTRODUCTION

Manipulation of objects requires stable grasps; the objects should not be dropped. To prevent slipping of the objects, when people manipulate hand-held objects they adjust grasping force to the friction at the digit tip-object interfaces (Westling & Johansson 1984; Johansson & Westling 1984; Westling & Johansson 1984; Edin et al. 1992; Forssberg et al., 1995; Cadoret

& Smith, 1996; Kinoshita et al., 1997; Goodwin et al. 1998; Birznieks et al., 1998; Burstedt et al., 1999a; Burstedt et al., 1999b; Aoki et al., 2006; Aoki et al., 2007; Niu et al., 2007).

In the literature, different methods of skin friction measurements have been used. Two recent review papers (Sivamani et al. 2003; Gitis & Sivamani, 2004) cite 11 and 6 different methods, respectively. The measurements were mainly performed by dermatologists (Highley et al., 1977; Sivamani et al., 2003a, b, c; Gitis & Sivamani, 2004) and were motivated by practical purposes such as cosmetics applications (Koudine et al., 2000) as well as by other issues, such as blister prevention (Knapik et al. 1995). The knowledge of skin-object friction is also important in ergonomics (Bobjer et al. 1993). Frictional properties of the skin (reviewed by Cua et al. 1990; Krouskop & van Rijsijk 2005; Knapik et al. 1995; Zatsiorsky, 2002) depend on many factors, such as air humidity, skin wetness, sweating, etc. The friction is different for different parts of the body; the difference is almost three-fold. In experiments (Cua et al., 1990), the skin friction on teflon was mainly determined. Majority of authors assumed that the skin obeys Amonton's law (also known as Coulomb's law). According to the law the force of friction is directly proportional to the load and does not depend on the area of contact or the skidding velocity. When the materials follow the Amonton's law, the coefficient of friction can be determined as the tangential force/normal force ratio. To which extent the skin obeys this law is not clear. Comaish and Buttom's (Comaish and Buttom's, 1971) concluded that skin obeys the Amonton's law over a limited range of loads only. In a broader range, a logarithmic relation exists between the friction force and the normal force.

Friction at the digit tips has been an object of research due to its effect on grasping coordination (Westling & Johansson, 1984; Johansson & Westling, 1984; Edin et al., 1992; Bobjer et al., 1993). The digit tip measurements differ from other skin friction studies at least in two aspects: (a) friction on different materials (not only on teflon) is an object of interest and (b) methods commonly used in skin friction research (such as rotating teflon wheels) are not convenient for working with the finger tips. Therefore another method was suggested (Westling & Johansson, 1984): to grasp an instrumented object and then to voluntarily decrease the grasping force until the object is dropped (this method was not cited in the above mentioned review papers). The coefficient of friction is then computed as the ratio *tangential force: normal force* at the beginning slip. The same method was used to analyze the neuronal activity in somatosensory cortex of monkeys using a precision grip during friction perturbation (Salimi et al., 1999). The method is however not without the shortcomings: dropping an object with the mounted sensors can harm them. Besides, the method implies that the subjects keep the orientation of the grasped object perfectly vertical while changing the grip force. It also implies that the friction at the opposing digits is identical. We used this method in our lab several years and found that the intra-rater variability of the method is large: raters not always agree when exactly the slipping starts (the variability decreases with experience). A more convenient method of skin friction measurement is desired.

Various experimental designs have been developed to measure the friction of skin (Sivamani and Maibach, 2006). To complete the list, an "imposed displacement" method to measure the dynamic coefficient of friction is proposed in this paper. The present study has the following goals: (a) to develop a simple technique of determining the coefficient of friction between the finger tip and external objects; (b) to determine the reliability of the method; (c) to determine whether the friction coefficient depends on the normal force, i.e. whether the skin friction follows the Amonton's law; and (d) to compare the present technique with the "beginning slip" method. While we have also determined the friction coefficients for several commonly used materials, the establishing of the normative values of the coefficients for different skin-material combinations was not a main goal of the present research. With the exception of the tested sandpaper (no. 320), other materials such as silk or polyester may come in many varieties with

different friction properties. Testing all of the varieties is impossible while testing one of them is not representative.

METHOD

Twelve young volunteer subjects: 6 males (hand length: 196.67 ± 8.09 mm, age: 30.34 ± 2.37 , stature: 1.81 ± 0.04 m, weight: 84.67 ± 14.39 kg) and 6 females (hand length: 174.17 ± 10.75 mm, age: 28.34 ± 4.58 , stature: 1.66 ± 0.05 m, weight: 60.17 ± 12.39 kg) participated in the study. Subjects had no previous history of neuropathies or trauma to the upper limbs. All subjects gave informed consent according to the policies of the Office for Research Protections of the Pennsylvania State University. Subjects were innocent with regard to the specific purpose of the experiment. Before the experiment (5–10 min.) subjects were asked to wash their hands with soap and water. All subjects participated in two experiments presented below. The first and second experiments were performed on different days.

Experiment 1: “imposed displacement” method

In the first experiment the proposed new technique to calculate the coefficient of friction was used. The method is based on straightforward application of the concept of friction: the subject exerts a constant normal force on the force sensor in downward direction while the sensor is being moved horizontally (Figure 1) by a motor. During the experiment, the subject's lower arm was fixed and visual feedback of the applied normal force was provided on a computer screen. The 3-component force sensor (KISTLER Types 9317B, Kistler Instruments, Amherst, NY) was covered with a cap (30 mm in diameter) with different surface materials (Figure 1). The sequence of the changed materials was: polyester, sandpaper, cotton, rayon and silk. The sequence was not randomized because the main study objective was to develop a technique to measure the coefficient of friction, not to compare the friction of the finger tips on various materials.

The instructions given to the subjects were limited to a demonstration carried out by the experimenter and the verbal instruction: “Press the cap (i.e. the cap which covers the sensor) with the index fingertip until you reach the red, yellow or blue line (i.e. a fixed level of the normal force: red line = 4N, yellow line = 8N and blue line = 12N) and then try, as accurately as you can, to keep the force constant. Keep the finger in the same position and do not move your arm.” To avoid the variability due to effects of velocity on the coefficient of friction estimation, the same sensor speed (6mm/s) was used for all subjects and all tested materials. The sensor moved along the finger, away from the body. The top of the cap was covered with different materials: polyester, sandpaper (no. 320), cotton, rayon and silk. All subjects performed each task ten times. They performed practice trials (as many as they needed but never more than 5) before the experiment. The data recording did not begin until at least two successful trials had been completed. A trial was considered successful if the imposed normal force was in the range $\pm 10\%$ of the nominal force. The total of 150 trials were recorded for each subject, i.e. 3 (normal force amplitude) $\times$ 5 (materials) $\times$ 10 (trials) = 150 trials. The data (recorded at 200Hz) were filtered with Butterworth low-pass filter (the interval frequency: 1/200, the cut-off frequency: 0.8 Hz and the filter order: 4). The dynamic coefficient of friction (μ_d) was calculated as the ratio between the tangential force (i.e. the force due to the sensor motion; during the data recording the sensor was always moving under the finger) and the normal force (i.e. the downward force applied by the subject). The sensor initial position was the same for all trials. Only the data when the normal force was in $\pm 10\%$ interval of the nominal normal force were used to calculate the coefficient of friction.

Experiment 2: “beginning slip” method

During the second experiment, the subjects sat in an ordinary chair with their upper arm parallel to the trunk and with their unsupported forearm extending anteriorly. From this position, the instrumented object was grasped with the index finger and the thumb from above as shown in Figure 2. The subjects were allowed to flex the wrist as necessary. The same three-dimensional force sensor as in the first experiment was used to record the index fingertip normal force (i.e. the force applied by the subject normally to the sensor surface) and the tangential force (shear force). The sensor was positioned horizontally; therefore the normal force was exerted in the horizontal direction and the tangential force in the vertical direction. The surfaces touched by the subjects were two easily exchangeable discs mounted in a horizontal plane at a distance of 60 mm. Like in the first experiment, the tops of the caps (30 mm in diameter) were covered with different materials: polyester, sand paper (no. 320), cotton, rayon and silk. The object was loaded with different weights (200g, 500g, 1000g) using a long, thin metal rod attached in the center of the handle (weight handle + metal rod: 207g). To help the subjects in maintaining the vertical orientation of the handle, the rod passed through a hole in a metal piece fixed on a table border and a level was fixed at the handle top. No visual feedback on the screen was given to the subject. To prevent the instrumented assembly from an impact after dropping, 50 mm-thick foamy material covered the metal piece (needed to support the handle after dropping) fixed on the table.

Before performing the experiment, a demonstration was carried out by the experimenter. During the experiment a verbal instruction was given to the subject: ‘I will give you two instructions: “GO!” and “DROP!”. At the “GO!” instruction you will grasp the object with your index finger and the thumb, and lift the object. At the “DROP!” instruction you will slowly move the index finger and the thumb apart until you drop the object.’ Only the experimenter received a feedback on the applied force. The instruction “DROP!” was given by the experimenter when the object was at rest (according to the visual observation). The procedure involving the dropping of the object was carried out in order to measure the minimal grip force required to prevent slippage. This force was denoted as the *slip force* and measured at the moment when the object began to slip. A 3-D accelerometer (ACL300, Biometrics, UK) was affixed using double sided tape on the top of the device to better estimate this moment. The total of 75 trials were recorded for each subject, i.e. 3 (loads) $\times$ 5 (materials) $\times$ 5 (trials) = 75 trials.

The coefficient of friction was calculated as the ratio between the recorded tangential force (i.e. the vertical force) and the recorded normal force (i.e. the force applied by the subject normal to the sensor surface in a horizontal direction) at the moment of the beginning slip. To help in determining the instance of the beginning slip the acceleration signal was used. Still, the instant was difficult to estimate precisely and its determination could be affected by subjective biases. Figure 3 presents an example of a recorded trial for the sand paper and 500g load.

Preliminary results: the gender effect

Some previous studies (Sivamani et al., 2003) have concluded that the coefficient of friction of the skin on the volar forearm is similar across genders, age, or ethnicity. Results presented in Figure 4 support the conclusion that the coefficient of friction does not depend on subject’s gender. Based in this observation, the results for the male and female subjects were pooled for further analysis.

RESULTS

The following results of the experiments are presented: (1) Reliability of the suggested method, (2) Dependence of the friction coefficient on the normal force, (3) The friction coefficients for different materials, (4) Comparison between the proposed method and the 'beginning slip' method.

Reliability

The reliability of the proposed method (Experiment 1) was determined by comparing the inter-trial variability (Figure 5 A) with the inter-subject variability of the coefficients of friction (Figure 5 B) for all 15 force and material combinations. The intra-class coefficient of correlation was used (McGraw & Wong, 1996). The method was found to be highly reliable. The intra-class coefficients of correlation (Cronbach's alpha) were 0.91, 0.88, 0.86, 0.83 and 0.62 for rayon, cotton, silk, polyester and sandpaper, respectively.

Dependence of the friction coefficient on the normal force

For all materials, except the sandpaper, the coefficient did not depend on the normal force (Figure 6). For the sandpaper the friction coefficient decreased with an increase in the normal force, i.e. the friction during fingertip-sandpaper interaction did not obey Amonton's law. For this material, the coefficient of friction was 0.96 ± 0.09 at the 4-N normal force and decreased to 0.70 ± 0.09 at 12 N. For the others materials the difference in the friction coefficient between the three normal force levels was almost nonexistent.

The friction coefficients for different materials

Using the proposed method, friction coefficients for different materials were obtained (Table 1). The highest coefficient was found for the sandpaper ($\mu_d = 0.96 \pm 0.09$ for 4N normal force, Figure 4) and the smallest for the rayon ($\mu_d = 0.35 \pm 0.11$).

Comparison between the proposed method and the 'beginning slip' method

The results of the comparison are presented in Figure 7. No statistically significant differences between the results obtained with the two methods were found.

DISCUSSION

The present results show that the proposed technique to measure the coefficient of friction on fingertip skin is reliable. With this method important parameters that can influence the coefficient of friction (i.e. normal force, skipping speed) can be controlled. While for the materials that obey Amonton's law the dynamic coefficient of friction is not influenced by the skidding velocity and/or the applied normal force, whether the specific materials obey the law or not is not known *a priori*. It can be established only in experiments. In majority of studies the validity of Amonton's law for the skin friction is assumed. However, some researchers (Comanish & Bottoms, 1971; Bobjer et al. 1993) found that the coefficient of friction decreases with the increasing normal force. Our results agree with these findings only for the friction at the skin-sandpaper interface. Other materials (polyester, cotton, silk and rayon) obey Amonton's law. The decrease of the coefficient of friction with an increase in the normal force at the skin-sandpaper interface may be provisionally explained by wearing the skin due to the sandpaper roughness; the reduction in friction arises from clogging/contamination with skin debris (we thank an anonymous reviewer for suggesting this explanation). Our preliminary data favor this explanation (Figure 8): in some subjects the coefficient of friction decreases in consecutive trials. The explanation is however only a hypothesis that should be experimentally

tested. Another hypothesis was recently suggested by Adams et al. (2007) who interpreted the influence of the normal load on friction coefficient by the adhesion model of skin friction.

Usually static friction is higher than dynamic friction (Blau, 1996). Hence if the “beginning slip” method measures the static friction while the “imposed displacement” technique measures the dynamic friction it could be expected that these two methods would yield different results. However, in our experiments, there were no statistically significant differences between the friction values determined with the two methods. The explanation of these results can be that the coefficient of friction at the beginning slip is not really a static coefficient of friction because at the instant of measurement the surfaces are not at rest relative to each other. If the two contact surfaces are sliding relative to each other, the coefficient of friction is called the coefficient of kinetic friction (Pytel and Kiusalaas, 1999). While the both methods yielded similar results, in our opinion the “imposed displacement” technique (suggested technique) is more convenient than the “beginning slip” method: (a) it is easier to administer; (b) the risk to damage the experimental apparatus (i.e. due to dropping the object) is absent; (c) the method allows for the measuring effects of such factors as the normal force and speed of skidding; (d) the method does not require maintaining the vertical handle orientation (the deviation from the vertical would affect the digit forces); (e) the assumption that the friction under the digits involved in grasping is the same is not needed; (f) the last but not least, the method does not depend on subjective judgment of the instant of beginning slip.

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Figure 1.

Experimental set up: experiment 1. During testing, the subjects pressed down on the sensor covered by a cap while the sensor was moved in the direction shown by the arrow. Both the horizontal (tangential) and vertical (normal) components of the force were recorded.

Figure 2.

Experimental set up: experiment 2. During testing, the subjects grasp and hold a handle equipped with a 3D force sensor. The sensor was covered by a cap with different materials. Then, the handle was dropped and both the horizontal and vertical components of the force are recorded.

Figure 3.

Tangential force, normal force and vertical position shown as a function of time for cap covered with sand paper material and 500g loaded device. The dotted vertical line indicates the start of normal force decrease. The normal force value at the instant the object slipped (vertical line) was estimated as the slip force. The force was used to calculate the coefficient of friction.

Figure 4. Coefficient of friction for females (n=6) and males (n=6) for different material: 1=sandpaper, 2=silk, 3=polyester, 4=cotton, 5=rayon. The effect of subject's gender was not statistically significant.

B

Figure 5.

Coefficients of friction at various normal forces and on different materials: 1=sandpaper, 2=silk, 3=polyester, 4=cotton, 5=rayon. The inter-trial (A) and inter-subject (B) variability is shown as the standard deviation bars. (A) A representative subject. The averages (10 trials) and the standard deviations. (B) The group means (n=12 subjects) and the standard deviations.

Figure 6. Coefficient of friction as function of normal force magnitude represented for all tested materials. Coefficient of friction for the sandpaper (marked with an asterisk *) depended significantly on the load.

Figure 7.

Group means and SD of the coefficient of friction for different materials: 1=sandpaper, 2=silk, 3=polyester, 4=cotton, 5=rayon. The highest coefficient was found for the sandpaper ($\mu_d = 0.96 \pm 0.09$ for the normal force of 4 N) and the smallest for the rayon ($\mu_d = 0.35 \pm 0.11$).

Figure 8.

Coefficient of friction between the finger tip and sandpaper in ten consecutive trials in one of the subjects. The normal force was 4 N.

Table 1

Coefficients of friction for different materials and normal forces

Material	Coefficient of friction		Recorded Normal Force [N]	
	Mean	SD	Mean	SD
Sandpaper (no. 320)	0.96	0.13	4.03	0.09
	0.78	0.09	7.99	0.11
	0.70	0.08	11.92	0.12
Silk	0.45	0.13	4.03	0.05
	0.43	0.15	7.95	0.08
	0.43	0.14	11.93	0.09
Polyester	0.44	0.11	4.02	0.07
	0.42	0.13	7.98	0.09
	0.43	0.13	11.92	0.11
Cotton	0.39	0.12	4.03	0.08
	0.39	0.11	7.93	0.11
	0.38	0.11	11.88	0.10
Rayon	0.36	0.11	4.03	0.05
	0.34	0.11	7.95	0.08
	0.33	0.09	11.91	0.07