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Dynamic and tribological contact study for human fingertips at very low speeds

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Abstract. Nonlinear elastic models have been widely used to describe the mechanical behaviour of complex materials such as skin. The subject of skin modelling is fairly new and of great importance to fields such as robotics and the development of skin-like materials to orthopaedics and prosthetics. The present article serves to add to the findings of previous authors and present experimental values gathered using the "Stick-Slip Experimental Stand" within the Machine Elements and Tribology Department on the tribological aspects regarding friction at very low speeds. The scope of this article is to evaluate the static and kinetic friction coefficients of the human skin in contact with different materials. A total of 5 different materials were tested to find the static and kinetic friction coefficient. The tested materials were steel, bronze, and 3 types of materials found on the inside of working gloves in direct contact with human skin: leather (bovine origin) and 2 types of textiles (cotton and nylon). All tests were performed at 1.8 mm/min, with an initial load of 7.5 Newton and a test time of 1000 seconds. The total distance evaluated was 9.25 mm.

1. Introduction
The evolution process and natural selection have provided human beings with an excellent tool for manipulation that can be mimicked artificially. Skin is the only part of the human body that interacts with the environment directly and has adapted to perform difficult tasks in the most challenging situations. Its behaviour was therefore analysed in contact with 5 materials and the coefficient of static friction, as well as for kinetic friction were determined. The results gathered can be used to compare to the performance of artificial grabbing tools designed to be replacements for loss of limb or even for robotic manipulation of objects. As such this report aims to make strides forward for a reliable model of the skin behaviour in contact with different artificial materials to be produced. Several authors studied in vivo testing of skin [1-8], utilising different measuring methods and on different parts of the body.

2. Experimental Setup

2.1. Experimental Stand Description
All experiments were performed on the "Stick-Slip experimental stand" in the Tribology Laboratory within the Machine Elements and Tribology Department at Politehnica University, Bucharest. The "Stick-Slip experimental stand" is capable of generating linear movement in the range of 0-50 mm/min, a range that is ideal for studying contact phenomenon at very low speeds. The experimental stand is

specially designed for studying interactions between surfaces at very low speeds. The slider is actuated through a reduction drive by a motor that is driven by a variable DC transformer and is isolated from parasitic vibrations by the use of roller bearings.

A schematic of the experimental stand is presented in Figures 1, 2 and 3 below along with a Table 1, describing the components.

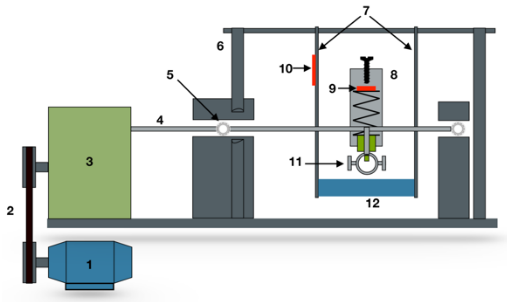

Figure 1. Schematic representation of the experimental stand.

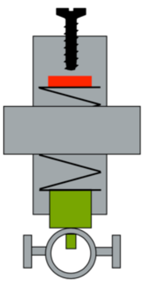

Figure 2. Holding device for finger.

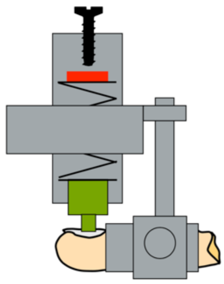

Figure 3. Position of the finger in the holding device.

Table 1. Component Table

No.	Component Name	Role
1	Electric motor	Generates rotational movement
2	Belt drive	Transfers the rotational movement from the electric motor to the reduction gearbox
3	Linear motion gearbox	Converts rotational motion to linear motion
4	Push/Pull rod	Supports and drives the normal force generating device and the finger
5	Guides and roller bearings	Guide, isolate and reduce friction
6	Struts	Framework
7	Rods with known rigidity	Support the test piece and measure the tangential contact force
8	Normal force generator and sensor device	Applies a measurable normal force on the finger
9	Normal force sensor	
10	Tensometric sensors	
11	Finger fixing device	
12	Sample holder	

2.2. Measuring Method

The measuring method is relatively simple, the finger was clamped to the moving part of the machine as seen in the figure above, and the material sample was held stationary. The normal force was measured using a force sensor and the tangential force that corresponds to the friction force generated by the contact was measured by a set of tensometric sensors positioned on the rods supporting the sample material.

The finger was immobilised and secured by the use of a plaster casing inside an aluminium tube, letting out only the distal phalange of the finger for measurements. The aluminium tube and finger were then fixed to the moving part of the machine by the use of a device that allows for optimal height and depth adjustment.

The finger was then placed in contact with the sample material and adjusted for height and depth, clamped into position and a normal force was applied by the use of a screw and was continuously measured by the force sensor.

All tests were performed using the same index finger of one young adult male individual. The finger did not present any callouses, bruises, cuts or any other skin lesions.

All tests had the same initial conditions, with a velocity of 1.8 mm/min, an initial load of 5 Newtons and a test time of 1000 seconds. The total driven distance was 9.25 mm. Before every test, the test surfaces were cleaned and degreased using alcohol.

2.3. Material samples

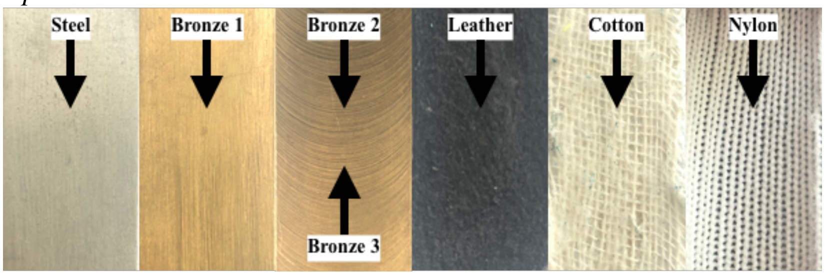

Figure 4. Material samples, the arrow indicates the direction of testing.

3. Experimental Results

3.1. Evaluation of the static and kinetic coefficients of friction

The static coefficient of friction was calculated as the ratio between the recorded tangential force (tensometric sensors) and the recorded normal force (normal force sensor) at the moment of the beginning slip. The kinetic coefficient of friction was evaluated in the same manner at the beginning of the stick period. Table 2 below presents the static and kinetic friction coefficients calculated by taking the average of at least 10 relevant data points.

Table 2. Static and Kinetic Friction Coefficients

Material	Static friction coefficient	Kinetic friction coefficient	Amplitude of stick-slip	Frequency of stick-slip (Hz)	Surface roughness Ra (µm)	Surface roughness Rz (µm)
Steel	1.1196	0.5809	0.5386	0.03	0.89	5.63
Bronze 1	0.8472	0.8245	0.0227	0.05	1.03	5.26
Bronze 2	1.14612	0.8734	0.27272	0.05	3.22	15.6
Bronze 3	1.27967	1.13098	0.14869	0.1	3.6	17.5
Leather	0.87486	0.7055	0.16936	0.11	12.6	57.8
Cotton	1.26212	0.53486	0.72726	0.025	13.5	57.1
Nylon	0.60075	0.4211	0.17965	0.01	12.2	50.8

Surface roughness was measured using the Surtronic 25 Surface Roughness Tester manufactured by Taylor Hobson Ltd, which provides a resolution of Ra 0.01 µm - Rz, 0.1 µm and an accuracy of 2%. The stylus is diamond tipped with a 5 µm radius and the digital filter is Gaussian (ISO 11562).

A sample of 200 seconds was used for each material to determine and extract the data presented in Table 2, above. The time snippet was selected after the contact was stabilised.

3.2. Steel

As it can be observed from Table 2 above, the amplitude of the "stick-slip" motion was the highest in this case. The difference between the mean static friction coefficient and the mean kinetic friction coefficient is almost 50% meaning that steel is prone to a "stick-slip" response in contact with skin.

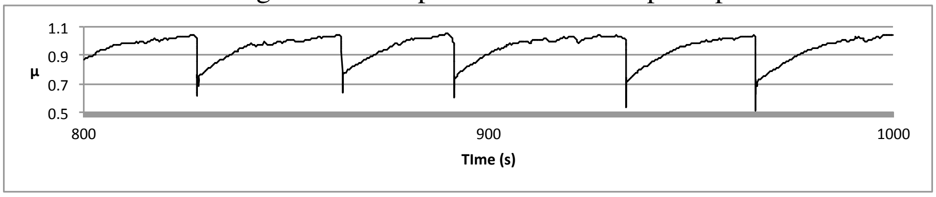

Figure 5. Friction Coefficient for Steel, v=1.8 mm/min Ra=0.89 µm.

3.3. Bronze

A more interesting approach was for bronze. The first test was performed on a sample that had a surface roughness measured at Ra=1.03 µm, as seen in Figure 6 below, and had no detectable imperfections to the touch and the results showed very little "stick-slip" behaviour. The variation for the coefficient of friction was, within reason, almost non-existent. Consequently, a decision was made for two additional tests using the same material but with altering the surface finish. Milling produced a surface that could be tested in two directions and the end-milled surface can be observed in Figure 4 below. This alteration to the surface produced a significant change in the way in which the friction coefficient varies with time. Figures 7 and 8 below depict a more prominent "stick-slip" behaviour and the direction of testing had a profound impact on the amplitude and frequency of the oscillatory response of friction.

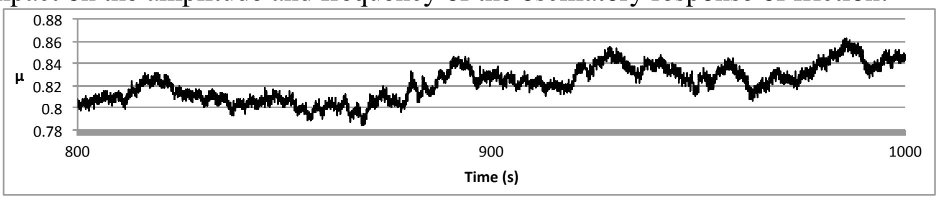

Figure 6. Friction Coefficient for Bronze 1, v=1.8 mm/min Ra=1.03 µm.

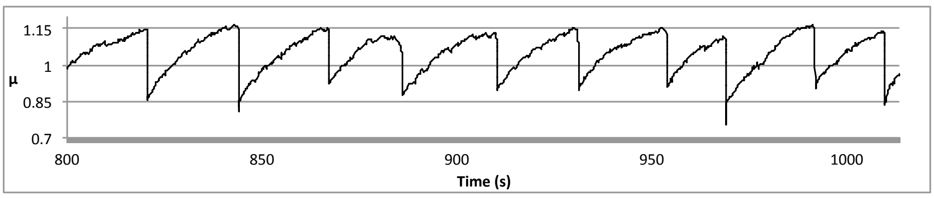

Figure 7. Friction Coefficient for Bronze 2, v=1.8 mm/min Ra=3.22 µm.

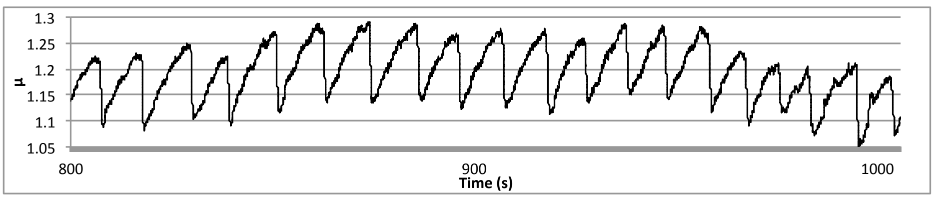

Figure 8. Friction Coefficient for Bronze 3, v=1.8 mm/min Ra=3.6 µm.

3.4. Leather

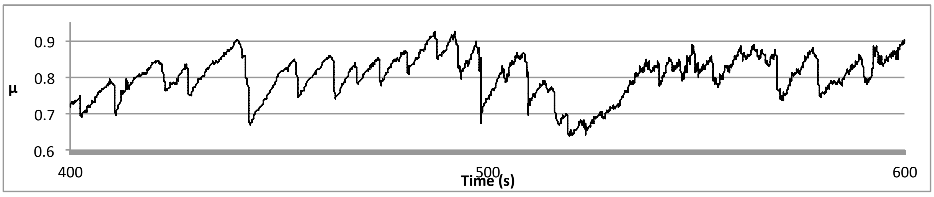

Figure 9. Friction Coefficient for Leather, v=1.8 mm/min Ra=12.6 μm.

3.5. Cotton

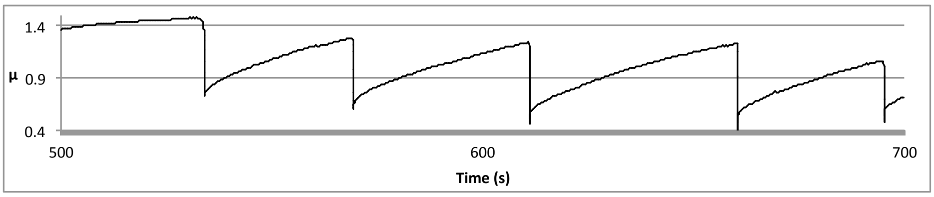

Figure 10. Friction Coefficient for Cotton, v=1.8 mm/min Ra=13.5 μm.

3.6. Nylon

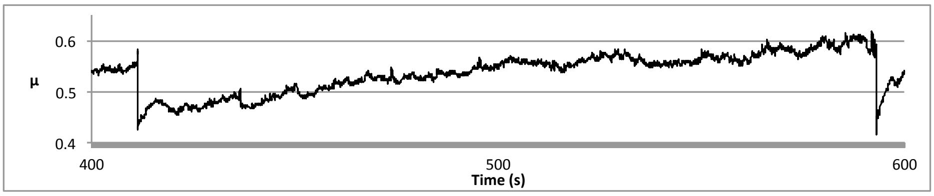

Figure 11. Friction Coefficient for Nylon, v=1.8 mm/min Ra=12.2 μm.

4. Theoretical model

4.1. Experimental Stand Description

The proposed dynamic model for the sample material in relative motion to the fingertip is [9-11]:

$$m_s\ddot{x} + F_f(\dot{x}, \gamma_s) + \frac{h}{\omega}\dot{x} + kx = kv_o t + \frac{hv_o}{\omega_n} \quad (1)$$

where: m_x is the mass of the specimen, x - the displacement in the direction of slip, t - time, $\dot{x} = dx/dt$ - the instantaneous linear velocity and $\ddot{x} = d^2x/dt^2$ acceleration, $F_f(x;\gamma)$ is the friction force that acts to resist the motion of the mass and depends on the sliding velocity ($v_o - \dot{x}$) and the state of contact area ("age" of contact or saturation contact area) (γ_s), k is the axial stiffness, h is hysteresis damping in sample material, ω is the frequency of oscillation if the system is excited from the outside or frequency of natural oscillation and ω_n if the system is a free vibratory system.

Static friction reaches its maximum value when the contact between the finger and the sample material is saturated. This translates to the real contact area not being able to become larger over time under a specific set of initial conditions.

For the variable of state γ_s, we assume the following simple kinetic equation [9-11]

$$\frac{d\gamma_s}{dt} = \frac{1-\gamma_s}{t_{cr}} - \frac{\dot{x}}{D} \quad 0 \le \gamma_s \le 1 \quad (2)$$

The solutions of this differential equation for the two extreme cases are:

1) For the period of "stick", $\frac{dx}{dt} = 0$

$$\gamma_s\,(t) = 1 - e^{\frac{-t}{t_{cr}}} \quad (3a)$$

2) For $\frac{dx}{dt} = v_o$(steady-state) γ_s increases exponentially with time.

$$\gamma_s(t) = (1 - \frac{v_o t_{cr}}{D}\ )(1 - e^{\frac{-t}{t_{cr}}}) \quad 3b)$$

Approximating the saturation parameter (real contact area γ_s) by developing the exponential function (3) in series and considering the first two terms.

1) For the period of "stick":

$$\gamma_s \approx \frac{t}{t_{cr}} \text{ if } \frac{t}{t_{cr}} \leq 1 \text{ and } \gamma_s \approx 1 \text{ if } \frac{t}{t_{cr}} > 1 \tag{4a}$$

2) For steady-state:

$$\gamma_s \approx 1 - \frac{v_o}{D} t \tag{4b}$$

If the body is put into motion, then the variables of state decrease faster at higher velocities. The physical meaning of t_{cr} in (3a) is the characteristic relaxation time of the parameter γ_s when the system is at rest, while D is the characteristic "relaxation length" at the initiation of motion. In a physical point of view, the contact between two rough surfaces, t_{cr} can be understood as the characteristic time of the creep process and D, as the average real contact diameter. The creep velocity can be considered as $v_{cr} = \frac{D}{t_{cr}}$.

5. Conclusions

The present results show that the proposed technique to measure both the static and kinetic friction coefficients on the fingertip skin is of consistently good quality and performance.

Surface finish plays an important role in the behaviour of friction, as seen from the bronze samples.

It can be stated that an ideal material that allows for a stable manipulation has to have a high coefficient of friction (preferably >1) and, ideally, without "stick-slip".

The microscopic region of contact between the skin and sample materials, the surface roughness of the sample material, the direction of contact and the mechanical characteristics of the skin layers are of great importance and require further examination in order to enhance the knowledge of the complex mechanics of the human hand grasping.

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