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The stick-slip phenomenon occurring between human skin and other surfaces

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Abstract. This paper analyses the stick-slip phenomenon in tribosystems that include human skin and biocompatible polyethylene UHMWPE. The study focuses on the theoretical stability conditions of the movement of the UHMWPE polyethylene specimen in contact with human skin, considering the rheological and tribological properties of human skin, the rigidity of the system, and the speed of training. The proposed dynamic model involves the equation of relative motion of the UHMWPE polyethylene specimen relative to the finger, considering the force of friction, axial stiffness, hysteresis damping, and frequency of oscillation. The results can be useful for choosing materials for lower and upper human endoprosthesis and designing robot gripping systems. The paper presents experimental and analytical models and explores the effects of contact pressure, real contact area, and kinetic friction coefficient on the phenomenon. The study aims to improve the understanding of the stick-slip phenomenon and contribute to the development of more reliable tribological systems.
Keywords: *stick-slip, biotribology, rheological model of human skin, UHMWPE.*

Introduction

In tribosystems with relative moving elements, the stick-slip phenomenon occurs as a result of the variation in the friction coefficient as a function of velocity. This phenomenon is frequently observed at low and very low speeds, depending on the system's rigidity in the direction of the drive speed. The amplitude of this phenomenon is influenced by the system's rigidity characteristics, working speed, and skin-synthetic materials' friction behavior [1, 2, 3].

It is known that the dynamics of the micro-contact friction process (real area) depend on the elasto-visco-plastic properties of the materials. In the case of conventional dry rubbing (no special lubricant), two specific phenomena are observed: stick-slip (intermittent) movement occurring when the dynamic friction coefficient decreases with increasing speed and rigidity, and the slip direction has a certain value; steady motion occurs when the dynamic friction coefficient increases with the sliding speed increase.

The visco-elastic properties of human skin are investigated in various papers, revealing a behavior close to the Voight-Kelvin rheological model [4-8]. Models of friction coefficient between human skin and different artificial or natural materials take into account the effect of adhesion and the effect of loss through hysteresis [5], [6], [9]. The stick-slip phenomenon's experimental results are analyzed in detail in the paper [5].

Our paper aims to analyse the theoretical stability conditions of the movement of a UHMWPE polyethylene specimen in contact with human skin based on our experimental results and literature [4-7]. The amplitude of the stick-slip phenomenon is analysed as a function of the rheological and tribological properties of human skin, system rigidity, and training speed. The analytical model's applicability is evaluated in selecting the material needed for the lower and upper human endoprosthesis and designing robot gripping systems.

Experimental model and analytical model

To analyse the stability of the movement and highlight the amplitude of the stick-stick phenomenon between the human skin and the biocompatible polyethylene UHMWPE, we consider a simplified model consisting of a mass (m_s) fixed in an elastic rigidity system (k) and subject to the friction of a continuous or stepwise (v_o) test specimen. The friction coefficient (μ) between the skin and the UHMWPE depends on the relative velocity between the specimens and the contact pressure. We press the polyethylene sample to the finger with a known displacement and continually measure and record the normal force, friction force, and time. The tribological experimental system is shown in Figure 1.

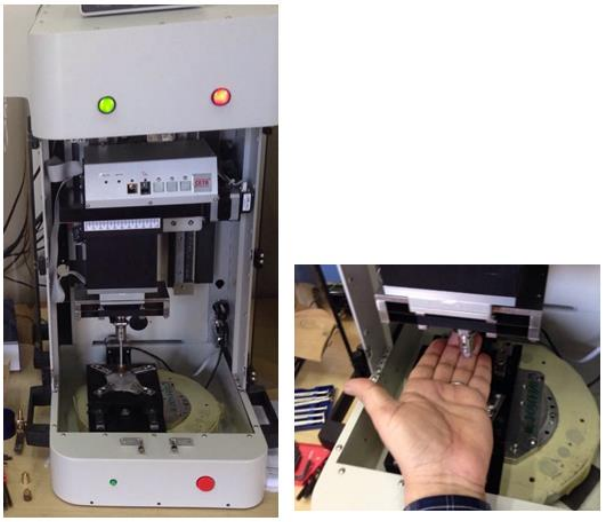

Figure 1. CETR test bench adapted for skin tribology

For the proposed dynamic model (Figure 1), the equation of relative motion of the UHMWPE polyethylene specimen relative to the finger (fixed in the stand support) is given by [2], [3] when the specimen moves at a velocity v_0:

$$m_s\ddot{x} + F_f(\dot{x}, \gamma_s) + \frac{h}{\omega}\dot{x} + kx = kv_0t + \frac{hv_0}{\omega_n} \quad (1)$$

The mass of the specimen is denoted by mx, where x represents the displacement in the direction of slip. The variables t, $x = dx/dt$, and $x = d^2x/dt^2$ represent time, instantaneous linear velocity, and acceleration, respectively. The force of friction $F_f(\dot{x}, \gamma_s)$ represents the resistance to motion of the mass, which depends on the sliding velocity $(v_0 - x)$ and the state of contact area γ_s ("age" of contact-saturation contact area). The axial stiffness is represented by k, h represents the hysteresis damping in UHMWPE polyethylene, and ω represents the frequency of oscillation if the system is excited from the outside or the frequency of natural oscillation ω_n if the system is a free vibratory system.

It is well-known that static friction depends on the contact time. The transfer of contact pressure from one friction element to the other is comprised of elastic, elasto-plastic, relaxation, and creep deformations. The real contact area can be used to trace the geometric appearance of this transfer. The coefficient of static friction is dependent on the real area's size, deformation resistance, and shearing of the roughness. This transfer results in an increase in the static friction coefficient with time, and it is known as "contact saturation." The real contact area is used to measure the saturation of contact [1], [2]. The variable of state γ_s is assumed to follow the simple kinetic equation [1], [2].

For the variable state γ_s, the following simple kinetic equation is assumed:

$$\frac{d\gamma_s}{dt} = \frac{1-\gamma_s}{t_{cr}} - \frac{\dot{x}}{D} \tag{2}$$

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

1. For stick time $\frac{dx}{dt} = 0$, γ_s

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

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

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

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

- for the stick time

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

- for steady state

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

When the body is set in motion, the variable of state decreases more rapidly at higher velocities. The parameter t_{cr} in equation (3a) represents the characteristic relaxation time of γ_s when the system is at rest, while D is the characteristic "relaxation length" or the "age" [1] of this parameter at the onset of motion. From a physical perspective of contact between two rough surfaces, tcr can be viewed as the characteristic time of the creep process, and D represents the average real contact diameter. The creep velocity can be expressed as $v_{cr} = \frac{D}{t_{cr}}$.

To investigate friction between the UHMWPE specimen and the skin (located on the lower area of the ring finger), experiments were conducted under the following conditions: normal force $F_n = 1N$, sliding velocity $v_0 = 0.1\ mm/min$, and rigidity in the sliding direction, $k = 1470\ N/m$. Under these conditions, the "relaxation length" D was determined to be 37.4 µm and the creep time t_{cr} was 0.5 s. Therefore, the creep velocity was calculated to be $v_{cr} = 75\mu m/s$ as seen in Figure 2.

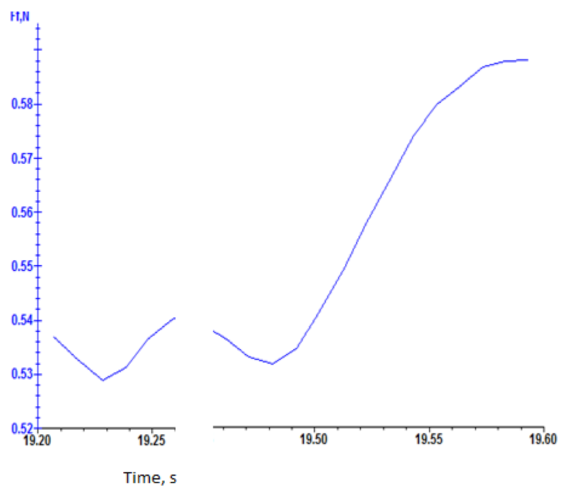

Figure 1. Friction force (F_f, N) vs time(s) on the lower area of the ring finger

The friction force will be:

$$F_f(\dot{x},\gamma_s) = F_k + (F_s - F_k)\gamma_s = ((\mu_k + (\mu_s - -\mu_k)\gamma_s)pA_c \quad (5)$$

where F_s and F_k are the static and kinetic friction forces, μ_s, μ_k are the static and kinetic friction coefficients, p is the contact pressure and $A_{.c}$ is the nominal contact area.

It has been widely accepted, as supported by numerous studies [4-7, 10, 13], that the kinetic friction coefficient is dependent on the sliding velocity. Specifically, it is commonly acknowledged that the coefficient exhibits a linear variation relative to the steady velocity (v_o).

$$\mu_k = \mu_{ko} + \Delta\mu_k(1 - \exp(-a|V_{rel}|)) \approx \mu_{ko} + \Delta\mu_k a(v_o - \dot{x}) \quad (6)$$

where $\Delta\mu_k = \mu_{kmin} - \mu_{ko}$;$V_{rel} = v_o - \dot{x}$; μ_{ko} is the friction coefficient at the beginning of the sliding phase; μ_{kmin} is the minimum friction coeficient for the velocity Striebeck curve; a is the inverse of the velocity constant (velocity gradient).

Derler and Rotaru [5] conducted experiments to investigate the friction of human skin with smooth glass at low velocities, specifically focusing on the stick-slip phenomena. Their measurements included friction as a function of sliding velocity and normal load (F_n, N), revealing the dependence of kinetic friction on velocity (v_o, m/s) and contact pressure (p, N/m^2):

$$\mu_k = 0.25v_o^{-0.37}\mu_k = 0.7F_n^{-0.4} = 57.9p^{-0.526} \quad (7)$$

It is possible to non dimensionalise the system (1)-(7) using the relations provided by [3], [11]:

$$\xi = \frac{\omega_n}{v_o}x;\ \zeta = \frac{h}{2k};\ \omega_n = \sqrt{\frac{k}{m_s}};\ v_a = av_o;\ \tau = \omega_n t;$$

$$\tau_{cr} = \omega_n t_{cr};\ \Delta\mu_s = \mu_s - \mu_{ko} v_{acr} = \frac{v_o}{v_{cr}};\ w = \frac{pA_c}{v_o\sqrt{m_s k}}$$

The equation of motion (1) in dimensionless form can be written as:

$$\ddot{\xi} + 2\alpha\dot{\xi} + \xi = M\tau - N = f(\tau) \quad (8)$$

Where:

$$\alpha = \zeta + \Delta\mu_k\frac{v_a w}{2} \quad (9a)$$

$$\mathrm{M} = 1 + \Delta\mu_s\frac{\mathrm{w}}{\tau_{cr}} \quad (9b)$$

$$N = (\mu_{ko} + \Delta\mu_k v_a)w \quad (9c)$$

The solutions to the non-homogeneous differential equation (6) are dependent on the value of the parameter α. Depending on the value of α, the solution may exhibit damped vibration if α is positive, vibrations without damping if α is null, or self-friction vibration if α is negative. Therefore, the associated homogeneous differential equation is:

$$\ddot{\xi} + 2\alpha\dot{\xi} + \xi = 0 \quad (9c)$$

and it describes vibrations of the type:

1) vibration without damping $\alpha=0$;
2) small damping $0 < \alpha < 1$;
3) critical damping $\alpha = 1$;
4) strengthening damping $\alpha > 1$;
5) self excitation by friction $\alpha < 0$.

For the initial conditions $\xi = \xi_o$ and $\dot{\xi}_o = \xi_{v0}$ at $\tau = 0$, the solutions of the non-homogeneous differential equation are obtained from the homogeneous equation (6b) and the Duhamel type

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integrals. For example, the solution of movement UHMWPE sample to human skin in the slip stage without damping ($\alpha = 0$) is:

-displacement*:*

$$\xi(\tau) = \xi_o \cos(\tau) + \xi_{v0} \sin(\tau) + \int_0^{\tau} \sin(\tau - t)\, f(t) dt \tag{10a}$$

-velocity:

$$\xi_v = \frac{d\xi}{d\tau} \tag{10b}$$

-acceleration:

$$\xi_a = \frac{d\xi_v}{d\tau} \tag{10c}$$

Figure 3 illustrates the movement characteristics (phase plane) during the slip cycle for undamped vibration of UHMWPE on human skin.

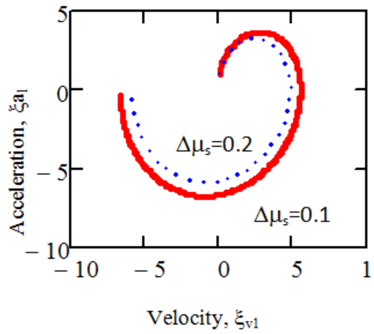

Figure 3. Phase plane of slip without damping

Stability of polyethylene movement on human skin

To analyse the stability of the movement and highlight the amplitude of the stick-stick phenomenon the homogeneous differential equation for the sliding period is used:

$$\ddot{\xi} + 2\alpha\dot{\xi} + (\xi - \xi_o) = 0 \tag{11}$$

is the displacement at the end of slip phase.

The slip period begins when the displacement:

$$\xi_p = \frac{\mu_s p A_c \omega_n}{v_o k} = \mu_s w \tag{12}$$

The dimensionless displacement of mass m_s at dimensionless time τ is:

$$\xi(\tau) = \xi_o + e^{-\alpha\tau}\left[(\xi_p - \xi_o)\cos(\tau\sqrt{1-\alpha^2}) + \frac{1}{\sqrt{1-\alpha^2}}\sin(\tau\sqrt{1-\alpha^2}) + \frac{\alpha}{\sqrt{1-\alpha^2}}(\xi_p - \xi_o)\sin(\tau\sqrt{1-\alpha^2})\right] \tag{13}$$

The velocity:

$$\xi_v(\tau) = \frac{d\xi}{d\tau} \tag{14}$$

If the system described by equations (11) and (12) is at the boundary of stick-slip, both expressions become zero simultaneously. To determine the slip phase duration and implicitly the amplitude of the movement, we need to examine the conditions under which the space ξ(τ) attains its maximum. This condition is met when the velocity is zero. Therefore, we can infer that:

$$\tau_{max} = \frac{1}{\sqrt{1-\alpha^2}} \text{atan}\left[\frac{1}{\frac{\alpha}{\sqrt{1-\alpha^2}} + \sqrt{1-\alpha^2(\xi_p - \xi_o)(1+\frac{\alpha^2}{1-\alpha^2})}}\right. \tag{15}$$

The amplitude of oscillation

$$A_\xi = \xi_{max} - \xi_o = \xi(\tau_{max}) - \xi_o \tag{16}$$

Figure 4 illustrates the impact of friction on the amplitude of the stick-slip motion of UHMWPE polyethylene on the skin of the finger region.

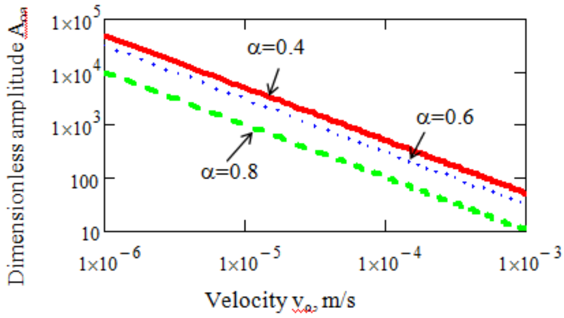

Figure 4. The amplitude of stick-slip

The times at which the mass has zero acceleration can be written as:

$$\tau_{oc} = \frac{1}{\sqrt{1-\alpha^2}} \text{atan}\left[\frac{\sqrt{1-\alpha^2}\Phi_c}{2\alpha^2+\Phi_c\alpha-1} + n\pi\right] \quad (17)$$

where $\Phi_c = w(\Delta\mu_s - v_a)$ and n is the integer number in the periodic function.

If eq. (17) is substituded into the condition for zero velocity (14):

$$\xi_v(\tau_{oc}) = 0 \quad (18)$$

An implicit relationship between the damping complex parameter (α) and loading parameter (Φc) was obtained. The numerical solution of equation (18), denoted by $\Phi_{cr}(\alpha, n)$, is presented in Figure 5, indicating the stability limit of stick-slip between the skin and the UHMWPE polyethylene.

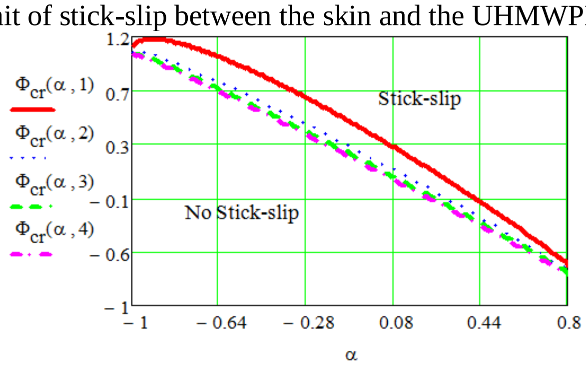

Figure 5. Loading parameter vs hysteretic and friction parameter

Based on the experimental results and those of previous studies [4-6], the value of the load parameter (Φc) was determined.

At the end of the slip time, the relative speed is zero, $V_{rel} = v_o - \dot{x}$, $\xi_v = 1$ and the acceleration is zero. The system of equations formed by (2), (3), (4) and (8) has a steady – state solution:

$\dot{\xi} = 1,\ \gamma_s = 1 - v_{acr}$ if $v_{acr} \leq 1 \quad \gamma_s = 0$ if $v_{acr} > 1$

The sliding at $v_{acr} \leq 1$ is unstable, when the oscillation time is much larger than the characteristic creep time (t_{cr}).

To obtain the stability limit as a function of sliding velocity, friction, and damping, we applied a small perturbation to the steady-state solution [2], [14].

$$\xi = \xi_o + \tau + \delta\xi \quad (19)$$

and:

$$\gamma_s = \gamma_{so} + \delta\gamma_s \quad (20)$$

The linearised equations of (19) and (20) are:

$$\ddot{\delta\xi} + 2\zeta\dot{\delta\xi} + \delta\xi + \alpha[1 - \Delta\beta(1 - e^{-v_a})]\delta\gamma_s = 0 \quad (21)$$

and:

$$\delta\dot{\gamma}_s = \frac{-1}{\tau_{cr}}(\delta\gamma_s + v_{acr}\delta\dot{\xi}) \tag{22}$$

A solution to system of equations (21) and (22) is exponential :

$$\delta\xi = Ae^{\varphi\tau};\ \delta\gamma_s = Be^{\varphi\tau} \tag{23}$$

Manipulating (22) and (23) the constants A, B and φ can be obtained. The linear system of equations (unknowns A, B) has a non-trivial solution, when determinant vanishes.

$$\begin{vmatrix} \varphi^2 + \varsigma\varphi + 1 & \alpha \\ \varphi\frac{v_{acr}}{\tau_{cr}} & \varphi + \frac{1}{\tau_{cr}} \end{vmatrix} \tag{24}$$

The stability of the system is determined by the roots of equation (22). In the case of damped oscillations, two out of three solutions of the third-order algebraic equation of φ are purely imaginary and complex conjugates, while the third solution is real and negative:

$$\varphi_1 = -\Phi,\ \varphi_2 = i\Omega_c,\ \ \varphi_3 = -i\Omega_c \tag{25}$$

The stability limit can be written as:

$$\left(\frac{1}{\tau_{cr}} + \zeta\right)\left(1 + \frac{\zeta}{\tau_{cr}} - \frac{v_{acr}\,\alpha}{\tau_{cr}}\right) = \frac{1}{\tau_{cr}} \tag{24}$$

The critical friction parameter is defined:

$$\Pi_{fc} = \alpha v_{acr} = \frac{\Delta\mu_s p A_c}{v_{cr}\sqrt{m_s k}} = \frac{\zeta^2\tau_{cr} + \zeta(1+\tau_{cr}^2)}{1+\zeta\tau_{cr}} \tag{25}$$

The stability curve depicting the movement of skin in contact with the hysteretic UHMWPE is presented in Figure 6.

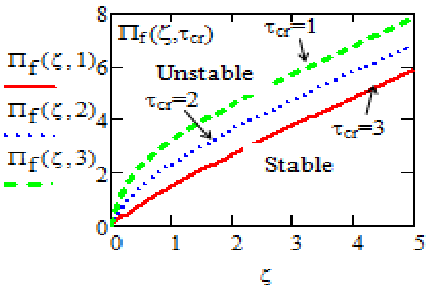

Figure 6. Critical friction parameter vs hysteretic coefficient of UHMWPE

The stability of sliding between skin and biocompatible polyethylene depends on the friction parameter, which is denoted by Π_{fc}. When the friction parameter is smaller than Π_{fc}, the sliding is stable. Conversely, when the friction parameter is larger than Π_{fc}, the sliding becomes unstable. Figure 6 illustrates the stability curve of the skin's movement in contact with the hysteretic UHMWPE. Notably, the hysteretic damping of UHMWPE polyethylene has a strong effect on the stability of the sliding movement.

Conclusions

By using a model system consisting of biocompatible UHMWPE material in contact with human skin, the dynamics of dry and limited friction at low velocities have been studied. In vivo analysis of stick-slip phenomena of UHMWPE sliding on human skin was conducted using a modified tribometer. The normal force and both static and kinetic friction forces were determined for stationary sliding and stick-slip friction. During stick time, creep phenomena were observed, and the static friction force increased. An analytical model for stick-slip of skin and UHMWPE was proposed, where the amplitude of stick-slip phenomena was defined by the difference between static and kinetic friction.

The stability conditions of movement between skin and UHMWPE polietylene were determined by the contact pressure, sliding velocity, and rigidity of the system.

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