

# The adhesion and hysteresis effect in friction skin with artificial materials

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**Abstract.** Human skin is a soft biomaterial with a complex anatomical structure and it has a complex material behavior during the mechanical contact with objects and surfaces. The friction adhesion component is defined by means of the theories of Johnson-Kendall-Roberts (JKR), Derjaguin-Muller-Toporov (DMT) and Maugis – Dugdale (MD). We shall consider the human skin entering into contact with a rigid surface. The deformation (hysteresis) component of the skin friction is evaluated with Voigt rheological model for the spherical contact, with the original model, developed in MATHCAD software. The adhesive component of the skin friction is greater than the hysteresis component for all friction parameters (load, velocity, the strength of interface between skin and the artificial material).

## 1. Introduction

Tribology science and technology mating surfaces being in relative opposite motion are not limited for improving engineering problems in mechanical engineering applications. Nowadays, the important part of the actual solutions is related to the human skin tribological aspects. The human skin in vivo is commonly one of the famous interacting surfaces which are found in relative motion in many of the daily activities of man. So many questions are typically related to optimizing the friction problems of the skin-product interactions, rather than to optimizing the use [1].

A well-known method for examining and analyzing the tribological performance is based on a general treatment, which is called the systems approach [2]. This means that a tribological contact condition is separated from the application studied, by using an envelope system as proposed (contact area specifications). The contact condition separated by this envelope is considered as a system, that is, a set of factors interconnected by structure and function. The human skin is a biomaterial soft with a complex anatomical structure and it has a complex material behavior while coming into mechanical contact with the object and with the end prosthesis. Amonton's empirical rules of friction are not suitable for skin and the theoretical concept of elastomer friction can be used. Thus, the friction of elastomers involves two terms (non-interacting), adhesion and deformation [3]. The report of these two components for the skin is the function to state of lubrication (dry friction, limit or mixed lubrication).



The adhesion component is defined by the surface energy of skin and three adhesion theories are used. The deformation component of human skin is determined by a new model, which uses the hysteresis and plowing phenomena.

The aim of this paper is to define quantitatively these two components of friction, for the elastic and viscoelastic properties of skin, with the new model for the hysteresis component of friction between the human skin (Voight material) and the rigid sphere.

## 2. Adhesive contact mechanics theories for skin

The theories explaining the adhesion and separation of two spherical elastic contact surfaces under the action of purely normal forces are investigated [4]. The adhesions between the rigid spheres where the surface forces are controlled by the Lennard–Jones potential equations, which give the total force–separation relations, were analyzed by Bradley in 1932 [5]. The adhesion theories taking elastic deformations into account were presented by the scientists Johnson, Kendall & Roberts (JKR) in 1971 Derjaguin, Muller & Toporov (DMT) in 1975 [5] and Maugis-Dugdale (MD) in 1992 [6]. When two elastic spheres come into contact with each other or with another flat surface, the resulting contact area can be estimated by using single-asperity contact mechanics models, such as those detailed by Hertz (H), Johnson, Kendall, and Roberts (JKR) [7], Derjaguin, Muller and Toporov (DMT) [8] or Maugis and Dugdale (MD).

We shall consider the contact between one rigid sphere (radius  $R_r$ ) and equivalent elastic plane (elasticity  $E_r=(3/4)K_e$ ):  $K_e=\frac{3}{4}\left(\frac{1-\nu_1^2}{E_1}+\frac{1-\nu_2^2}{E_2}\right)$  where  $\nu_1$  and  $\nu_2$  are the Poisson coefficients,  $E_1$  and  $E_2$  are elasticity modulus for contact materials.

The contact parameters are: the surface energy of sphere with elastic plane ( $\gamma$ ), the equilibrium spating in the Lennard- Jones potential ( $z_o$ ) and the maximum tension (strength) of Lenard-Jones potential ( $\sigma_o$ ). The Derjaguin ( $\beta$ ), Tabor ( $Z$ ) and Maugis ( $\lambda$ ) dimensionless parameters can be used for describing the characteristics of the adhesion contact of skin with the rigid sphere:

$$\beta = \frac{64}{3\pi} \left( \frac{R_r \gamma^2}{\pi K_e^2 z_o^3} \right)^{1/3}; \quad Z = \left( \frac{16 R_r \gamma^2}{9 K_e^2 z_o^3} \right)^{1/3}; \quad \lambda = 2\sigma_o \left( \frac{R_r}{\pi \gamma K_e^2} \right)^{1/3} \quad (1)$$

The relations between these parameters are  $\lambda = 0.4Z$  and  $\lambda = 1.157\beta$ .

In order to define the adhesion effect about the friction coefficient, it is accepted the dimensionless parameters of Johnson and Maugis, for normal load ( $F_{na}$ ), contact radius ( $a_a$ ) and penetration ( $\Delta$ ) [5, 6]:

$$a_a = a \cdot \left( \frac{K_e}{\pi \cdot \gamma \cdot R_r^2} \right)^{\frac{1}{3}} \quad F_{na} = \frac{F_n}{\pi \cdot \gamma \cdot R_r} \quad \Delta = \delta \cdot \left( \frac{K_e^2}{\pi^2 \cdot \gamma^2 \cdot R_r} \right)^{\frac{1}{3}} \quad (2), (3), (4)$$

Thus, the Hertz ( $a_{aH}$ ), JKR ( $a_{aJC}$ ), DMT ( $a_{aDC}$ ) and MD ( $a_{aMC}$ ) radius contact for Hertz, JKR, DMT and MD models are

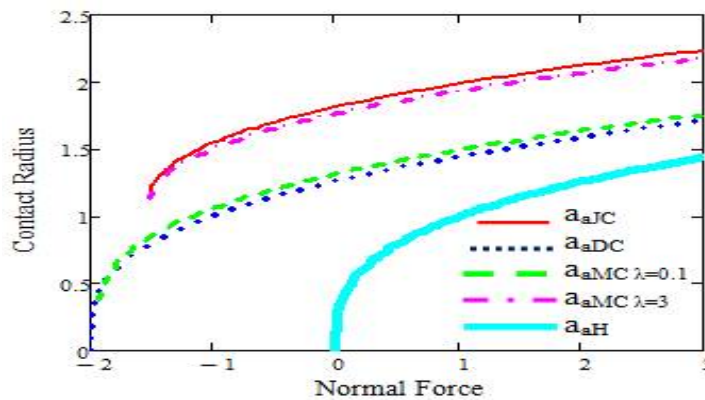
$$a_{aH} = F_{na}^{1/3};$$

$$a_{aJC} = 6^{1/3} \left( \frac{1 + \sqrt{1 + \frac{2F_{na}}{3}}}{2} \right)^{2/3} \quad a_{aDC} = 2^{1/3} \left( 1 + \frac{F_{na}}{2} \right)^{1/3} \quad a_{aMC} = \left( \frac{\alpha + \sqrt{1 - \frac{F_{na}}{F_{nc}}}}{1 + \alpha} \right)^{2/3} a_{oc} \quad (5)$$

To solve contact parameters for Maugis-Dugdale model (MD), it is adopted the numerical solution of Carpick [9]. Thus,

$$\alpha = \frac{1 - \exp\left(\frac{-\lambda}{0.924}\right)}{1.02}; F_{nc} = \frac{-7}{4} + \frac{1}{4} \frac{4.04\lambda^{1.4} - 1}{4.04\lambda^{1.4} + 1}; a_{oc} = 1.54 + 0.279 \frac{2.28\lambda^{1.3} - 1}{2.28\lambda^{1.3} + 1} \quad (6)$$

Figure 1 shows the contact radius in Hertz (H), JKR, DMT and MD models, respectively, determined by the Mathcad software. It is observed the effect of the adhesion parameter ( $\lambda$ ) is related to the contact radius and the penetration in MD model. When the adhesion parameter of skin is small ( $\lambda < 0.1$ ), the contact radius can be defined by the DMT theory and for greater values ( $\lambda > 3$ ), the radius contact can be determined by JKR theory.



**Figure 1.** Contact radius vs normal load in H, JKR, DMT and MD ( $\lambda = 0.1$  and  $\lambda = 3$ ) models.

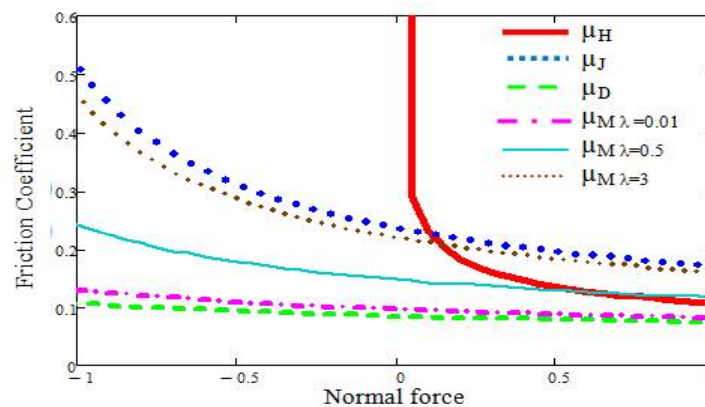
The adhesion parameter of skin varies between large limits ( $\lambda = 0.01 \dots 6$ ), as a function of strength of Lenard – Jones potential, surface energy, equivalent elasticity and equivalent radius.

We accept the constant shearing strength ( $\tau_o$ ) in contact, as a function to friction. In accordance to this hypothesis, the conventional Coulomb friction coefficient can be evaluated directly:

$$\mu_H = \frac{\pi^{2/3} a_{aH}^2 \tau_a}{F_{na}}; \mu_J = \frac{\pi^{2/3} a_{aJC}^2 \tau_a}{F_{na} + 1.5}; \mu_D = \frac{\pi^{2/3} a_{aDC}^2 \tau_a}{F_{na} + 2}; \mu_M = \frac{\pi^{2/3} a_{aMC}^2 \tau_a}{F_{na} - F_{nc}} \quad (7)$$

where  $\tau_a = \tau_o \left(\frac{R_r}{\gamma K_e^2}\right)^{1/3}$  is the friction shear strength of interfacial surfaces.

Figure 2 shows the conventional friction adhesion coefficient for H, JKR, DMT and MD models as a function to normal load.



**Figure 2.** Friction coefficient vs normal load in H, JKR, DMT and MD ( $\lambda = 0.01$ ,  $\lambda = 0.5$  and  $\lambda = 3$ ).

It is observed that adhesion friction component decreases with normal load for all adhesion models.

### 3. Hysteresis friction component

The human skin can be considered as an elastomeric material. It is applied the Voigt rheologic model of behavior material properties (elasticity modulus  $E_1$  and  $E_2$  and viscosity  $\eta$ ) [10]:

$$E_p = \frac{E_1 E_2^2 + \omega^2 (E_1 + E_2) \eta^2}{E_2^2 + \omega^2 \eta^2}; \quad \eta_p = \frac{\eta E_2^2}{E_2^2 + \omega^2 \eta^2}, \quad (8)$$

where  $\omega$  is angular frequency in dynamic model [10].

The asymmetry of pressure distribution of rigid sphere with equivalent Voigt viscoelastic material of plane is characterized by  $L$ ,  $x_o$  and  $y_o$  (figure 3) [10].

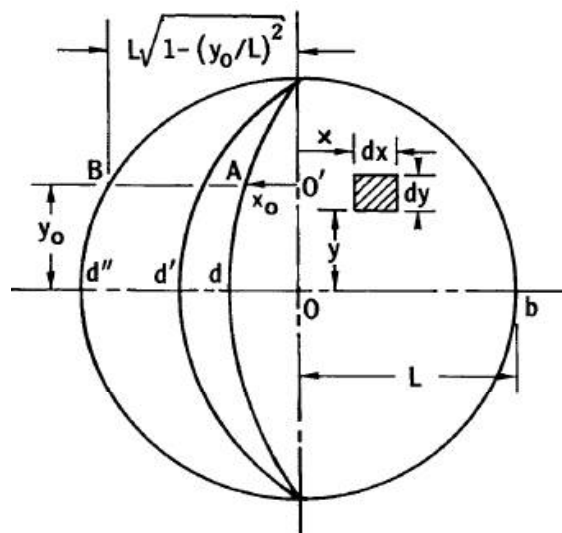


Figure 3. Asymmetrical spherical contact [10].

The mechanical equilibrium and boundary condition are

$$F_n = \int_{x_o}^L \int_{y_o}^L p(x, y) dx dy \quad \text{and} \quad p(x_o, y_o) = 0. \quad (9)$$

In the rolling sphere in  $x$  direction appears the moment ( $M_f$ ) of all pressure force about the centre  $O$  of the sphere. Thus, the hysteresis force in rolling direction is

$$F_{hyst} = \frac{M_f}{R_r} = \frac{\int_{x_o}^L \int_{y_o}^L x p(x, y) dx dy}{R_r}. \quad (10)$$

The hysteresis friction component ( $\mu_h$ ) can be obtained by the integral (10) ( $F_{hyst}$ ) and the normal load ( $F_n$ ) (9):

$$\mu_h = \frac{F_{hyst}}{F_n} = \frac{F_{hysta}}{F_{na}}. \quad (11)$$

It is used the following dimensionless parameters:

$$F_{na} = \frac{2F_n L}{E_p R_r^3}; \quad F_{hysta} = \frac{2F_{hyst} L}{E_p R_r^3}; \quad x_1 = \frac{x_o}{L}; \quad y_1 = \frac{y_o}{L}; \quad (12)$$

where  $L_a = L/R_r$ ,  $\gamma_v = \frac{\beta_v}{L_a}$  with  $\beta_v = \frac{\eta_p}{E_p}$ ,

and is obtained the normal load and hysteresis force:

$$F_{na} = L_a^3 (1-x_1)(1-y_1) \left[ 1 + \frac{\beta_v}{L_a} (1+x_1) - \frac{1}{3} (1+x_1+x_1^2) + \frac{1}{4} L_a (1+x_1+x_1^2+x_1^3) \right], \quad (13)$$

$$F_{hysta} = L_a^5 (1-x_1)(1-y_1) \left\{ \begin{array}{l} (1+x_1) \left[ \frac{1}{2} - \frac{1}{6} (1+y_1+y_1^2) + \frac{L_a}{8} (1+y_1+y_1^2+y_1^3) \right] + \\ \frac{2\beta_v}{L_a} (1+x_1+x_1^3) + \frac{\beta_v L_a}{5} (1+x_1+x_1^2+x_1^3+x_1^4+x_1^5) \end{array} \right. . \quad (14)$$

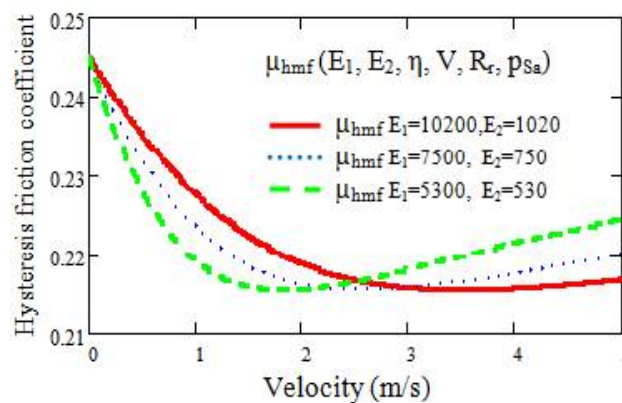
From the boundary condition,  $x_1 = (1 + \gamma_v^2 - y_1^2)^{1/2} - \gamma_v$ .

The medium hysteresis friction coefficient from circular contact will be obtained by

$$\mu_{hm} = \frac{1}{L_a} \int_0^{L_a} \mu_h dy_1 . \quad (15)$$

Thus, the figures 4 and 5 show the hysteresis friction components as a function to sliding velocity (V) and the normal load of the rigid spheres with same radius ( $R_r$ ) in contact with the viscoelastic skin for three viscoelastic properties of skin, as a function to age. The rheological properties of human skin are considered and adapted by Zahouani [11]. In the other sections of the paper, it is necessary to extend the experimental results about the rheology properties of the human skin, in some parts of the human body. These results will be used to define the friction between the skin and artificial materials, used in endoprosthesis.

The normal load is appreciated by means of the dimensionless Stribeck pressure  $p_{Sa} = \frac{F_n}{\pi R_r^2 E_p}$ .

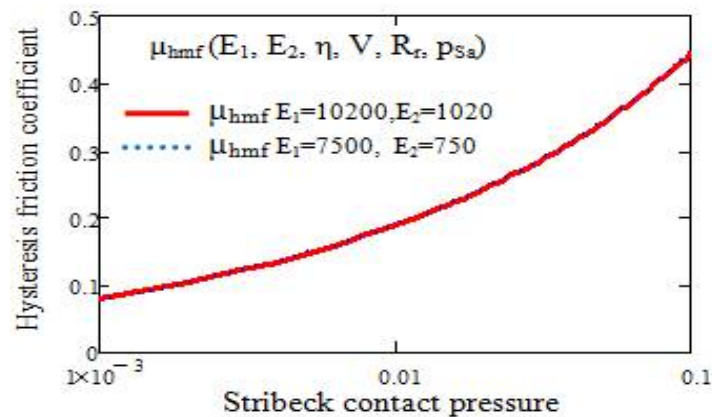


**Figure 4.** Hysteresis friction coefficient vs velocity.

The rolling contact implies a micro slip rather than a gross sliding within a mating surface. During the rolling process, only part of the work expanded elastically compresses, the material is recovered and the remaining one will appear as hysteresis friction and it ultimately become the same as it was when it was generated.

In the theoretical model of the hysteresis component of the skin friction with a rigid sphere we shall use some values of elasticity and viscosity in the Voight rheological behavior of skin. In this model, it is possible to analyze the effect of the velocity and the normal load of the hysteresis friction component for some rheological properties of skin (figures 4 and 5). It is noticed that the deformation

(hysteresis) friction component is at its minimum with respect to velocity values and increases non-linearly with the normal load, evaluated by Stribeck contact pressure (figure 5).



**Figure 5.** Hysteresis friction coefficient vs Stribeck contact pressure.

#### 4. Conclusions

Human skin can be treated as viscoelastic material due to its specific mechanical properties. The adhesion with the other contacted surface is also exhibited and it can be complied with by using the intermediate model Maugis-Dugdale, model which represents the approximate solution between the two theories JKR and DMR models. The friction conditions of the human skin can be analyzed by all adhesion theories.

The adhesive component of the coefficient of friction decreases proportionally with the normal force ( $F_{na}$ ) the force increases and so does the hysteresis component non-linearly with normal load. The new model of hysteresis friction coefficient of viscoelastic skin with rigid sphere can explain the effect of the velocity in terms of the friction of the skin coming in contact with some artificial materials.

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