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Twist static friction and creep between UHMWPE and bovine skin for human exoprosthesis

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Abstract. The twist static friction and the creep behavior of bovine skin in contact with Ultra High Molecular Weight Polyethylene (UHMWPE) indenters were studied by employing both theoretical and experimental methods. Loads (1 and 2 N) were applied to bovine skin using different indenter shapes. Moreover, the creep area and the coefficient of static friction were also discussed and analysed for different time durations. The experimental and theoretical results showed that the Voight-Kelvin rheological model could be used to represent the mechanical response of the cattle skin. As a conclusion, the creep parameter and the coefficient of static friction of bovine skin increased in time. For the circular indenter, the creep area was higher than in the case of the other shapes.

The study provides a base for more investigations on cattle skin behavior in order to be utilized on a rigid support (UHMWPE) as a new solution for “exoprosthesis support”.

1. Introduction

The mechanical and physical properties of the ex vivo skin have been the main topic of numerous studies in the past twenty years. Some of these studies have also analysed the properties of in vivo skin. Several studies [1-3] investigated the mechanical properties of animal skin and compared them to properties of human skin. The studies reported that the skin properties of some animals have similar mechanical properties to human skin. One of the most important mechanical effects of the skin in contact with artificial materials is the change of elasticity and viscosity in time (viscoelasticity) [4].

It is known that the friction force in the case of contact between skin and different artificial solids has two components: a mechanical component and an adhesion component. The mechanical component of friction is defined by the coefficient of friction [5].

The adhesion component depends on the geometry of the contact and the surface energy of the skin at the interface region with the other material of the tribological system.

Soldatenkov [6] has carried out a number of investigations on the deformation component of the friction force for standard viscoelasticity. Based on the energy approach, the author proposed a new formula to estimate the viscoelasticity of the materials (standard viscoelastic – the Voight-Kelvin mechanical model) in order to calculate the force of friction for a flat indenter and a rounded corner of an indenter.

With the same objective, Cheng et al. [7] studied the viscoelastic behaviour of a standard material by indentation, where a three-element viscoelastic material (Voight-Kelvin material) has been selected under the boundary conditions of flat-punch indentation of a viscoelastic half-space.



The method for determining the viscoelastic characteristics of a Voight-Kelvin material can also be used to determine the properties of human or bovine skin. However, the skin viscoelastic properties depend on many factors such as the applied normal force, the contact area, the materials in contact and the coefficient of friction between the two mating surfaces.

In this direction, in the tribology laboratory of the Machine Elements and Tribology (OMT) department of the University POLITEHNICA of Bucharest (UPB), the behavior of the skin in contact with Ultra High Molecular Weight Polyethylene (UHMWPE) has been tested as a biocompatible anti-friction material for the joint prosthesis.

In order to provide theoretical and experimental basis for building this proposed solution, the present study includes an examination of the static twist friction and of the creep phenomenon at load step (partially). The shape of the support was assessed based on area and perimeter using three different shapes with the same cross-sectional area (circular, square, and triangular).

The present paper proposes a theoretical and experimental analysis of the cattle skin creep viscoelastic behavior and the twist behavior in contact with UHMWPE. The mechanical component of the friction is highly dependent on hysteresis losses and the distribution of contact pressure. The static twist friction torque is determined as a function of the constant loading time, the shape of punch and the same average contact pressure.

2. Experimental procedure

The classic four-ball machine (Figure 1a) is modified for this experimental study. The original device (Figure 1b) was modified with the special device (Figure 1c). The bovine skin is fixed in this device and is in contact with the rotating indenter (punch). The only possible movement between skin and indenter is twist (spin). Three different indenter shapes (circle, square and triangle), all made of UHMWPE and having the same area equal to 16 mm^2 were used to apply the load on the skin.

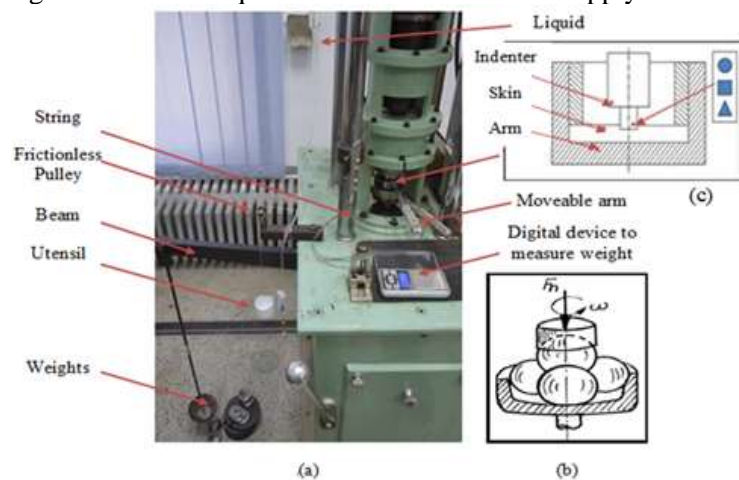


Figure 1. The four-ball tester: (a) Image of the test device during the experiment depicting the contact with the skin; (b) Original testing device of the device; (c) New device for skin.



Figure 2. Types of indenters employed:(a) circle; (b) square; (c) triangle.

The ex-vivo skin was harvested from a one-year-old male calf. $25 \times 25 \times 4 \text{ mm}$ pieces were prepared for testing by shaving the hair and washing the resulting samples by using only fresh water in order not to chemically degrade the biological tissue.

2.1. Testing procedure

A piece of bovine skin was placed in the device in the specified place as shown in Fig 5c. The circular indenter (radius R_0) was fixed and the normal loads (1 and 2 N) were applied. In order to determine the conventional coefficient of static friction, the following procedures were applied: the torque-measuring lever is loaded with variable weights of small amount (drops of water) until the lever begins to move continuously. The torque generated by the weight of the water in the collector immediately before the twist motion begins is considered a static friction torque. The conventional friction coefficient is defined as the ratio between the friction force and normal force. The friction force is determined based on the static friction torque and the contact radius. For the circular surface, the radius of contact is evaluated by the reduced radius of the circle, and for the surfaces of the square-shaped and the equilateral triangle-shaped, the contact radius is considered as the average of the radii of the inner circle and outer circle for square or triangle.

In order to make the arm begin or try to begin moving, water, W_{Liquid} is added resulting in a force F_{Static} . The device with skin was left in place for one minute in order for the real contact area to be determined. The test was repeated three times with the same operating conditions to reduce the variations. At the same operating conditions, the test was repeated for different times T (2, 3 and 4 minutes). Then the applied load was changed to 2 N and all the steps were repeated. The test results were collected by the computer. The indenter was changed to the square-shaped indenter (length of the square, L_{so}) and then to the triangle-shaped indenter (length of triangle side, L_{to}).

The twist friction coefficient (μ_t) is calculated based on the "r_{sf} specific friction radius"

$$M_t = \frac{M_{ft}}{F_n r_{sf}}, \tag{1}$$

where: M_{ft} is the friction torque, experimentally measured on the modified 4 ball machine and F_n is the normal contact force introduced.

3. Results and discussion

The results included in this part of the study were recorded in room temperature and humidity conditions ranging from 24 to 26°C and 30 to 34%, respectively. The operating times and loads applied were variable, as well as the indenter shapes (square, circular, and triangular) for UHMWPE. The results were acquired from the average of three stable and continuously measured values. The static twist friction coefficient is calculated by equation (1) with the static friction torque measured. These coefficients are presented in the Figures 3-6. The experimental results are used to obtain the static friction coefficient in Mathcad software package. These values are written in the metrical form. The explications of these matrices columns and rows: $Ext1_{i,1}$ = time t ; $Exc1_{i,2}$ = twist torque M_{tex} for normal load 1 N; $Exc2_{i,2}$ = M_{tex} for normal load 2N;

Thus, assuming the constant contact pressure on the circular surface (p_{am}), the coefficient of friction (μ_{tc}) has the following evolution in time ($t = Ext1_{i,1}$, s).

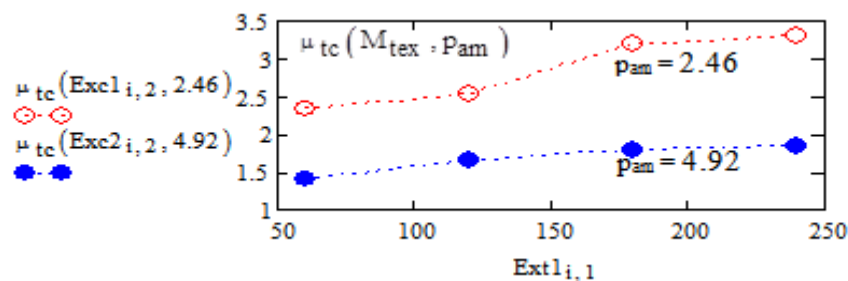


Figure 3. Static friction coefficient for pivoting for circular indenter at constant pressure

According to the theoretical model regarding the elastoplastic distribution of the contact pressure (5), the static friction coefficient of rotation is determined by the expression.

$$\mu_{exc} = \frac{M_{tex}}{\frac{2\pi}{3} R_0^3 M_{ta} P_{am} E_r} \tag{2}$$

where: M_{ta} is the theoretical twist torque.

Thus, Figure 4 shows the variation of the static friction coefficient (μ_{exc}) over time ($Exc1_{i,1}$ in seconds) for two dimensionless shear strengths ($\tau_{ac}=0.8, \tau_{ac}=0.6$), two average contact pressures ($p_m=2.48$ MPa, $p_m=4.96$ MPa) and the twist torque measured in device for the circular shape ($Exc1_{i,2}=M_{tex}$ for normal load 1 N and $Exc2_{i,2}=M_{tex}$ for normal load 2 N). The friction coefficient decreases when the contact pressure increases.

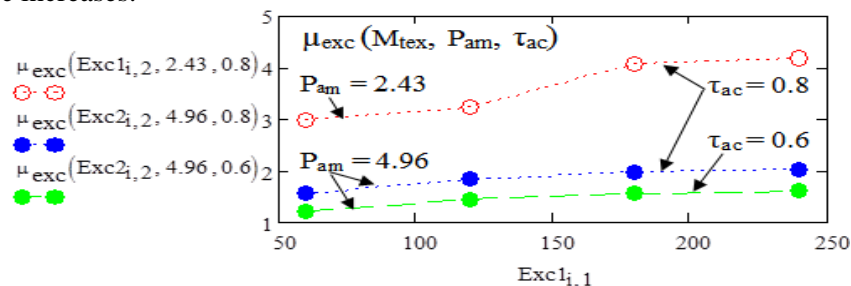


Figure 4. The coefficient of static friction in pivoting on a circular section at variable pressure

The evolution of static twist friction coefficient can be explained by the saturation contact phenomena in time and the creep of skin at the constant pressure. The decrease of friction coefficient when the contact pressure increases can be explained by the binomial friction force component.

The coefficient of friction for the triangular shape (μ_{tt}) and the square shape are shown in Figure 5 and Figure 6.

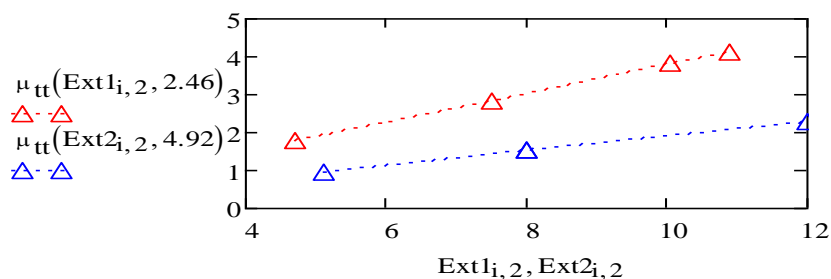


Figure 5. Static friction coefficient for pivoting on triangular shape at constant pressure

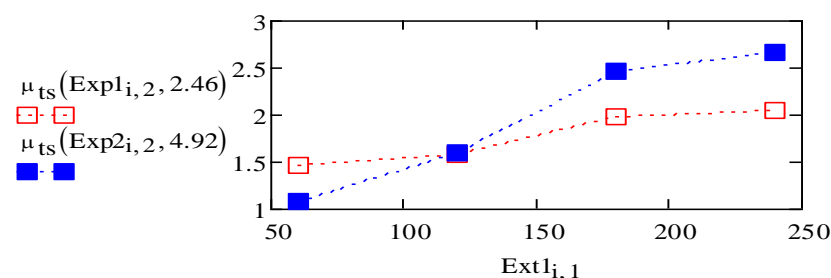


Figure 6. Static friction coefficient for pivoting on a square shape at constant pressure

The viscoelastic behavior of the bovine skin is highlighted by the analysis of the shape of the deformed zone and the variation of the penetration in time to the constant load. The effect of the creep parameter is used to analyse the changes of shapes (characteristic dimension- radius or length) of skin.

The creep parameter (φ) is the specific dimension of deformed shape (radius for the circular shape, length for the square and for the equilateral triangle) in time divided by the nominal initial dimension: $\varphi_c = R_t / R_0 ; \varphi_s = L_{st} / L_{so} ; \varphi_t = L_{tt} / L_{to}$. The variations of creep parameter at the step load depending

on time are shown in Figure 7. The results were obtained for the circle, square and triangle indenter shapes at an applied load equal to 1 and 2 N for different durations (1, 2, 3 and 4 minutes).

The variation in time of the constant load is a consequence of the viscoelastic behavior of the skin. The viscoelastic properties of skin were determined based on the Cheng model [7]. The following values for the rheology parameters of the cow skin were obtained by an original program developed in Mathcad software and the experimental results: $E_1 = 1.623$ MPa; $E_2 = 0.276$ MPa; $\varphi = 15.05$ MPa \times s. Thus, Figure 8 illustrates the dimensionless penetration of the circular-shaped indenter for a viscoelastic material, specific for cattle skin for one load evaluated by average contact pressure values.

The continuous curve is the theoretical curve of the Voight-Kelvin viscoelastic model (Figure 8), and the dotted curve is the experimental results.

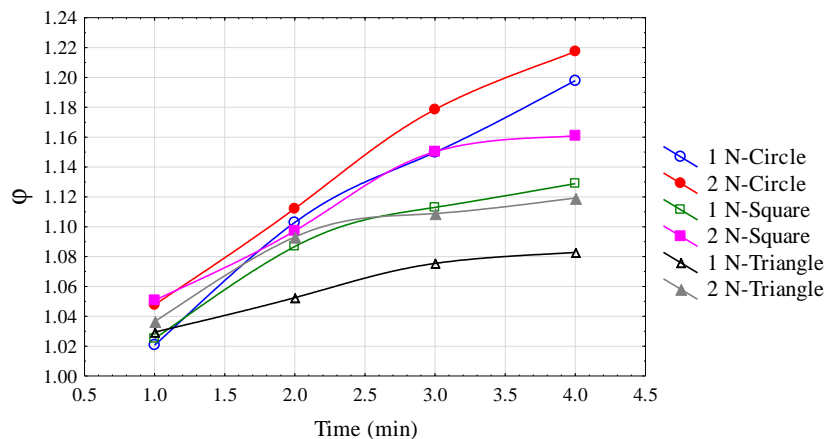


Figure 7. Variations of creep parameter (φ) respect with step load (1 N and 2 N) and shape of punch (circle, square, and triangle) for initial UHMWPE- skin contact

From the analysis of the theoretical and experimental curves of Figure 8, it can be seen that the Voight-Kelvin rheological model can be considered as suitable for bovine skin. It is appreciated that higher differences, about -12%, at the initiation of contact are due to measurement inaccuracy at zero theoretical time.

The differences between experimental and theoretical results for the analysis time interval (0-4) minutes) are between -12% and 4.3%.

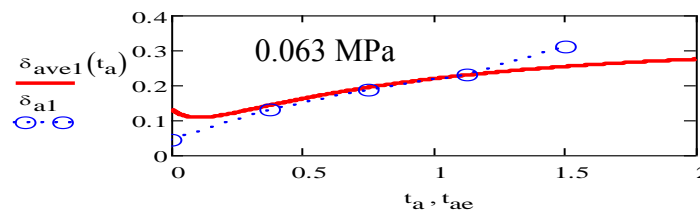


Figure 8. Theoretical penetration (continuous curve) and experimental (dotted curve) at constant average pressure 0.063 MPa

Based on this conclusion, to use the Voight-Kelvin model for tribological and damping of the bovine skin as part of the support for foot and hand exoprosthesis is proposed.

The effect of viscoelasticity of cattle skin can be seen by the evolution of the imprint in time [8]. Thus, Figure 9 shows the evolution of the imprint on the skin.

4. Conclusions

In this theoretical and experimental study, the viscoelastic behavior of bovine skin and the twist friction of rigid material (UHMW polyethylene) were highlighted.

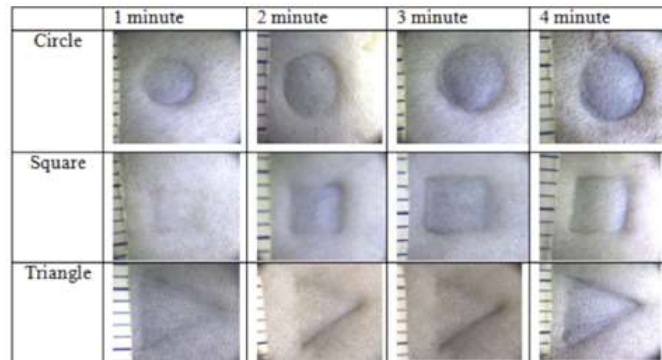


Figure 9. Imprints on the cattle skin

For establishing the viscoelastic behavior of the skin, the creep tests are used utilizing constant normal loads (1 and 2 N) that were applied using three different shaped indenters (circular, square and triangular) having the same contact area. This is an indication of the alterations in the imprints at the surface of the skin after the normal force has been removed.

The conclusions below are the outcome of the results' analysis:

- Cattle skin creep parameter increases with the increase normal load;
- The shape of contact has a high effect on the creep; for the three shapes considered (circular, square, triangular), the highest creep occurred in the case of the circle-shaped indenter and the lowest value was recorded in case of the triangle-shape indenter; the material of the punch (UHMWPE) has no effect in this case;
- There are three factors that have an effect on the conventional coefficient of static twist friction: contact shape, time and pressure;
- The static twist friction coefficient increases with time.

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