WEAR PREDICTION OF A TOTAL KNEE PROSTHESIS TIBIAL TRAY★

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By replacing the natural joint, a knee prosthesis must allow complex movements – flexion–extension (FE), antero-posterior translation (APT) and inner–outer rotation (IOR) – all of them defining a cyclic loading regime. The paper is devoted to the experimental determination of the wear of a UHMWPE prosthetic tibial tray, using studies of a ball/flat couple under constant compressive loading. The results obtained lead to the conclusion that many clinically reported failures of the tibial tray are caused by the mechanisms of adhesive and fatigue wear.

Key words: total knee prosthesis, wear, experimental methods, simulator.

1. THE HERTZIAN CONTACT MECHANISM

Two bodies that are in contact in a point become deformed when pressed against each other, thus creating a small contact surface. Hertz has calculated the deformations and stresses in the case of homogenous, isotropic, frictionless, linear elastic bodies.

For two different materials, having the elasticity modulus E_1 and E_2, and the Poisson ratios ν_1 and ν_2, the equivalent elasticity modulus E is defined, through the relation [1]:

$$E = \frac{E_1 E_2}{\left(1-\nu_1^2\right)E_2 + \left(1-\nu_2^2\right)E_1} \tag{1}$$

For a ball/flat type couple, where the ball is made out of CoCr alloy, with the elasticity modulus $E_1 = 1.9\cdot10^4$ daN/mm^2 and Poisson's coefficient $\nu_1 = 0.3$ and the plane sample made out of UHMWPE ($\nu_2 = 0.36$ and $E_2 = 106$ daN/mm^2), the equivalent elasticity modulus is $E = 121$ daN/mm^2.

Considering two revolution bodies having boundary surfaces with $1/R_1$ and $1/R_2$ curvatures, one introduces the relative curvature given by:

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$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \tag{2}$$

If one of the surfaces is concave, the curvature of that surface will be considered negative.

For the particular case of the contact between a sphere of radius r and a plane, we have.

$$\frac{1}{R_1} = \frac{1}{r} \quad \text{and} \quad \frac{1}{R_2} \to 0$$

Applying an F compression load between the two parts leads to the appearance of a contact area, due to surfaces deformation.

The F compression force causes an h movement of the center of the sphere, through its penetration in the flat body, according to relation:

$$h = \left(\frac{9F^2}{16rE^2} \right)^{1/3} \tag{3}$$

The relation between the circle diameter l (of the spherical contact spot) and the penetration h is [1]:

$$l^2 = 4 \cdot r \cdot h$$

Using (3) it result the diameter of the contact spot:

$$l = \left(\frac{6F \cdot r}{E} \right)^{\frac{1}{3}} \tag{4}$$

2. DETERMINATION OF WEAR PARAMETERS

An experimental device was created for the simulation of the wear process of total knee prosthesis components. For this purpose, a ball/flat type couple was used. It consists of a ball made of CoCr alloy, simulating a condyle of the femoral component, and a polyethylene disk of high density (UHMWPE) placed underneath representing the tibia component. The thickness of UHMWPE disk was 5 or 10 mm and was mounted on a CoCr alloy plate.

The movements made and the applied loadings were based on biomechanical studies. The complex movement consisted in: flexion–extension (FE), anteroposterior translation (APT) and inner–outer rotation (IOR). The FE movement is applied to the ball and the APT and IOR to the disk (Fig. 1).

These movements were made by intermediate of a rod-handle mechanism. The movements variation in time was almost sinusoidal, a movement cycle period being of 1 s. The experimental unit made is very similar to that used by V. Saikko, T. Ahlroos and O. Calonius at the Helsinky University of Technology [2].

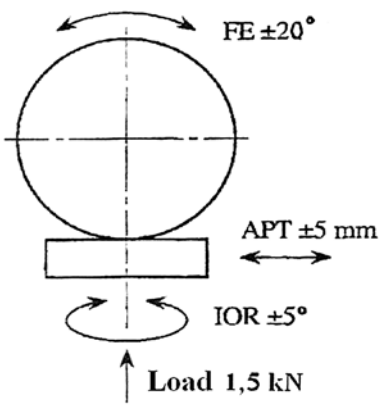

Fig. 1 – The friction couple kinematics.

The amplitude of the flexion–extension movement was of 40°. For FE movement only, the sliding distance between the extreme positions would be of 20 mm, for a 54 mm diameter ball. Anyway, the APT movement, with the amplitude of 10 mm, was synchronized with the FE movement so that the maximum flexion would coincide with the maximum posterior translation of the disk, and the maximum extension with the corresponding maximum anterior translation. This has shortened the sliding distance between the extreme positions. Due to both movements, the contact spot moved relatively cyclic on the disk surface.

The rod-handle mechanism was created so that the phase angle between the IOR and the APT sinusoids is $\pi/2$. As a consequence, the locus of the point where the force is applied on the disk (meaning the geometrical path of a theoretical contact point) was an antisymmetrical narrow figure, in the shape of an eight (see Fig. 2).

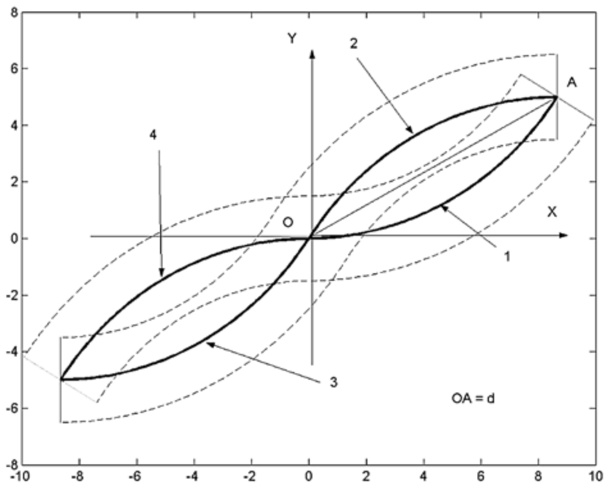

Fig. 2 – The trajectories of the contact point between the ball and the plane.

The parametrical equations of the curve (C_1) are:

$$x_1 = d \cdot k \cdot \cos(\varphi_0 \cdot k), \quad y_1 = d \cdot k \cdot \sin(\varphi_0 \cdot k); \quad k \in [0,1] \tag{5}$$

where:

– k is the adimensionalized time;
– d is the relative translation between the surfaces;
– φ_0 is the maximum IOR angle.

Similar, the equations of the curve (C_2) are:

$$\begin{aligned} x_2 &= d \cdot \cos\varphi_0 - d \cdot k \cdot \cos(\varphi_0 \cdot k) \\ y_2 &= d \cdot \sin\varphi_0 - d \cdot k \cdot \sin(\varphi_0 \cdot k), \quad k \in [0,1] \end{aligned} \tag{6}$$

The curves (C_3) and (C_4) are antisymmetrically defined:

$$x_3 = -x_1, \; y_3 = -y_1, \quad k \in [0, 1] \tag{7}$$

$$x_4 = -x_2, \; y_4 = -y_2, \quad k \in [0, 1] \tag{8}$$

The length of one of the curves is:

$$L = \int_0^1 \sqrt{\left((x_1')^2 + (y_1')^2\right)} \cdot \mathrm{d}k \tag{9}$$

From (5) it result:

$$L = d\int_0^1 \sqrt{1+k^2} \cdot \mathrm{d}k \tag{10}$$

The area of the circular segment defining the vertical profile of the wear imprint is:

$$S_u = \frac{r^2}{2} \cdot \left(\arcsin\left(\frac{l}{2r}\right) - \frac{l}{2r}\right) \tag{11}$$

where l is the width of the imprint.

The volume of the theoretical imprint can be calculated as:

$$V_u = 2S_u \cdot L \tag{12}$$

The APT movement was realized so that lever fixed on the FE shaft led to a low-friction movement of a straight, horizontal beam, coupled to a force transducer. The transducer signal was proportional to the friction force between the ball and the disk. This method allow for the determination of the friction coefficient μ.

The first experiments carried out, using only FE and APT movements, led to a very small wear rate. By adding the IOR movement, the wear rate increased, the wear phenomenon becoming more complex.

The vertical loading of 1.5 kN loading was constant, corresponding to the maximum load induced in the knee by the routine activities. Due to translations, the stresses in the disk modify in a cyclic manner, even for a constant compression force.

The disk samples (having a diameter of 40 mm) were made out of high density polyethylene, type GUR 1050. The tests were made on five different disks. Oxidation was simulated through the ageing of the polyethylene after the gamma irradiation. The lower part of the disk was placed on a level support of CoCr alloy.

The lubricant used was sterilized, filtered 0.1 μm physiological serum with a low content of proteins and endotoxines. The tests were carried out at the room temperature. During the tests, the value of the friction force was also achieved.

The duration of the tests was of $5\cdot10^6$ cycles, at a frequency of 1 Hz. The tests were stopped every 500,000 cycles in order to change the lubricant.

The elastic deformation of the polyethylene under pressure, has as consequence an increase of its radius in the contact area. By noting r – the radius of the undeformed contact area and r_m – the radius of the area deformed by the contact, it can be seen in Fig. 3b that $r_m > r$.

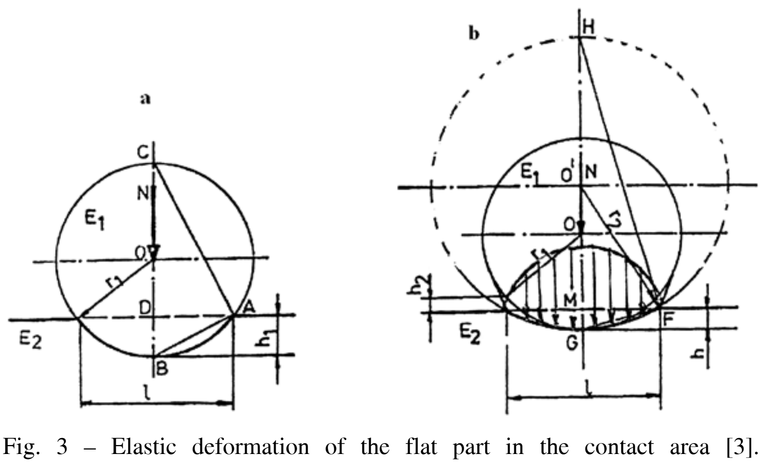

Fig. 3 – Elastic deformation of the flat part in the contact area [3].
a – theoretical case; b – practical case.

The equivalent curvature radius in the point where the l_m impression width was measured, noted by r_m, can be calculate from (4):

$$r_m = \frac{E \cdot l_m^3}{6F} \tag{13}$$

The volume of material for the flat element, removed through wear, will be:

$$V_u = \frac{L_m \cdot r_m^2}{2} \cdot \left(\arcsin\left(\frac{l_m}{2r}\right) - \frac{l_m}{2r} \right) \tag{14}$$

where L_m is the measured length of the imprint.

Solving numerically one obtains the solution:

$$r_m = 27{,}3212 \text{ mm } \cong 1{,}012r$$

Practically, the microscopic measurement of the imprints width in five established points, allow computation of the medium width of the imprint. Based on this value, the volume of worn material of the flate polyethylene element V_u is determined as well as the medium depth of the layer removed through wear h_{mu}.

3. RESULTS

The results obtained from the experimental trials, for a constant force of 150 daN, having an FE of ± 20° and an APT of ± 5 mm, are presented in Table 1.

Table 1

Wear of polyethylene disks and average coefficient of friction

Test	Wear	Wear factor	Wear pit dimensions			μ
	(10^{-3} mm^3)	(10^{-11}mm^3/Nm)	Length (mm)	Width (mm)	Depth (10^{-3} mm)	
1	72,258	0,935	10,3	1,32	0,6	0,036
2	128,559	1,697	10,1	1,61	1,3	0,053
3	71,311	0,914	10,4	1,31	0,5	0,035
4	120,399	1,514	10,6	1,55	0,9	0,034
5	112,475	1,428	10,5	1,52	1,0	0,047

The tests 1 and 2 were performed on polyethylene disks having a 5 mm width, and tests 3, 4 and 5 on disks having 10 mm width. The theoretical length of the frictional distance covered by the contact spot, on each movement cycle, was 10 mm. The measurements carried out with the microscope have shown an effective increase of these values, probably caused by the shear stresses occurred on the edges of the contact area.

For tests 2 and 3, the UHMWPE samples were sterilized through γ irradiation and aged through air convection. Tests 1 and 4 were carried out on samples that were not irradiated and test 5 on samples that were irradiated but not aged.

The wear factor was determined based on Archard’s relation [4]:

$$V_u = F \cdot k \cdot v \cdot t \tag{15}$$

where:

V_u – volume of material removed through wear (cm^3);

F – working load (daN);

v – relative sliding velocity (cm/s);

t – test duration (hours);

k – wear factor ($cm^3 \cdot s$/ daN·m·h).

Relation (15) expresses a general law for the dependency of the wear as function of the compressive force between the bodies in contact and the space covered by friction.

Therefore we can write:

$$k = V_u /(F \cdot v \cdot t) = V_u /(F \cdot L_f) \tag{16}$$

where $L_f = v\ t$ is the space covered by friction.

Table 1 also shows the medium values of the friction coefficient, determined based on the measurements carried out by intermediate of the force transducer coupled on the bearing with low linear friction, part of the generator of the APT movement.

4. CONCLUSIONS

Appreciating the wear of the tibial tray of total knee prosthesis is very difficult. Measuring the wear becomes more challenging due to polyethylene's considerable yield. It is also difficult to establish the value of the wear factor because measuring the volume of material removed is also complicated to do.

At the moment, appreciating the wear of the tibial tray through simulation is generally done using qualitative methods, based on the microscopical investigation of the wear impressions. The initial polishing of the polyethylene's contact surface is a sign certifying the adhesive nature of wear.

The tests carried out for a different number of cycles prove that the wear rate of the γ irradiated and air convection aged disks was greater in the beginning, decreasing afterwards and getting stabilized around the values of the wear rates for not irradiated specimens. The wear rate of the γ irradiated and aged 10 mm thick disks is about twice as for those that were not irradiated.

The wear rate for 5 mm, aged disks is greater than that of similar disks, with a 10 mm thickness.

REFERENCES

1. K. L. Johnson, , *Contact Mechanics*, Cambridge University Press, Cambridge, 1985.
2. V. Saikko, T. Ahlroos, O. Calonious, *A three-axis Wear Simulator with ball-on-flat Contact,* Wear, **249**, pp. 310–315, 2001.
3. L. Capitanu, *Durabilitatea endoprotezelor ortopedice*, Ed. Bren, Bucharest, 2004.
4. J. F. Archard, *Contact and Rubbing of flat Surfaces*, J. Appl. Phys., **24**, pp. 438–455, 1953.