International Journal of Engineering Trends and Technology
ISSN: 2231 – 5381 / https://doi.org/10.14445/22315381/IJETT-V70I5P222
Volume 70 Issue 5, 201-208, May 2022

Original Article

Free Rolling Friction Model of the Femural Component on the Tibial Plateau in knee prosthesis

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Received: 13 February 2022 Revised: 14 April 2022 Accepted: 21 April 2022 Published: 23 May 2022

Abstract **-** *The current study proposed analyzing the free-rolling motion between the metal femoral part and the tibial polyethylene intermediate element UHMWPE. The effect of movements is evaluated by the moment of friction and the coefficient of rolling friction. The average coefficient of rolling friction depends on contact pressure distribution. A rapid decrease is observed for large values of the coefficient of friction at maximum angular velocities. The coefficient of friction on the free-rolling of the femoral component on the flat polyethylene support can be determined when the total number of oscillations ($n=N_{OSC}$)is known from experiments. The frictional losses between the femoral metal component and the UHMWPE polyethylene tibial intermediate are determined. The loading device of the friction moment and the friction losses are observed by adapting the total knee prosthesis. In experimental part used inertial measurement connected to an integrated system using a sensor that records and displays the angle of rotation and the time until the moment of stopping (record oscillations). Oscillations are made by the femoral component on the flat polyethylene support when an imbalance is achieved compared to the initial state. The experiment was repeated ten times under identical conditions. The coefficient of statistical variation, defined as the ratio between the mean square deviation and the arithmetic mean, is 3.2%.*

Keywords **-** *Normal force, Rolling friction, Rolling angle, Knee prosthesis.*

1. Introduction

The knee is an amazing mechanism both by its architecture and the degree of finishing of the bone surfaces. The functional aspects of the joints that define and ensure movement are essential for human activity. Many specialists notice the complexity of the hip and knee joints**.** Replacement of the joints is an idea that has preoccupied the orthopedic world since the 18th century. The development of knee arthroplasty is characterized by research conducted to discover biocompatible materials, develop a safe method of fixing prosthetic components in the bone, and ensure its stability. The knee joint is one of the most complex and largest joints in the human body. Despite all the advances made in the biomedical field, it has not yet reached the point where it can be completely replaced by nature, no matter how advanced and perfect a technical creation [1]. It has an articular structure that includes the same anatomical formation as the tibiofemoral and patellofemoral joints [2][3]. According to some authors, the knee is in a certain category that analyzes it mechanically; the knee allows the flexion-extension movement associated with a certain degree of rotation. [4][5]. Articular surfaces have specific anatomy. This explains the presence of thick articular cartilage, but especially the presence of articular menisci that alleviates the lack of unity [6][7][8]. The stent is designed to replace the normal shape and function of the joint and consists of several parts and the patient's joint [8][9]. Stiffness causes blocking of the prosthesis parts, leading to loss of range of motion of the knee [10]. The prosthesis must reproduce most realistically the action of the joint which it replaces (as a bio-mechanism and ergonomics) and be as well tolerated by the body. To fulfill these goals, many types of knee prostheses have been designed [11]. Prosthesis components: femoral part, intermediate part, and tibial plateau [12]. The main cause of the initial stiffness drop is caused by force [13]. The total knee prosthesis allows the transmission of body weight in the presence of various forms of movement. The knee joint allows for six movements:

- The extension flexion movement (F-E) which the femur rolls over the tibia; the angular amplitude is 140º;
- Antero-posterior sliding movement (A-P) which the tibia slides back and forward;
- The pivoting movement of the tibia (inner-outer rotation I-E) which the sliding takes place around its axis; the angular amplitude of this motion is 25 ° with momentary transmission (active motion) and 40 ° in passive motion;
- Adduction abduction movement in which the tibia rolls in the frontal plane; the angular amplitude is about 11-12º;

- Median - lateral sliding movement of the tibia;
- Axial compression movement in the direction of the normal force.

The total knee prosthesis is designed to perform all six movements. In all types of movements between the prosthesis components, forces and moments are transmitted accompanied by friction. In Fig. 1, the knee prosthesis can be seen in a balanced position on a UHMWPE polyethylene surface [10].

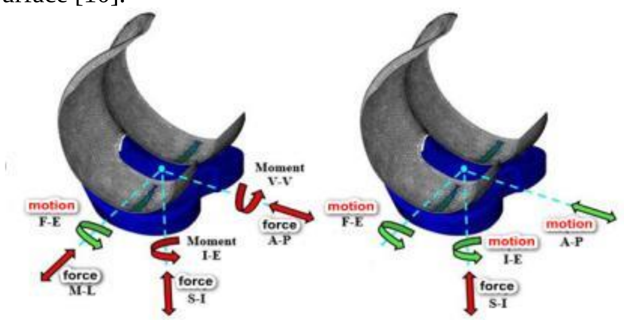

Fig. 1 Knee prosthesis and movements in prosthesis

2. Theoretical Model

Consider the device consisting of the femoral component and the weight plate in the balanced position. Attach an axis system with the center at the initial point of contact (Fig. 2); when a weight is placed on the plate (F), the device rolls (without slipping) to point A.

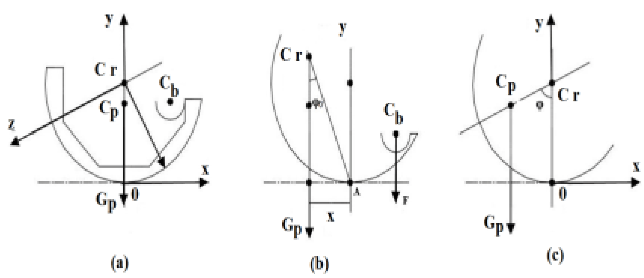

Fig. 2 Positions of the center of gravity at the moment of free rolling

The coordinates of this point are determined from the condition of static balance of forces, the weights of the prosthesis (G_p), and the load ball (F). Suppose the coordinates of the centers of gravity of the femoral component (x_{Cp}, y_{Cp}) and the loading plate (x_{Cb}, y_{Cb}), the weights of the femoral component (G_p), and the load body (usually the ball) (F) are known. In that case, the coordinates of the point of contact are determined at equilibrium A (x_A, y_A):

$$x_a = x_{Cb} \cdot \frac{F}{F + G_p}, \; y_A = 0 \tag{1}$$

From the condition of rolling without slipping the femoral component, the rotation angle φ_0 is obtained:

$$\varphi_0 = \frac{x_A}{R_p} \tag{2}$$

R_p is the radius of the femoral component in the oscillation zone. This radius is assumed to be constant in the respective angular area. It can also be extended if this radius is continuously or discretely variable in portions. When the weight F is removed from the loading plate, the femoral component begins to oscillate around an instantaneous axis parallel to the Ox axis and passes through the center of curvature of the femoral component. For any position of the femoral component, the center of gravity C_p is characterized by the angle φ and the abscissa x_{cp}, then:

$$x_{Cp} = R_c \cdot \varphi; \; y_{Cp} = R_p - R_c \cdot \cos(\varphi) \tag{3}$$

Where R_c is the oscillation radius of the center of gravity of the femoral component (R_c=R_p-h); where h is the distance from the center of gravity to the center of rotation. The equations of rotation and translation motion (movement) of the center of gravity are:

$$J_p \frac{d^2\varphi}{dt^2} = -m \cdot g \cdot R_c \cdot \sin(\varphi) + M_f \tag{4}$$

$$\frac{d^2 x}{dt^2} = R_c \cdot \frac{d^2\varphi}{dt^2} \tag{5}$$

Where g is the gravitational acceleration; J_p is the moment of inertia of the femoral component concerning an axis Oz, perpendicular to the plane xOy, in the center of curvature C_r; M_f represents the rolling friction moment of the femoral component on the flat tibial plateau in UHMWPE and is calculated with the relation:

$$M_f = \mu_r \cdot G_p \cdot R_p \tag{6}$$

Where μ_r is the average rolling coefficient of friction depends on the contact pressure distribution. It should be noted that the distribution is a function of the dynamic reaction of the flat tibial plateau. We accept a constant average rolling friction coefficient with this specification, specific to the material torque. Differential equation 4 can also be written as:

$$\frac{d^2\varphi}{dt^2} = -\frac{g}{l} \cdot \sin(\varphi) + \frac{g}{l_r} \tag{7}$$

$$l = \frac{J_p}{m_p \cdot R_c} \text{ and } l_r = \frac{J_p}{m_p \cdot \mu_r \cdot R_p}$$

are the reduced lengths of an equivalent physical pendulum of the femoral component with constant rolling friction. The 2nd order differential equation 7 has no analytical solution. The solution of this differential equation will be determined numerically from the expression of the angular velocity (ω) as a function of φ. To determine the speed of oscillation and translation (moving), the total energy theorem, according to the total energy (kinetic and potential), is conserved if taken into account the mechanical work consumed by friction during each period of oscillation:

$$0.5(J_p.\ \omega^2_0) - 0.5\ (J_p\ \omega_2) + 0.5\ (m_p.\ v^2_0) \quad (8)$$

$$-\ 0.5\ (m_p.v_2) = mp.\ g.\ R_c\ [(1-\cos(\varphi) - M_f.\ \varphi]$$

Where ω_0, ω, v_0, and v is the angular and linear velocities, respectively, corresponding to the crossing through the equilibrium position, $v=R_c.\ \omega$, $v_0=R_c.\ \omega_0$, (ω=dφ /dt) from the expression of the energy balance (equation 8), it is possible to determine the maximum angular velocity (ω_0) when passing through the equilibrium position. Angle φ_0 (equation 2) and the beginning of the movement (ω=0)

$$\omega_0 = \sqrt{\frac{2\cdot g\cdot\left[1-\cos(\varphi_0)-\mu_r\cdot\varphi_0\cdot\frac{R_p}{R_c}\right]}{R_c\cdot\left[1+\frac{J_p}{m_p\cdot R_c^{\ 2}}\right]}} \quad (9)$$

$$v_0 = R_c\cdot\omega_0 \quad (10)$$

The oscillation condition is deduced from equation 9:

$$\cos(\varphi_0)+\left(\frac{\mu_r}{R_{ac}}\right)\varphi_0 < 1 \quad (11)$$

Where R_{ac}= (R_c/R_p). Fig. 3 shows the limit of the angle φ_0 for different dimensionless radii of the center of gravity (R_{ac}) and values of the coefficient of rolling friction (μ_r). For cases where the initial position of the femoral component (angle φ_0) and the coefficient of rolling friction (μ_r) lead to points below the limit curves in Fig. 3, the movement cannot occur. The femoral component remains in the initial position determined by the balance between the weight of the ball on the plate (G_b) and the weight of the femoral component (G_p).

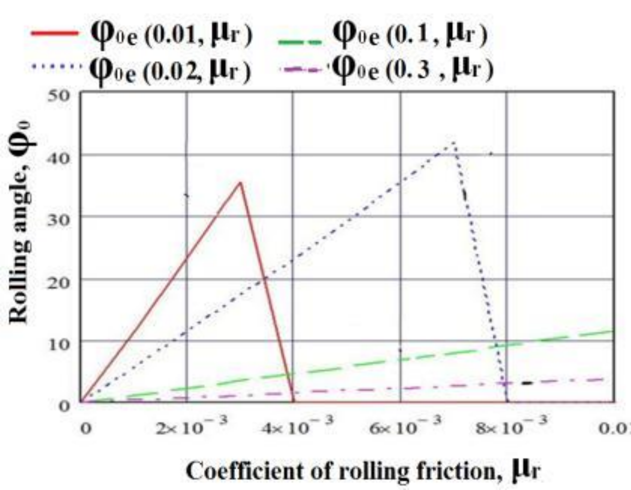

Fig. 3 Angle limit φ_0 for different dimensional radii of the center of gravity

The effect of the rolling friction coefficient on the maximum angular velocity (ω_0) is illustrated in Fig. 4; a rapid decrease is observed for large values of the coefficient.

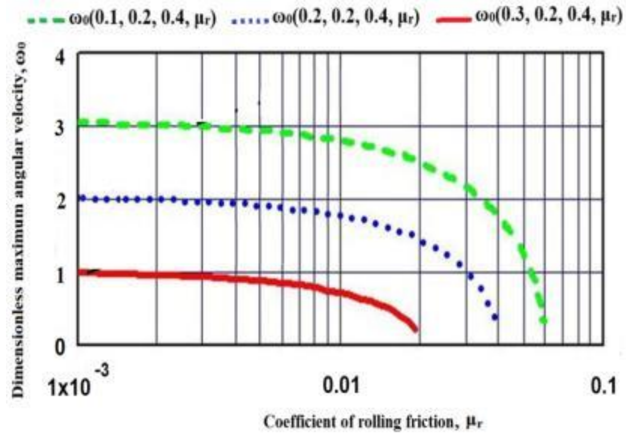

Fig. 4 Effect of the rolling friction coefficient on the angular velocity

Noting, ω_a= (ω/ ω_0) from (equation 8) and (equation 9) results the angular velocity (ω_0) on the area (0, φ_0)

$$\omega_a = \left[1-\frac{1-\cos(\varphi)-\frac{\mu_r\cdot\varphi}{R_{ac}}}{1-\cos(\varphi_0)-\frac{\mu_r\cdot\varphi_0}{R_{ac}}}\right]^{\frac{1}{2}} \quad (12)$$

If it is derived concerning time in equation 12, the dimensionless angular acceleration results:

$$\varepsilon_a = \frac{\varepsilon}{\omega_0^{\ 2}}$$

$$\varepsilon_a = \frac{d\omega_a}{dt} = \frac{\sin(\varphi)-\frac{\mu_r}{R_{ac}}}{2\cdot\left(1-\cos(\varphi_0)-\frac{\mu_r\cdot\varphi_0}{R_{ac}}\right)} \quad (13)$$

Fig. 5 and 6 exemplify angular velocity and acceleration variations in the angular range (0, φ_0).

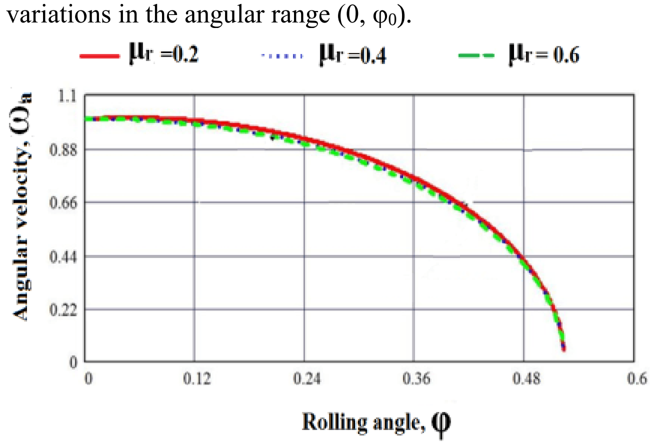

Fig. 5 Variation of the angular velocity as a function of the rolling angle

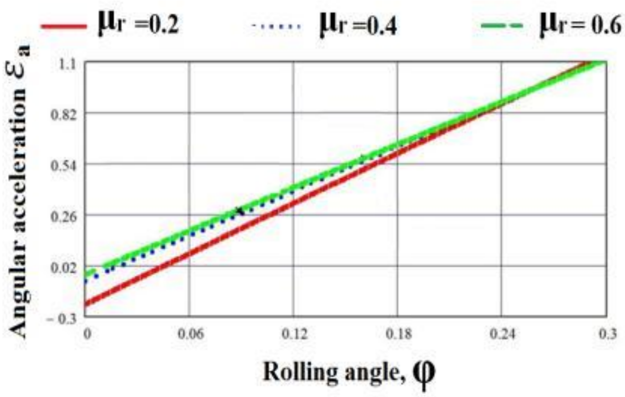

Fig. 6 Variation of angular acceleration

Thus,

$$\sin^2\left(\frac{\gamma}{2}\right) = \sin^2\left(\frac{\varphi_0}{2}\right) - \frac{R}{2 \cdot R_c} \cdot \mu_r \cdot \varphi_0 \qquad (14.1)$$

$$\sin^2\left(\frac{\beta}{2}\right) = \frac{1-\cos(\varphi) - \dfrac{\mu_r \cdot \varphi}{R_{ac}}}{2 \cdot \left(1 + \dfrac{J_p}{m_p \cdot R_c^{\,2}}\right)} \qquad (14.2)$$

the expression for the linear velocity of moving the center of gravity of the female component during oscillation is obtained:

$$v^2 = 4 \cdot g \cdot R_c \cdot \left(\sin^2\left(\frac{\gamma}{2}\right) - \sin^2\left(\frac{\beta}{2}\right)\right). \qquad (15)$$

This movement oscillates on the arc -γ≤β≤γ. The movement period is:

$$T=4.(Rc/g)^{0.5}. K(\gamma) \qquad (16)$$

Where $\sin(\psi)\cdot\sin\left(\frac{\gamma}{2}\right) = \sin\left(\frac{\beta}{2}\right)$ and $\mathrm{K}(\gamma)$ is the complete elliptic integral of the first case,

$$\mathrm{K}(\gamma) = \int_0^{\pi} \frac{d\psi}{\sqrt{1-\sin^2\left(\frac{\gamma}{2}\right)\cdot\sin^2(\psi)}}$$

Suppose the notation (equation 14.1) is taken into account. In that case, the period of the oscillating movement (equation16) can be determined as a function of the geometry of the femoral component (R, R_c), the rolling friction (μ_r), and the initial position (φ_0) depending on the weight. Component (G_p) and the applied weight (F). Thus, Fig. 7 shows the period of oscillation for different forces F and coefficients of friction (μ_r).

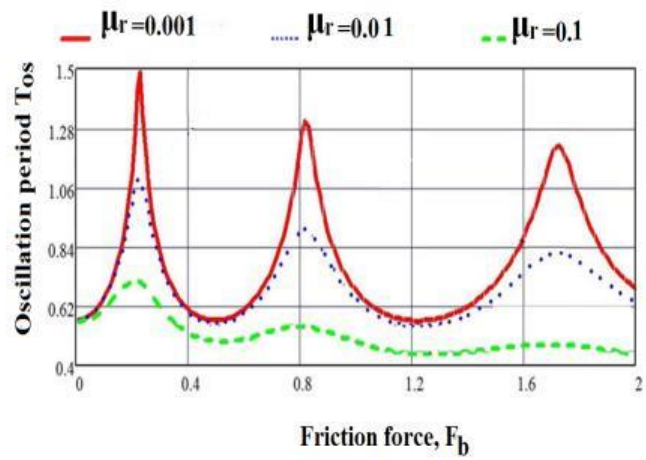

Fig. 7 Variation of the oscillation period at different loading forces

From fig. 7, it is found that at the same force on the plate (F_b), the period decreases with an increased coefficient of friction. The effect of decreasing period of oscillation with increasing force on the plate (F_b) and the value of the coefficient of rolling friction (μ_r) is exemplified in Fig. 8 by defining the period of relative oscillation.

$$T_{osr} = \frac{T_{os}(F_b,0) - T_{os}(F_b,\mu_r)}{T_{os}(F_b,0)} \qquad (17)$$

where is the period of oscillation calculated with the equation 16 for a certain force on the plate (F_b) and the coefficient of friction of rolling and is the period of oscillation at the same force F_b and another pair of material with the friction of rolling characterized by the coefficient μ_r?

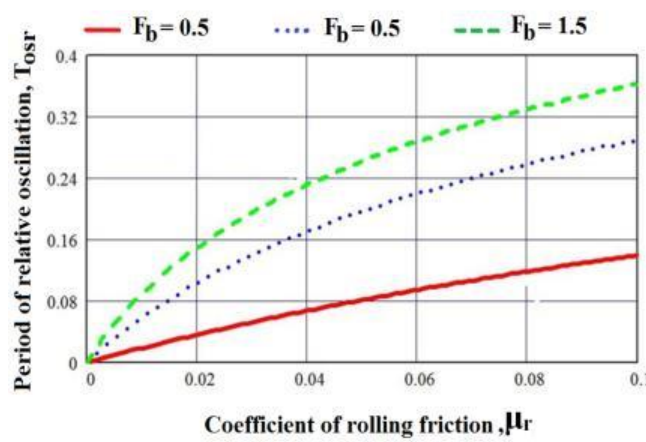

Fig. 8 Variation of the period of relative oscillation depending on the coefficient of rolling friction

To determine the number of oscillations of the femoral component up to the stop, the static balance between the weight of the femoral component (G_p) and the force on the loading plate (F_b), the angular (ω_0) and linear (*v_0)* velocities are given by equations 9 and 10. After crossing through the equilibrium position, the value of the angle φ_0 and the axial distance x_0 is no longer reached due to the oscillation resulting from the rolling friction. From the conservation of total energy, it will be

$$0.5\ J_p.\ (\omega^2{}_0) + 0.5\ mp.\ v^2{}_0 \quad (18)$$

$$mp.g\ .R_c(1\text{-}cos\ \varphi_1\ )) + \mu_r \quad (19)$$

$$\cos(\varphi_1) - \mu_r \cdot \frac{R_p}{R_c} \cdot \varphi_1 = \cos(\varphi_0) + \mu_r \cdot \frac{R_p}{R_c} \cdot \varphi_0 \quad (20)$$

This equation determines the angle φ_1 up to which the femoral component rolls after the first passage through the equilibrium position. Similarly, the angle φ_2 is determined at the second oscillation.

$$\cos(\varphi_2) - \mu_r \cdot \frac{R_p}{R_c} \cdot \varphi_2 = \cos(\varphi_1) + \mu_r \cdot \frac{R_p}{R_c} \cdot \varphi_1 \quad (21)$$

For example, if $\varphi_0 = \pi / 6$, $\mu_r = 0.001$, Rac = 0.4, the numerical solution of equation 20 is $\varphi_1 = 0.518$ and for the coefficient of friction $\mu_r = 0.005$ results in $\varphi_1 = 0.497$. The angle φ2, under the same conditions has the values $\varphi_2 = 0.513$ for $\mu_r = 0.001$ and $\varphi_2 = 0.471$ for $\mu_r = 0.005$. It is deduced by complete induction:

$$\cos(\varphi_n) - \mu_r \cdot \frac{R_p}{R_c} \cdot \varphi_n = \cos(\varphi_{n-1}) + \mu_r \cdot \frac{R_p}{R_c} \cdot \varphi_{n-1} \quad (22)$$

The oscillation can be considered closed when the angle $\varphi_n \rightarrow 0$. By summing terms in the equations (20 - 22), it is deduced:
Equation(23)

Given that with $\varphi_n \rightarrow 0$, $cos\ \varphi_{n=1}\ \mu_r \cdot \frac{R_p}{R_c} \cdot \varphi_n \approx 0$, the total oscillation angle results

$$\varphi_t = \varphi_1 + \varphi_2 + \ldots + \varphi_{n-1} = \frac{1-\cos(\varphi_0)}{2 \cdot \mu_r} \cdot \frac{R_c}{R_p} \quad (24)$$

If the number of oscillations is known, from the equations 20 – 24, the coefficient of friction can be determined. To compare with the experimental results, the function is developed in series

$$\cos(x) = 1 - \frac{x^2}{2} + \frac{x^4}{4!} + \ldots$$

Thus, from the equations 20 - 24, they are deduced

$$\varphi_1 = \varphi_0 - 2 \cdot \mu \quad (25)$$

$$\varphi_2 = \varphi_1 - 2 \cdot \mu$$

$$\varphi_n = \varphi_{n-1} - 2 \cdot \mu$$

with $\mu = \mu_r \cdot \frac{R_p}{R_c} = \frac{\mu_r}{R_{ac}}$

From equation 25, it is observed that the oscillation angle decreases in arithmetic progression with the ratio of 2μ. Putting the condition as $\varphi_n \rightarrow 0$ and adding term by term results in the progression ratio:

$$\mu = \frac{\varphi_0}{2 \cdot n} \text{ and } \mu_r = \frac{\varphi_0}{2 \cdot n} \cdot R_{ac} \quad (26)$$

Based on this expression, the coefficient of friction on the free-rolling of the femoral component on the flat polyethylene support can be determined when the total number of oscillations $n=N_{osc}$ is known from experiments. During oscillation at the point of contact, a dynamic component reaction occurs in both directions:

$$N_x = -m_p \cdot \omega^2 \cdot x_{Cp} - \varepsilon \cdot m_p \cdot y_{Cp} \quad (27)$$

$$N_y = -m_p \cdot g - m_p \cdot \omega^2 \cdot y_{Cp} + \varepsilon \cdot m_p \cdot x_{Cp} \quad (28)$$

Where ω, and ε are the angular velocity and angular acceleration of the center of gravity C_p of coordinates (x_{cp}, y_{cp}). These components define the dynamic state of stresses and strains, together with the relative contact speed, allowing the analysis of the process of friction and wear of the polyethylene support. The expressions for angular velocity (equation 12) and angular acceleration (equation 13), the components of the reaction at the point of contact, are deduced for any angle φ:

$$N_{ax} = N_x / m_p.\ g \quad (29)$$

$$N_{ay} = N_y / m_p.\ g \quad (30)$$

Fig. 9 exemplifies two initial angles ($\varphi_0 = \frac{\pi}{3}, \varphi_0 = \frac{\pi}{6}$) and the coefficient of rolling friction $\mu_r = 0.005$. Dimensionless components N_{ax} and N_{ay} depending on the rolling angle and the coefficient of rolling friction

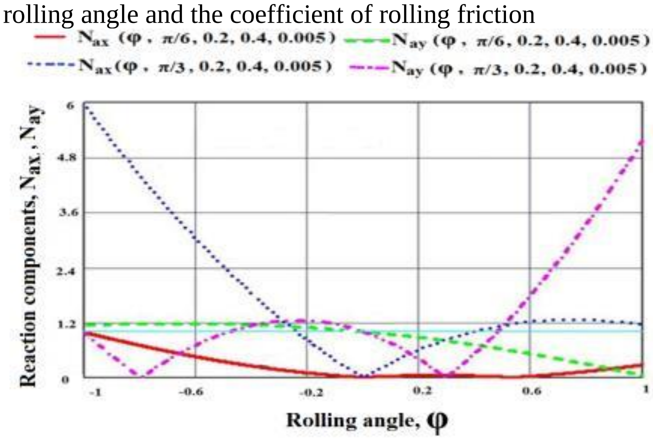

Fig. 9 Dimensionless components N_{ax} and N_{ay} versus rolling angle, φ

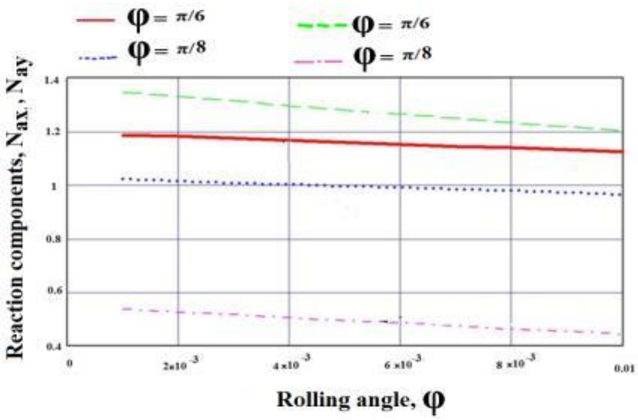

Fig. 10 Effect of the rolling coefficient on the reaction components

The effect of the rolling coefficient on the reaction components is illustrated in Figure 10. The equation of the oscillating motion can be determined by integrating the angular velocity $\omega_a = \omega/\omega_0$ (equation12) relative to the time (t). Noting the time, it is deduced

$$t_a(\varphi) = \int_{\varphi_0}^{\varphi} \frac{d\varphi}{\omega_a(\varphi)} = \int_{\varphi_0}^{\varphi} \frac{d\varphi}{\sqrt{1 - \dfrac{1-\cos(\varphi) - \dfrac{\mu_r \cdot \varphi}{R_{ac}}}{1-\cos(\varphi_0) - \dfrac{\mu_r \cdot \varphi_0}{R_{ac}}}}} \quad (31)$$

This integral has no analytical solution. A numerical solution is proposed as an application of the MATCHAD program. Thus, Fig. 11 exemplifies the variation of the angle φ with the dimensionless time (t_a) for three values of the rolling friction coefficient (μ_r). Fig. 11a, 11b, and 11c show that for low friction coefficients ($\mu_r = 0.001$), the number of oscillations is higher, and the frequency is higher. The density of the "lines" is significantly higher for low friction coefficients.

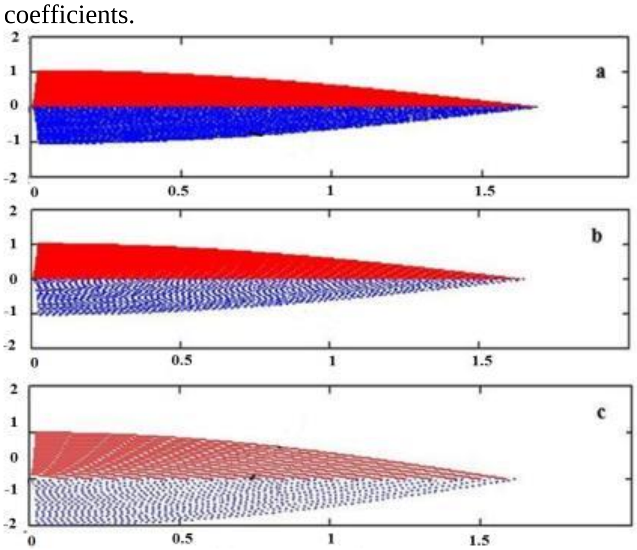

Fig. 11. Angular elongation (φ) and dimensional time (t_a) for three values of the coefficient of rolling friction: a) $\mu_r = 0.001$; b) $\mu_r = 0.005$; c) $\mu_r = 0.01$

3. Experimental Model

To determine the frictional losses between the femoral metal component and the UHMWPE polyethylene tibial intermediate, a device consisting of the femoral component adapted to variable loads and flat support made of polyethylene plate is proposed. Figure 12 the loading device of the friction moment and the friction losses by adapting the total knee prosthesis.

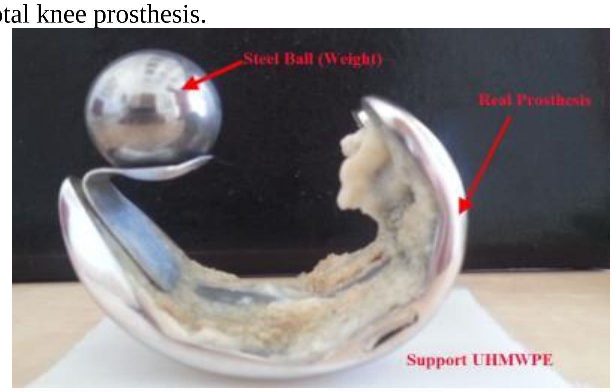

Fig. 12 Weighted femoral component on UHMWPE plane support

The experimental study aimed to record the oscillations made by the femoral component on the flat polyethylene support when an imbalance is achieved compared to the initial state. A known weight is placed on the plate adapted to the femoral component, usually in the form of a sphere (balls of different sizes and weights). The femoral component rolls freely, without slipping, on the flat surface until it returns to balance. Thus, a mechanical thing is introduced into the femoral component system - a flat surface. These mechanics can be determined by knowing the initial and final position of the plate and its weight. The weight is removed from the tibial plateau, and the femoral component will oscillate by rolling on the flat surface. This movement is filmed and recorded until it stops. Another solution for recording oscillations is to use an inertial measuring Sensor (Fig. 13) connected to an integrated system, which records and displays the rotation angle and time until the moment of stopping.

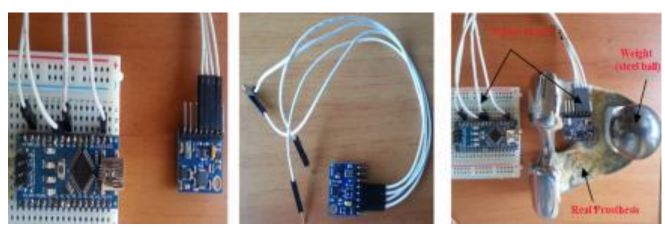

Fig. 13 Sensor acquisition board installed on the femoral component for data recording.

Fig. 14 shows the variation of the oscillation angle of the femoral component when a sphere with the weight $G_b = 0.67$ N is placed on the UHMWPE plate. The weight of the femoral component is $G_p = 2.72$ N, and the moment of inertia concerning the instantaneous axis of rotation $I_z = 271$ kg · mm ^{2}.

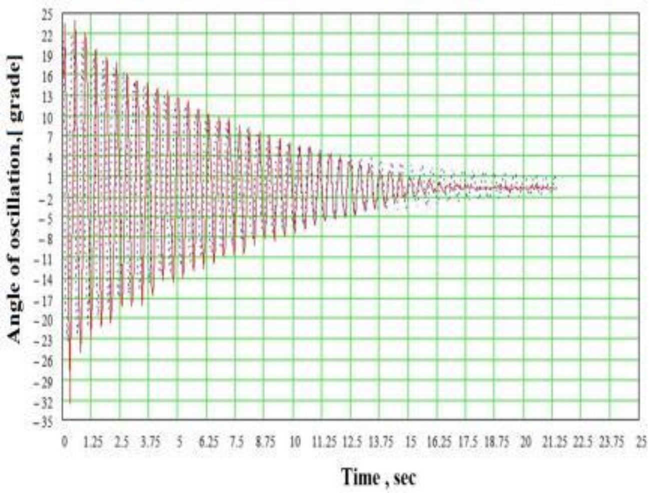

Fig. 14 Variation of the angle of oscillation of the femoral component

For the statistical analysis of the repeatability of the results, the experiment was repeated 10 times under identical conditions. The coefficient of statistical variation, defined as the ratio between the mean square deviation and the arithmetic mean, is 3.2%. Curves similar to those shown in (Fig. 14), the experiments were performed on various bearing surfaces, namely: steel support, glass, rubber, and wood with different fiber configurations. A certain total oscillation time (T_o) and a certain number of oscillations (N_o) at the same mechanical thing introduced in the system are highlighted. Thus, for polyethylene UHMWPE T_{op} = 34.3 s and N_{osp} = 74.3 oscillations, for steel T_{oo} = 140.8 s and N_{oso} = 269.6 oscillations, for glass T_{os} = 123.9 s and N_{oss} = 182.5 oscillations and for rubber T_{oc} = 4.6 s and N_{osc} =9.2 oscillations. These values of the oscillation time and the number of oscillations are obtained for the same value of the mechanical work introduced in the system (mechanical work W_m = 6.56 mJ). Different oscillations are obtained for other values of the mechanical work introduced in the system. The figure shows the variation of the number of oscillations for three weights on the device plate and three flat support materials.

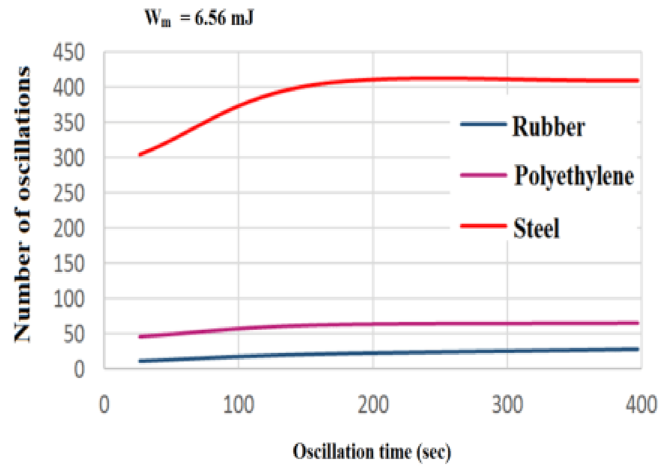

Fig. 15 Variation in the number of oscillations for different weights

4. Conclusion

The coefficient of friction on the free-rolling of the femoral component on the flat polyethylene support can be determined when the total number of oscillations $n=N_{osc}$ is known from experiments. The coefficient of statistical variation, defined as the ratio between the mean square deviation and the arithmetic mean, is 3.2%. The oscillation time and the number of oscillations are obtained for the same value of the mechanical work introduced in the system (mechanical work W_m = 6.56 mJ). The rolling coefficient of friction decreases with maximum angular velocities. For the low coefficient of friction, the number of oscillations is higher, and obviously, the frequency is higher.

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