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Wear Modelling of Total Knee Replacements

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Abstract

Beside prosthesis loosening, wear is the mechanical factor that most significantly influences the lifetime of total knee replacements (TKRs), which can only be described by a number of interrelated parameters. The examination of the wear occurring in TKRs is mostly carried out as a combination of experiments and mathematical modeling. The experiment can provide the real magnitude of wear , while the model is intended to mathematically describe the relationship between wear and the wear-inducing parameters. On the one hand, this study focuses on the mathematical description of wear as a natural-technical phenomenon, presenting the most important analytical and numerical models, while also providing an open view on exciting questions that still await answers.

Keywords: *wear, knee joint, prosthesis, Archard wear model.*

1. Introduction

Despite the fact that researchers and prosthesis manufacturing companies work together to create more reliable and efficient implants, there are still numerous cases of TKR failure. The main reasons why TKR failures still occur are infection of the knee joint, loosening of the TKRs, and the impermissible amount of wear in the implants. Wear can develop in the knee joint (or any other joints) for several reasons. It may be due to the incongruence of the joint itself, or due to the natural instability of the joint.

It must be noted that wear is a phenomenon that can be described only by multiple interrelated parameters, which must be treated as a system and not as a material property **[1]**.

Its importance should be highlighted, since this mechanical factor has the most significant effect on TKR lifetime **[2, 3]**, while its influence strongly depends on the local kinematics taking place in the knee joint **[4, 5]**.

Wear is directly and indirectly influenced by several parameters. The most important direct parameters are the sliding length, the load and the relative wear factor.

The most effective way to examine wear is a combination of experiments and mathematical models. It is important to mention, with regard to the experiments, that several important parameters, which are included in the measurements as adjustable parameters, unfortunately do not appear in mathematical models.

An example is the slide-roll ratio (S/R), which is a value that varies between 0 and 1. If the value is 0, the two surfaces purely roll on each other, while if it is 1, they predominantly slide. Between the two, sliding and rolling appear together.

The magnitude of this factor is usually applied between 0 and 40% during tribological tests e.g. on pin-on-disc, ball-on-disc or on knee simulators **[6, 7]**, These values are based on as the results of previous theoretical models **[8, 9]**.

These results are applicable for connections with simple geometry, such as pin-on-disc and ball-on-disc type tests, since a smooth flat surface (pin) or a spherical surface (ball) slides and rolls on the surface of a disc, therefore the condition of constant slide-roll provides a suitable kinematic description.

However, this condition is no longer adequate if the geometry is complex. The latest results related to this topic show that the constant slide-roll ratio cannot be applied to TKRs **[10, 11]**, since the complex geometry creates extremely complex local movements.

Another particularly important parameter, which should definitely be highlighted, is the so-called cross-shear ratio (CSR). This parameter appeared in the application of ultra-high molecular weight polyethylene (UHMWPE) in TKRs, as it has a special „motion-dependent" property. In case of TKRs, the tibial part is made of UHMWPE, while the femoral part is made of stainless steel. When the femoral and tibial parts come into contact with each other, as a result of sliding, the orientation of the polyethylene molecules changes and it is arranged in the direction of sliding. This type of arrangement of the molecules causes surface hardening, which increases the wear resistance of the material in this particular direction.

However, while the wear resistance of the material increases in one direction, it strongly decreases in the direction perpendicular to it. This ratio is expressed by cross-shear ratio, which in the literature is often related to the relative wear factor [12].

The purpose of this article is to provide insight into the mathematical modeling of TKR wear. The article provides an overview of the most frequently used models in the literature, as well as a description of the creation of a model that is already in use..

2. Models

Most authors start their modeling by the use of a commonly applied wear model. This is the so-called Archard model [13].

$$dW = k \cdot F_N \cdot ds, \tag{1}$$

where k is the so-called specific wear factor (mm³/Nm), which is a constant depending on the material property, F_N is the force occurring between the pressed surfaces, and ds is the instantaneous sliding length.

Despite its simplicity, the Archard model is still widely used in the relevant literature as a starting model.

Of course, in this form, it can only give a distant estimate, which is why the authors augment the model with additional parameters, such as the previously mentioned cross-shear factor, slide-roll ratio or the friction coefficient. It should be noted that there are some authors who do not define concentrated force (*F*) as load in their model, but surface pressure (*p*).

In Table 1 we have summarized the most often used wear models, which were used in the connection of TKRs.

Table 1. *Wear models*

Modell	*p/F*	*s*	*CSR*	*S/R*	*μ*
Archard [13]	*P*	○	*x*	*x*	*x*
Hussin [14]	*P*	○	*x*	*x*	*x*
Innocenti [15]	*P*	○	*x*	*x*	○
Turell [16]	*p*	○	○	*x*	○
O'Brien [17]	*p*	○	○	*x*	○
Abdelgaied [18]	*F*	○	○	*x*	○
Fekete [19]	*F*	○	*x*	○	○

As we see in the table, the majority of authors have not considered all parameters (*x*). In the best cases, three main parameters were added to their model, compared to the original Archard equation. In the next section, we present a way to expand and further develop this basic model.

3. Modelling steps

3.1. Analytical modeling

The first step is to consider the slide-roll ratio in the wear equation. The instantaneous slide length can also be written as the product of slip velocity and time.

$$ds = v_{slide}(t) \cdot dt \tag{2}$$

Based on our previous study [20] if we interpret slide-roll ratio as instantaneous velocities instead of instantaneous arc lengths, we can also use it according to the following relationship:

$$S/R(t) = \frac{v_{CTt}(t) - v_{CFt}(t)}{v_{CTt}(t)}, \tag{3}$$

where v_{CTt} and v_{CFt} are the tangential velocities interpreted at the contact point for the tibia and femur respectively. The difference between these velocities gives the slip velocity ($v_{CTt} - v_{CFt} = v_{cslide}$). Setting this expression for the slip velocity and substituting back into equation (1):

$$dW = k \cdot F_N \cdot v_{CTt} \cdot S/R(t) \cdot dt, \tag{4}$$

we obtain the augmented Archard equation, in which the slide-roll ratio is also taken into account.

Now consider the effect of the friction coefficient as follows: The wear mechanism between the femoral and tibial surfaces is assumed to be abrasive, which means that during contact, the harder metal femoral part ploughs into the softer polyethylene surface (Figure 1).

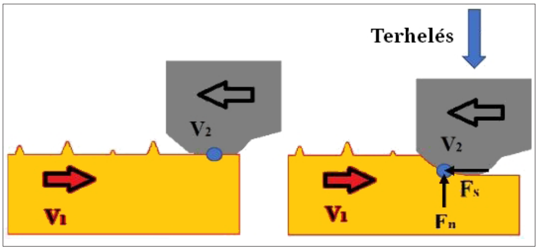

Figure 1. *Description of abrasive wear mechanism.*

In the abrasive wear mechanism, the frictional component is responsible for creating such a shear stress in the upper surface of the material that it begins losing small debris. Therefore, it provides us a more precise approximation if the friction force is introduced into our wear equation:

$$F_s = \mu_k \cdot F_N, \tag{5}$$

If we substitute this expression into equation (4), we obtain the following relation:

$$dW = k \cdot \mu_k \cdot F_N \cdot v_{CTt} \cdot S/R(t) \cdot dt \tag{6}$$

In this way, we have created a model, which involves the factors with the most significant influence on wear, except cross-shear ratio. As a next modeling step in the future, we shall integrate this missing factor into our model.

3.1. Numerical modeling

To be able to determine the evolution of wear on both sides of a TKR (lateral and medial), it is necessary to take the geometry into account. This is a challenging task to deal with analytically, since the function of the compressive force in the connection of the femoral and tibial parts of the TKR must be determined during the movement.

Due to this problem, it is advisable to create a multibody dynamic (MBD) system and determine the forces in question using an adequate software. This can be performed in the following steps (**Figure 2**).

The first step is to select the wear model, which in this case will be equation (6). This is a linear first-order ordinary differential equation. To solve the equation, i.e. to calculate the wear volume, we need the compression force determined from the MBD simulations on the lateral and medial sides of the tibial plate. For the simulations, we used three different prosthesis geometries. The aim was to determine the amount of wear in the tibial part of the TKRs, and to classify which TKR has a higher chance of failure (**Figure 3**).

Using the TKR geometries, we created the MBD

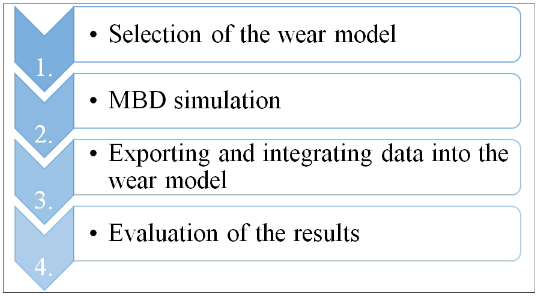

Figure 2. *Algorithm of the numerical solution.*

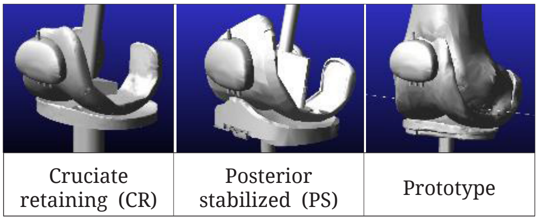

Figure 3. *The applied TKRs*

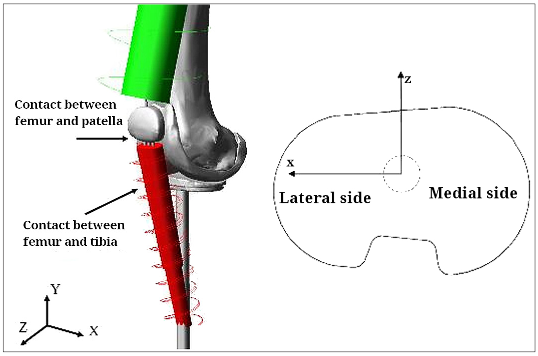

Figure 4. *The applied MBD model.*

models in MSC.ADAMS (**Figure 4**).

The boundary conditions were applied identically to all models.

After starting the simulation, the lateral and medial sides of the tibial part are in contact with the surfaces of the femoral part. MSC.ADAMS simultaneously stores contact points and forces for later evaluation. The resulting position vectors allow the differentiation of the lateral and medial sides, as well as the location of the contact forces on the surfaces. These force functions, as a function of time, serve as input to equation (6), which can be calculated as follows:

$$dW_{lat.} = k \cdot \mu_k \cdot F_{cn.lat}(t) \cdot v_{CTt}(t) \cdot S/R(t) \cdot dt \tag{7}$$

$$dW_{med} = k \cdot \mu_k \cdot F_{cn.med}(t) \cdot v_{CTt}(t) \cdot S/R(t) \cdot dt, \tag{8}$$

where $F_{cn.med}$ and $F_{cn.lat}$ are the forces obtained from the simulations. After creating the wear functions, time as a variable was replaced by the knee flexion angle (α).

4. Results

To evaluate the results, we introduced parameters that not only quantify the wear, but also provide deeper insight into the physiological effect of wear on the TKRs. In addition to the lateral and medial side wear, we introduced a new quantity, the so-called amount of total wear:

$$TW(\alpha) = (W_{med.}(\alpha) + W_{lat.}(\alpha)) \tag{9}$$

Furthermore, the magnitude of the relative lateral and medial wear:

$$RW_{lat.}(\alpha) = \frac{W_{lat.}(\alpha)}{TW(\alpha)} \cdot 100 \tag{10}$$

$$RW_{med.}(\alpha) = \frac{W_{med.}(\alpha)}{TW(\alpha)} \cdot 100 \tag{11}$$

These quantities can be used to express the so-called wear imbalance:

$$WIB(\alpha) = RW_{medial}(\alpha) - RW_{lateral}(\alpha) \tag{12}$$

Wear imbalance demonstrates, as a percentage, how much medial wear deviates compared to lateral wear. It also implies that if a TKR is exposed to uneven medial load (and wear) then a so-called hollowing mechanism can commence on the above-mentioned TKR plateau. In the long term, hollowing leads to the point that the physiological tibiofemoral alignment of the TKR will be tilted and this abnormal tilt becomes a wear-inducing factor [21].

Let us review the results after the introduced wear factors. First, we determined the amount of total wear for all prostheses (Figure 5):

Then, we determined the amount of lateral and medial wear for each TKR separately (Figures 6, 7 and 8).

Last but not least, by using these results, we created the most important result: the wear imbalance function (Figure 9):

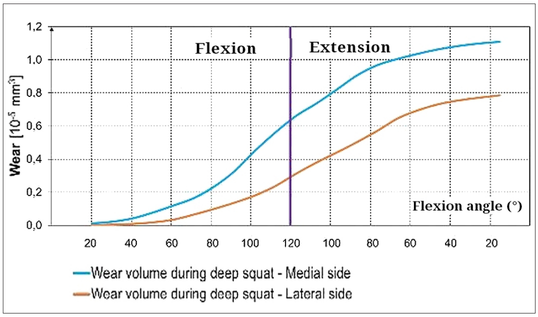

Figure 7. *Lateral and medial wear (CR).*

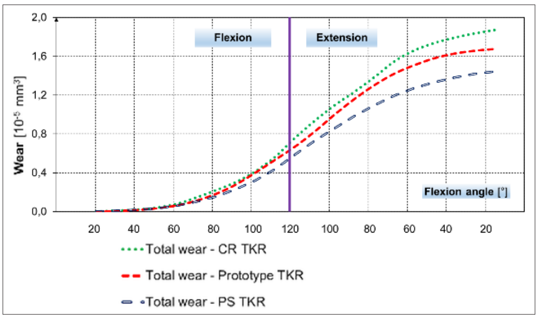

Figure 5. *Total wear in different TKRs.*

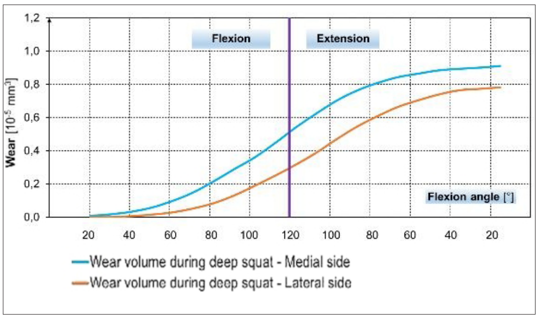

Figure 8. *Lateral and medial wear (Prototype).*

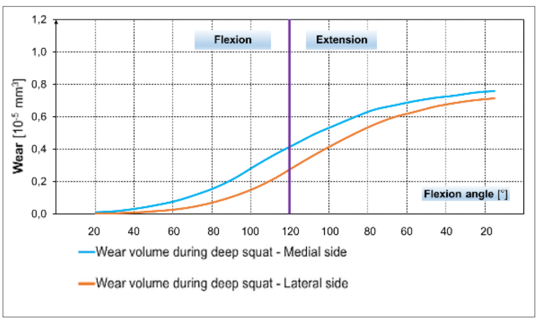

Figure 6. *Lateral and medial wear (PS).*

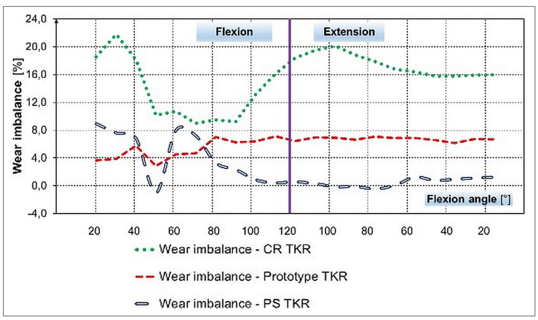

Figure 9. *Wear imbalance function of different TKRs.*

4. Conclusions

The wear results clearly highlight that the Biotech PS TKR (**Figure 6**)) provided the lowest total wear with the least wear imbalance (approximately 2.3% averaged WIM). Such wear propagation on both sides of the tray can ensure that the „worn-through" stage would be postponed and implant revision could be significantly prolonged.

As we look at the following result (**Figure 7**), the CR type prosthesis performed ~23% higher total wear compared to the PS type. Even less favorably, the averaged lateral and medial wear imbalance was ~15.6%, which can lead to severe abrasion on the medial side and possible TKR retrieval before time.

A prototype TKR (**Figure 8**), designed by the late Professor Gábor Krakovits, has also been included in the investigations, which yielded the following results: this specific TKR produced only 13.7% more wear compared to the reference PS TKR while the averaged wear imbalance between the lateral and medial side was only 5.9%.

To have an adequately balanced wear on both sides, it would be required that the percentage difference should not exceed 5%, which is a generally accepted level in engineering. As can be seen, only the PS could stay within such limits, while the Prototype TKR was close to it.

Therefore, the CR type TKR should be modified in its geometry in order to avoid generating high wear imbalance on its medial side, or even TKR failure.

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