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Effect of Changes in Posterior Tibial Slope Angle Under Continuous Dynamic Loading During the Gait Cycle on the Wear of Knee Implant Polyethylene Insert

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ABSTRACT: Knees are the joints that allow us to do our daily tasks such as walking, running, sitting, standing and carrying the weight of our body. Knee pain occurs due to wear and tear in the cartilage tissues of the knee joints. Various medical and physical treatments are applied to patients to relieve this pain. Total knee arthroplasty (TKA) treatment is applied to patients whose pain does not decrease despite these treatments. Arthroplasty is performed by cutting the damaged joint tissues and adding polyethylene and metal parts instead. Arthroplasty is an application made by adding metal components and polyethylene intermediate component material to the surface of the tibia, femur and patella bones in the damaged knee joint. Tibial slope is an important factor in knee kinematics and arthroplasty surgeries. Tibial slope is defined as the anatomical slope of the tibial plateau towards the posterior in the sagittal plane. This slope is the angle between the direction perpendicular to the axis of the tibia and the parallel direction of the tibial plateau. It has values that vary between 6° and 13°. This study aims to numerically calculate and obtain information on the Posterior Tibial slope angle change, pressure distributions on the interface due to the loads acting on the PE insert due to flexion effects and wear information. It is observed that the Posterior Tibial slope angle, which occupies an important place in the amount of load on the contact interface and the amount of wear on the insert after knee implant assembly, slightly decreases as the amount of wear increases with the number of cycles. The observed decrease results from the vertical loading force, quantified as 50 N in this study, applied to the PE insert-Femoral component interface at a 0-degree assembly. As the assembly angle varies, this force decomposes into two distinct components: one oriented perpendicular and the other parallel to the contact interface. With increasing assembly angles, the parallel force component intensifies, whereas the perpendicular force component correspondingly diminishes.

Keywords– *Posterior Tibial Slope, Finite Element Analysis, Gait Cycle, Wear*

1. Introduction

Knees are the joints that allow us to perform our daily activities such as walking, running, sitting, and standing, and they bear the load of our body. After a certain period, these joints begin to deteriorate and cause problems, limiting movement. Knee pain occurs due to the wear and tear in the cartilage tissues of the knee joints. This pain restricts people's daily activities such as walking, sitting, standing, lying down, and climbing stairs. The causes of joint wear can be osteoarthritis, rheumatoid arthritis, and traumatic arthritis. Osteoarthritis is the wear and tear of joint cartilage over time. Due to cartilage wear, bones come into contact with each other, leading to pain in the knee.

Damage occurs in load-bearing joints due to mechanical, biochemical, and genetic reasons. Various medical and physical treatments are applied to patients. For patients whose pain does not decrease despite these treatments, TKA treatment is applied (Bilge et al. 2022).

Arthroplasty involves cutting the damaged joint tissues and replacing them with polyethylene and metal parts. In arthroplasty, a metal component and a polyethylene intermediate component material are added to the surfaces of the tibia, femur, and patella bones in the damaged knee joint. In this study, the commonly used metal materials are cobalt-chromium and titanium-aluminum-vanadium alloys, and the polyethylene material used is ultra-high molecular weight polyethylene (UHMWPE). It is necessary to examine the wear mechanism of polyethylene and evaluate the design before arthroplasty. Modeling the design using the finite element method is an advantageous method in terms of time and budget (Zhang et al. 2017). Tibial slope is an important factor in knee kinematics and arthroplasty surgeries. Tibial slope is defined as the anatomical slope of the tibial plateau posteriorly in the sagittal plane. This slope is the angle between the line perpendicular to the axis of the tibia and the line parallel to the tibial plateau. It has values that vary between 6° and 13°.

Korkmaz et al. (2014) imaged the cut surface of the tibia bone from the patient's tomography and modeled a patient-specific tibial component. They analyzed the patient-specific model to eliminate the stress shielding effect, which is component loosening encountered in implants. Using the finite element method, they examined the differences between patient-specific designed knee implants under boundary conditions and standard knee implants.

Zhang et al. (2017) designed a patient-specific lower extremity musculoskeletal model that considered the interaction between kinematic load, wear, and contact mechanics. They created a wear model of TKA using the finite element method. Data from the model's gait simulation were used as boundary conditions for the finite element model. They investigated the effect of joint surface wear on contact forces and movements.

Li et al. (2019) aimed to determine the longest usable range for TKA applied to Chinese patients. They tried to analyze the effect of different stem lengths within this range on the implant. They performed three-dimensional modeling and surgical simulation to determine the cortices with 0° and 3° tibial posterior slope and to analyze the factors affecting the longest stem length. The implant showed stable characteristics within a certain length range, and using a longer implant increased stability.

Li et al. (2019) argued that a longer implant may not be an optimal choice. Lee et al. (2012) employed the finite element method to analyze the relationship between posterior tibial slope (0, 7, and 10 degrees), contact force, and stress distribution on the medial and lateral ligaments during knee flexion following posterior-stabilized TKA. They also examined the impact of posterior tibial slope on tibial component surface deterioration, finding a direct correlation between posterior tibial slope and stress distribution, while identifying an inverse relationship with contact stress in posterior-stabilized TKA.

Similarly, Shen et al. (2015) conducted a three-dimensional finite element analysis to assess the effects of posterior tibial slope on contact stresses within the polyethylene component of total knee implants. Their comparative study of four distinct posterior tibial slopes aimed to determine the most suitable configuration. They observed that von Mises stress, maximum and minimum principal stress distributions, and overall stress dispersion within polyethylene were more uniform at posterior tibial slopes of 3 and 6 degrees than at

0 and 9 degrees. Furthermore, they concluded that an appropriate tibial component slope range could mitigate polyethylene wear.

Koh et al. (2021) evaluated the effects of posterior tibial slope in mobile-bearing unicompartmental knee arthroplasty using finite element analysis. They used the contact stresses on the upper and lower surfaces of the polyethylene inserts and articular cartilage. Seven different posterior tibial slopes were used with seven finite element models under normal level walking conditions. In their study, forces were applied to the anterior cruciate ligament (ACL). They found that an increase in posterior tibial slope would lead to an increase in contact stress and force application on the ACL.

Özer et al. (2022) conducted a study on the wear of polyethylene inserts under dynamic loading validated by cadaveric experiments, integrating the Archard wear model and finite element analysis. This research specifically considered the variation in flexion angle during the gait cycle. Their findings revealed that for flexion, Anterior-Posterior (AP) translation, and Internal-External (IE) rotation, an increase in the number of cycles resulted in reduced pressure on the insert but a corresponding increase in wear.

The effect of the Posterior Tibial slope angle on the maximum contact pressure and wear amount on the polyethylene insert has not received sufficient attention. This study aims to numerically calculate and obtain information on the Posterior Tibial slope angle change, pressure distributions on the interface due to loads acting on the PE insert resulting from flexion effects during the gait cycle, and wear information. This can otherwise only be done experimentally with the help of setups found in very specialized companies in the world, which are not currently available in our country. With this study, information on how much and in which regions the knee implant insert will wear, over how many cycles and how much time, can be obtained. This will significantly contribute to science and practice.

2. Material and Methods

2.1. Wear

The Archard wear model (Archard, 1953) is a widely used sliding wear model that gives quite good results when used in conjunction with the finite element method to simulate wear. According to Archard's original model, the contact pressure and sliding speed at the contact surface are dependent on the rate of volume loss due to wear. The finite element software used employs a generalized version of this model that allows for accurate model dependency on contact pressure and speed. Wear occurs inside the surface, opposite to the normal contact direction. Consequently, the wear rate at the nodal point in Ansys is given as:

$$W = \frac{K}{H} P^m V^n \quad (1)$$

Where K is the wear coefficient, H is the material hardness, P is the contact pressure, V is the relative sliding speed, m is the pressure exponent, and n is the speed exponent.

2.2. Tibial slope

During rotational movement in the knees, the instantaneous change in the center of gravity creates tension in the cruciate ligaments. Tibial slope should be considered for the protection of the anterior and posterior cruciate ligaments. The force generated by the load transfer from the femur to the tibia creates a pushing force towards the knee joint. The tibial slope provides resistance against this pushing force. As the slope increases, the reaction force acting on the anterior cruciate ligament and tibia increases, and as the slope decreases, the force acting on the tibia decreases. Slopes with different angles also change the loads. Changes in loads also cause changes in wear. To predict wear in advance, the tibial slope must be carefully examined in the analysis of the model. An image of the tibial slope is given in Figure 1.

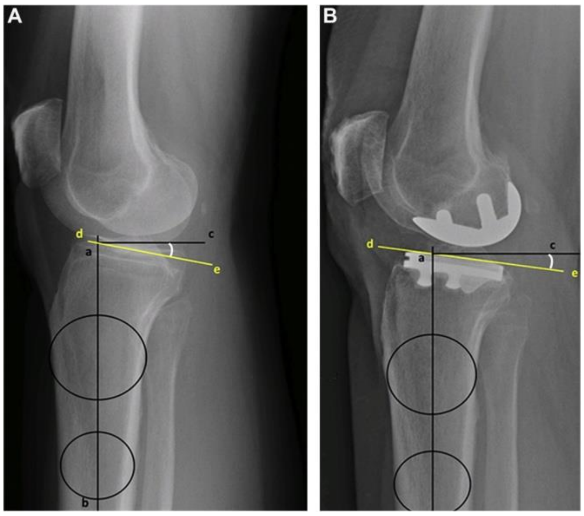

Figure 1. Tibial slope (Plancher et al. 2021)

2.3. Material properties

Perhaps the most important part of the components forming a knee implant is the part called the Polyethylene (PE) Insert, which is made of high-strength polyethylene and functions as the meniscus in the knee. While other parts are generally high-hardness metal parts, this PE Insert part is desired to be, to a certain extent, relatively softer, wear-resistant, and capable of shock absorption. Therefore, it is made of UHMWPE. The knee implant consists of three parts: the femoral and tibial components, and the polyethylene insert. Chrome-cobalt alloy was chosen for the femoral component. The properties of the chrome-cobalt alloy used were an elastic modulus (E) of 195 GPa and a Poisson's ratio (υ) of 0.3. Ti6Al4V titanium-aluminum-vanadium alloy was chosen for the tibial component. The material properties of this alloy used were an elastic modulus (E) of 115 GPa and a Poisson's ratio (υ) of 0.3. UHMWPE was chosen for the insert. The material properties of UHMWPE used were an elastic modulus (E) of 685 MPa and a Poisson's ratio (υ) of 0.47 (Suh et al. 2017).

2.4. Gait cycle

The gait cycle is the walking motion from the moment one foot contacts the ground until the same foot contacts the ground for the second time. In his study, Sridar (2017) investigated the change in flexion angle throughout a gait cycle and obtained the data in Figure 2. In this study, the data obtained by Sridar are used for the angular change of flexion.

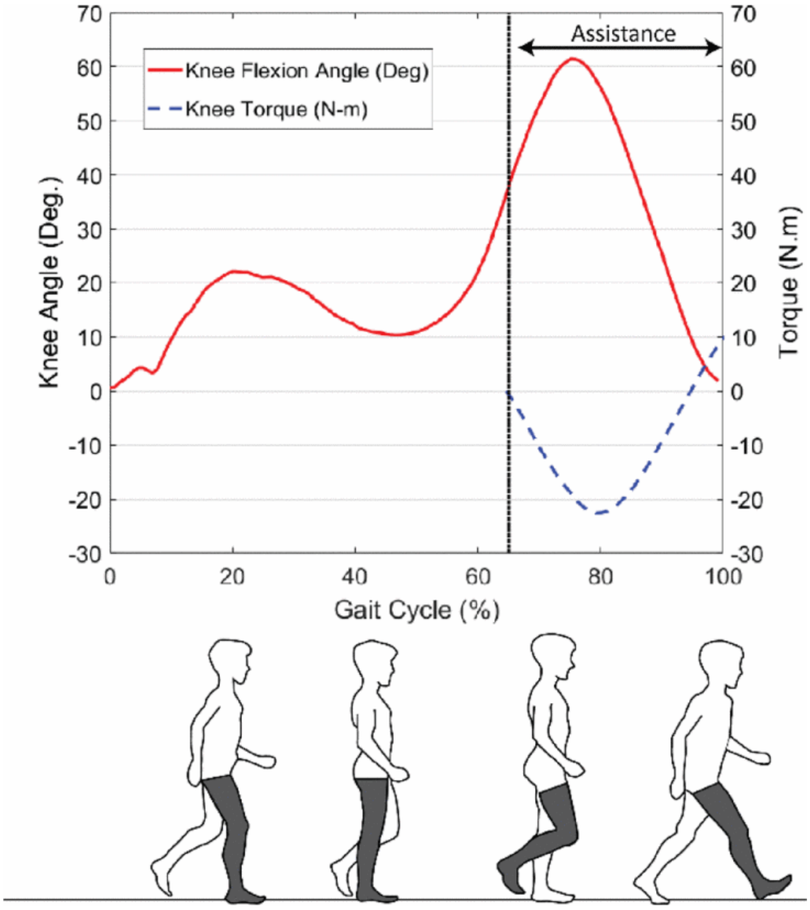

Figure 2. Variation of flexion angle throughout the gaitcycle (Sridar, 2017)

2.5. Finite element analysis

Perhaps the most important of the parts that make up the knee implant is the part called the Polyethylene Insert, which is made of high-strength Polyethylene and performs the function of the meniscus in the knee. While other parts are generally high-hardness metal parts, this PE Insert part is desired to be, to a certain extent, relatively softer and wear-resistant and capable of shock absorption. Therefore, it is made of UHMWPE.

In this study, a three-dimensional (3D) solid model of a size 2.5 right knee, obtained from Mikron Makine (Yenimahalle, Ankara, Turkey), was utilized (Figure 3). The finite element model was constructed using high-order tetrahedral solid elements, with a minimum element size of 1.5 mm following mesh refinement. The model comprised 148,805 elements and 223,069 nodes. To generate the computational models required for analysis, this 3D knee solid model was integrated with patient-specific femur and tibia solid models using SpaceClaim Software.

In the assembled knee model, the interfaces between the femoral component and the femur, as well as the tibial component and the tibia, were assumed to be fully bonded, reflecting actual physiological conditions. The contact interaction between the femoral component and the polyethylene (PE) insert was defined as frictional, given its continuous and dynamic nature across varying flexion angles. Based on previously published studies (Kang et al., 2008; Shen et al., 2015; Suh et al., 2017), the friction coefficient was set at 0.04.

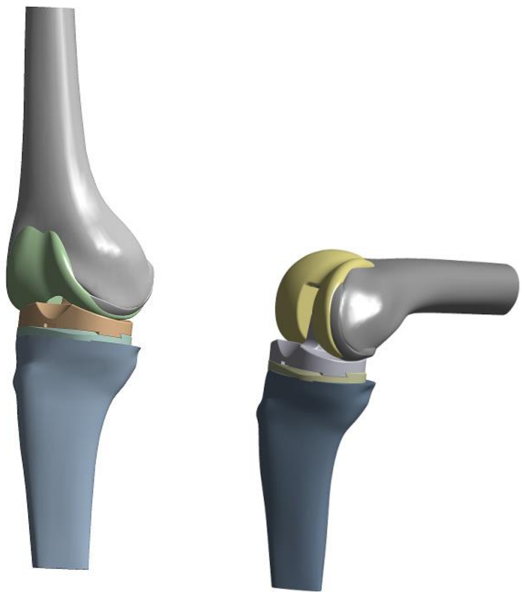

Figure 3. Left; 0 degree starting position right; 90 degree position (Ozer, 2022)

In this study, the materials and mechanical properties assigned to the model components were as follows: The femur and tibia were modeled with bone properties characterized by an elastic modulus (E) of 16.8 GPa and a Poisson's ratio (υ) of 0.47. The femoral component was composed of a cobalt-chromium alloy, with E = 195 GPa and υ = 0.3. Ultra-high molecular weight polyethylene (UHMWPE) was used for the PE insert, possessing E = 685 MPa and υ = 0.47. The tibial component was represented using a titanium alloy (Ti6Al4V), with E = 110 GPa and υ = 0.3 (Kang et al., 2008; Shen et al., 2015; Suh et al., 2017).

The wear behavior of the PE insert in the knee implant was assessed using the Finite Element Method under realistic loading conditions, validated through cadaveric experiments. The loading parameters varied based on flexion angles ranging from 0 to 90 degrees, incorporating anterior-posterior (AP) translation data. The results demonstrated that the direction-changing AP translation during flexion significantly influenced both contact pressure and wear. Unlike prior studies, the findings indicated that wear accumulation continued to increase with the number of cycles. Furthermore, posterior tibial slope—an influential factor in both contact load distribution and subsequent wear on the insert—exhibited a slight reduction in wear rate as the number of cycles increased. This reduction, correlated with increased posterior slope angles, suggests that employing a higher slope in knee implants could be advantageous. However, while higher posterior tibial slopes may mitigate wear, they also increase the parallel force acting on the contact interface, potentially inducing sliding even in static conditions.

For these analyses, the PE insert was positioned at posterior tibial slope angles of 0, 3, 5, and 7 degrees relative to the femur axis. The constant and variable loading conditions applied were derived from cadaveric experiments designed to characterize and validate knee joint loading under diverse conditions, based on literature findings (Wünschel et al., 2013). These applied loads included a vertical force of 50 N on the femur, a 10 N force on the hamstring, and a quadriceps actuator force that increased linearly, reaching 600 N at 90 degrees of flexion. The directions and lines of action of these forces were assigned in accordance with physiological loading conditions (Kornozek et al., 2013). Additionally, flexion data utilized in these simulations reflected dynamic variations throughout the gait cycle, as illustrated in Figure 4 (Wünschel et al., 2013).

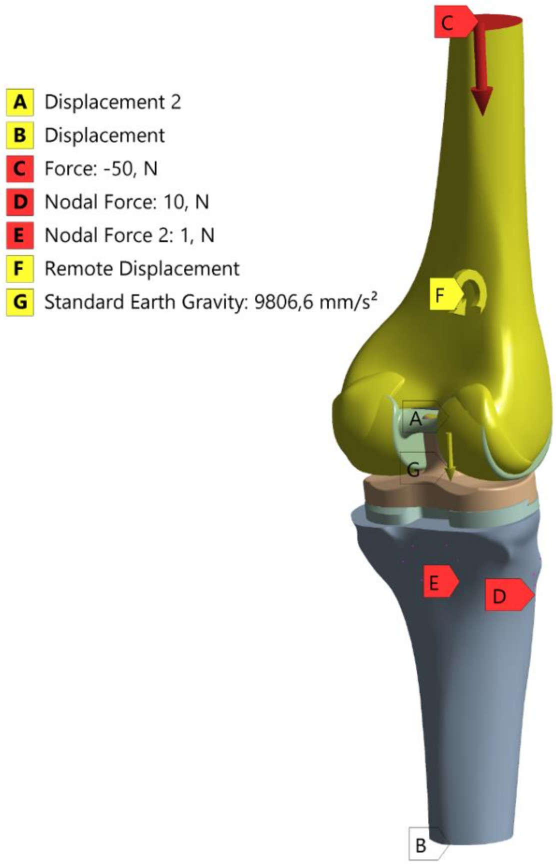

Figure 4. Boundary conditions and loadings applied to the model (Ozer, 2022)

In this study, the wear coefficient for the contacting surfaces was selected independently of contact pressure and was derived from a multi-directional pin-on-disk experiment (Liu et al., 2011). To evaluate wear on the polyethylene (PE) insert, an asymmetric contact model was employed.

The wear coefficient (K) was scaled to streamline the modeling process. Specifically, translational motion was not explicitly simulated; instead, its influence was incorporated into the wear calculation, significantly reducing computational time and complexity. Additionally, under the assumption that wear rate exhibits a linear dependence on sliding velocity, (K) was scaled accordingly. This approach ensured that wear rate remained linearly proportional to sliding speed without necessitating direct simulation of the sliding motion. This methodology was adopted in this study to further optimize computational efficiency. Figure 5 illustrates the finite element model of the implant.

Figure 5. Finite element model of the implant used in the analysis (Ozer, 2022)

3. Findings and Discussion

3.1. Findings

This study investigates the influence of posterior tibial slope angle variations on the maximum pressure distribution and wear characteristics of the polyethylene (PE) insert within a knee implant under highly realistic loading conditions, derived from cadaveric experiments. To quantify wear on the PE insert, experimentally validated loading data obtained from knee cadaver studies (Wünschel et al., 2011) were utilized, incorporating flexion angles ranging from 0 to 90 degrees. The resultant distributions of contact pressure and wear obtained from the analyses are presented in Figures 6, 7, 8, and 9, as well as in Table 1.

As seen in Table 1, in this study, analyses were performed for knee implants with posterior slopes of 3, 5, and 7 degrees under dynamic flexion varying with 5-degree increments between 0-90 degrees for 6 different cycle counts under the aforementioned loading conditions. As a result of the analyses performed for the knee implant with tibial slopes of 3, 5, and 7 degrees, it is seen in Figure 10 that the maximum contact pressure distributions on the PE insert decrease as the number of cycles increases. In contrast, the wear amount values increase as seen in Figure 11.

It is observed that as the Posterior Tibial slope angle increases, for the same number of cycles, the maximum contact pressure values decrease slightly. That is, while the contact pressure for 100 thousand cycles and 3 degrees is 2.0316 MPa, this value is 2.0295 MPa for 5 degrees and 2.0264 MPa for 7 degrees. Although this situation becomes somewhat irregular as the number of cycles increases, it is observed that the general trend is not disrupted. In contrast, while the wear amounts increase with increasing cycles for each tibial slope, they are observed to decrease with increasing tibial slope for each cycle count. That is, while the pressure values obtained for 100 thousand cycles are 2.0316 MPa, 2.0295 MPa, and 2.0264 MPa for 3, 5, and 7 degrees of tibial slope, respectively; the wear amounts also decrease in the same angular order. As seen in Figure 6 and Figure 7, while the increasing trend in wear amount is similar up to 3 million cycles, the amount of increase showed a rise after this cycle count.

Across 100 thousand, 1 million, and 3 million cycles, a reduction in contact pressure is observed as the tibial slope angle increases, albeit with minor variations. At 10 million cycles, the contact pressure for a 5-degree tibial slope is lower than at other angles, while the values for the remaining angles remain nearly identical. In simulations conducted for 20 million cycles, this decreasing trend in pressure persists with increasing tibial slope angle. Similarly, at 30 million cycles, the results align with those observed at 10 million cycles, where the contact pressure at 5 degrees is relatively high compared to other angles, while the lowest pressure value is recorded at 7 degrees.

Conversely, wear accumulation consistently increases with the number of cycles across all slope angles. Initially, this wear progression follows a steep incline but gradually stabilizes as cycle counts rise. Notably, as the tibial slope angle increases, wear exhibits a modest reduction, suggesting that higher slope angles may mitigate overall wear over extended loading cycles.

Table 1. Maximum contact pressure and wear values of 3, 5 and 7 degrees tibial slope angle at 100 thousand, 1 million, 3 million, 10 million, 20 million, 30 million cycles for flexion

Cycle	(Tibial Slope) Flexion					
	3 Degrees		5 Degrees		7 Degrees	
	Pressure (MPa)	Wear (mm)	Pressure (MPa)	Wear (mm)	Pressure (MPa)	Wear (mm)
100t	2.0316	0.0061495	2.0295	0.0061434	2.0264	0.0061341
1m	1.8544	0.04654	1.8526	0.046483	1.85	0.046397
3m	1.5098	0.099388	1.5068	0.099245	1.5043	0.099073
10m	1.0399	0.20896	1.0374	0.20867	1.04	0.20822
20m	0.85564	0.30619	0.85496	0.30573	0.85338	0.30494
30m	0.66597	0.38078	0.66875	0.38014	0.64804	0.37913

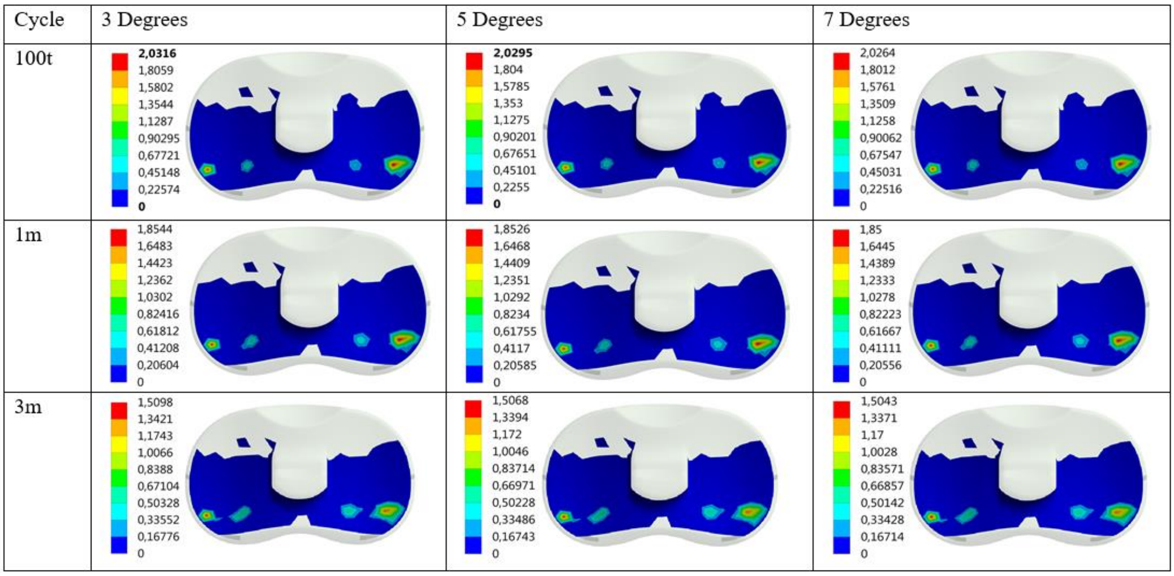

Figure 6. Contact pressure (MPa) distribution of 3, 5 and 7 degrees tibial slope angle at 100 thousand, 1 million and 3 million cycles for flexion

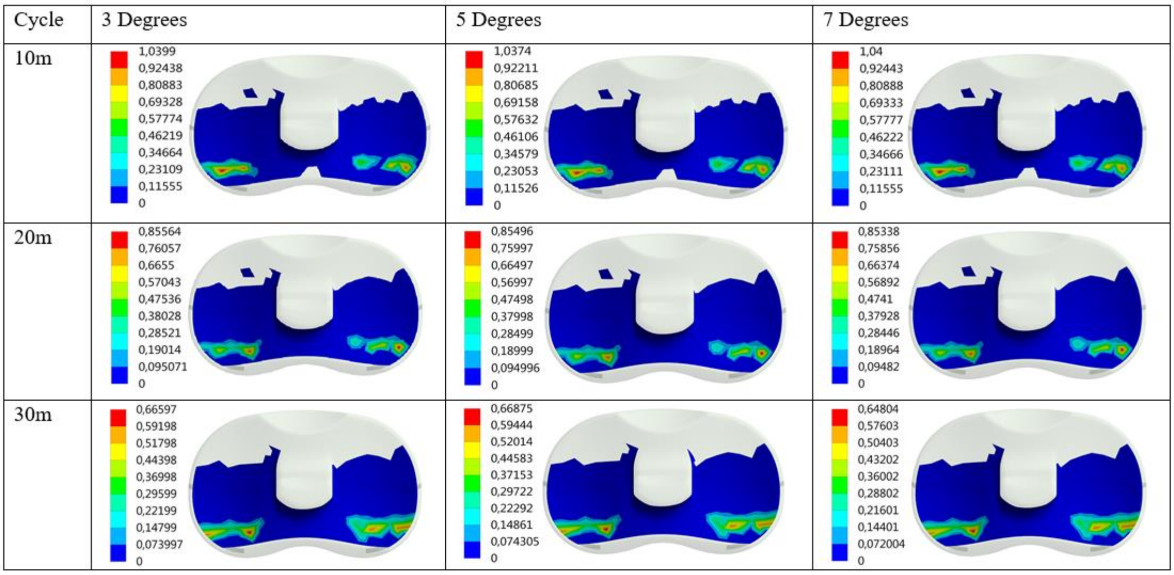

Figure 7. Contact pressure (MPa) distribution of 3, 5 and 7 degrees tibial slope angle at 10 million, 20 million and 30 million cycles for flexion

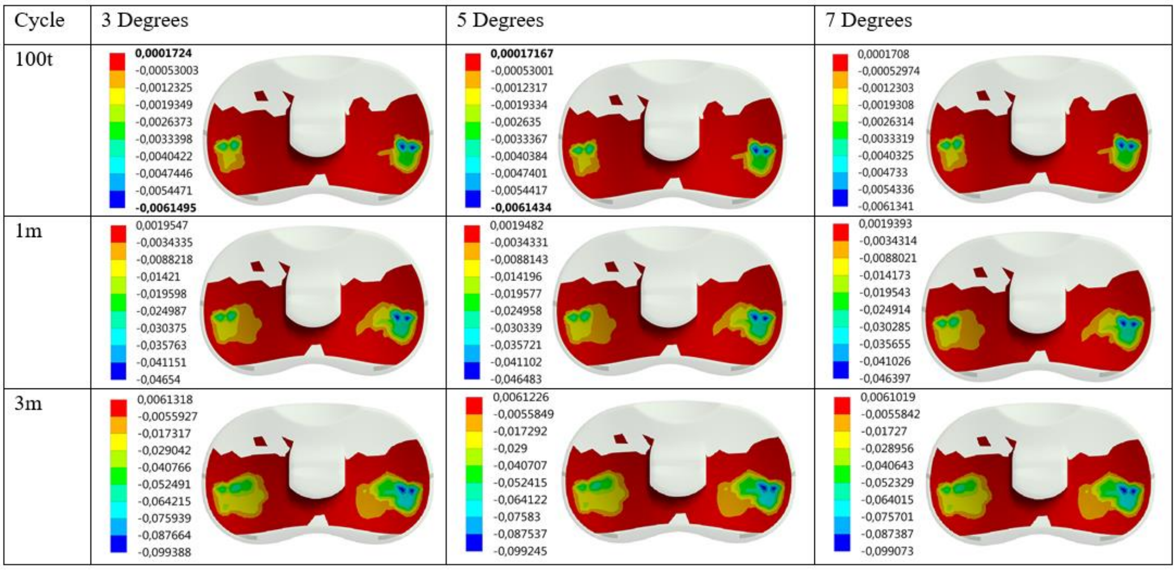

Figure 8. Distribution of wear (mm) of 3, 5 and 7 degree tibial slope angle at 100 thousand, 1 million and 3 million cycles for flexion

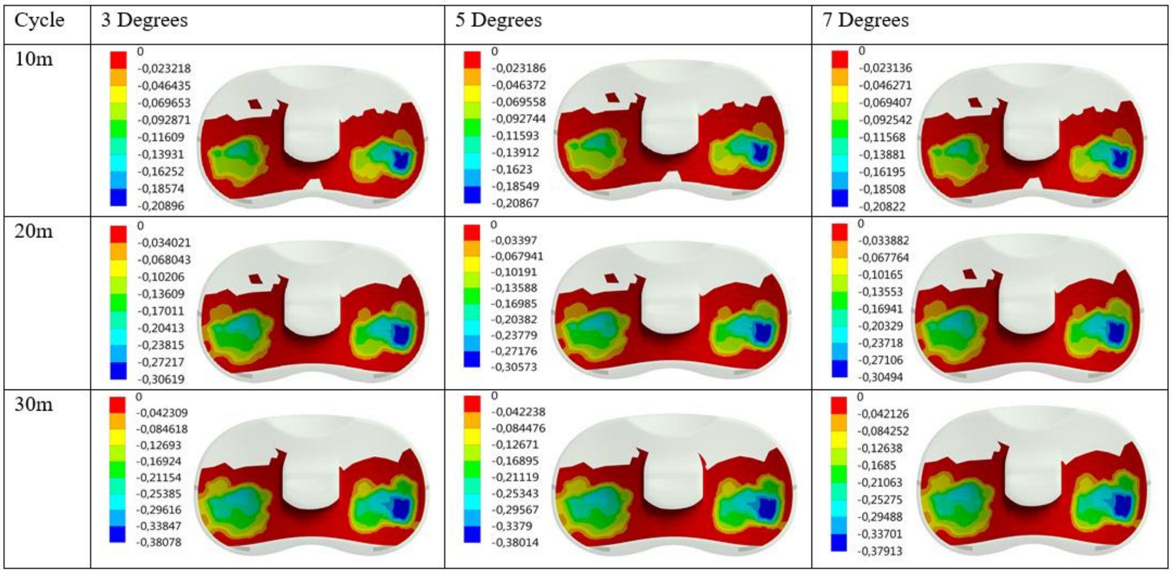

Figure 9. Distribution of wear (mm) of 3, 5 and 7 degree tibial slope angle at 10 million, 20 million and 30 million cycles for flexion

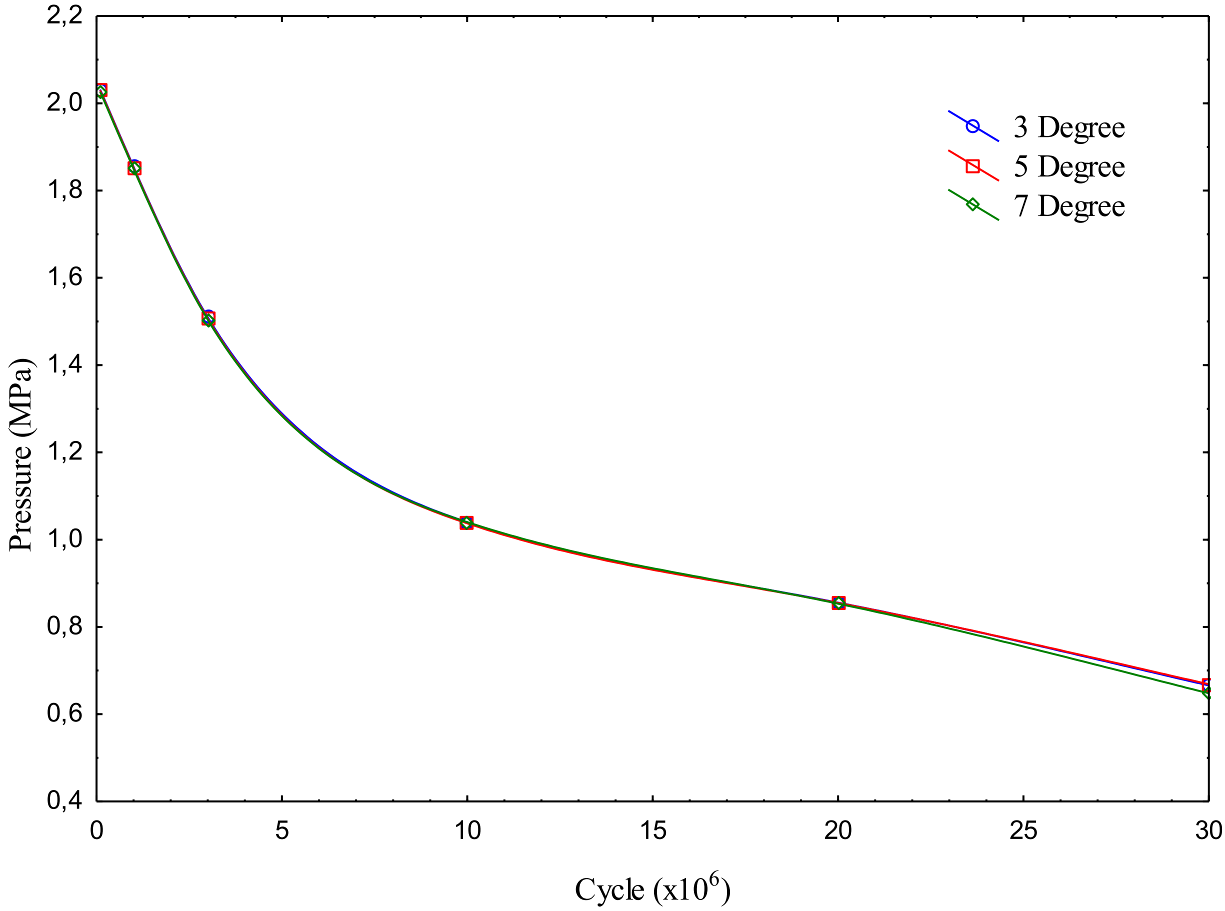

Figure 10. Maximum contact pressure values graph for 3, 5 and 7 degrees tibial slope angle at 100 thousand, 1 million, 3 million, 10 million, 20 million, 30 million cycles for flexion

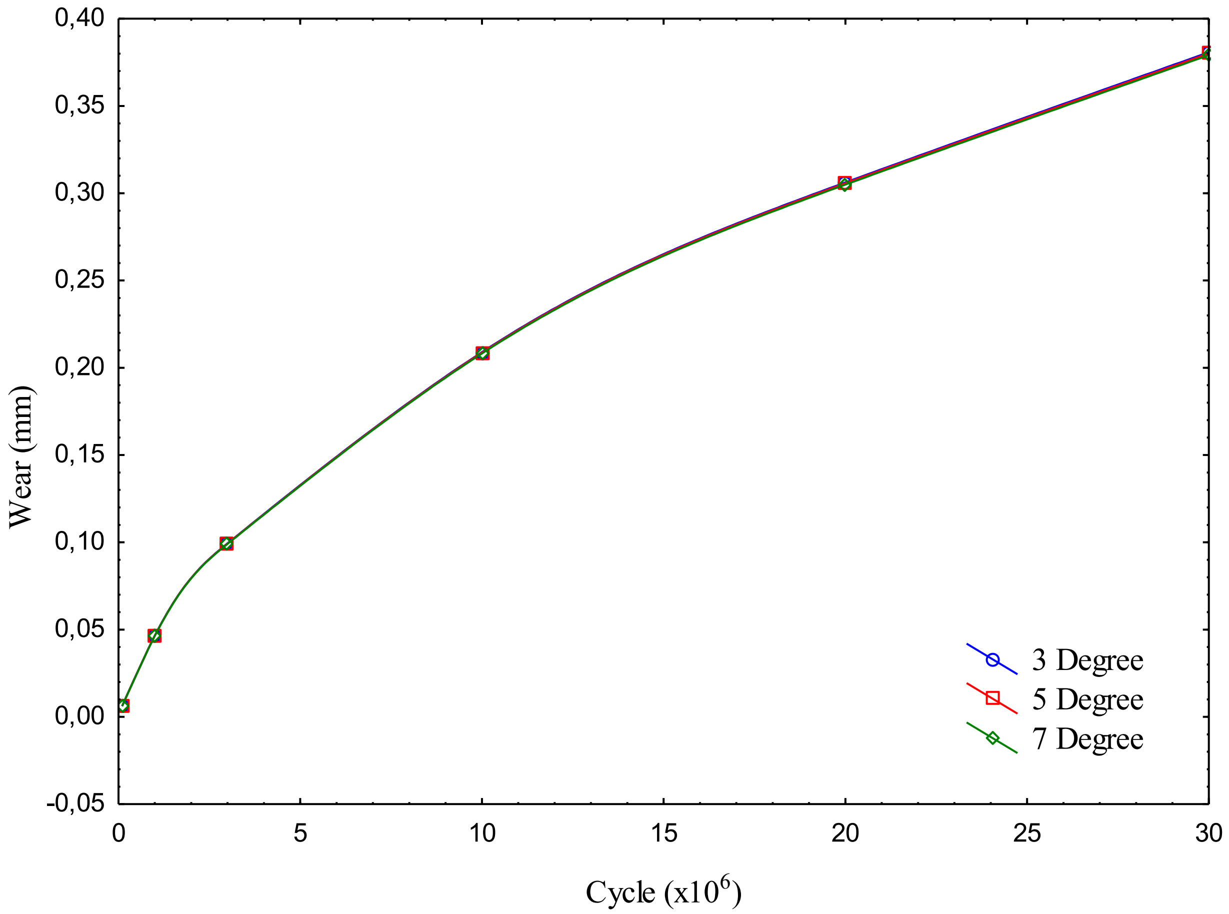

Figure 11. Maximum wear values graph of 3, 5 and 7 degrees tibial slope angle at 100 thousand, 1 million, 3 million, 10 million, 20 million, 30 million cycles for flexion

3.2. Discussion

As presented in the findings section, for each Posterior Tibial Slope angle, as the number of cycles increases, the maximum contact pressure on the PE insert decreases, and consequently, the amount of wear increases. However, it is observed that as the Posterior Tibial Slope angle increases along with the number of cycles, the amount of wear decreases. The reason for this is that the 50N force applied to the connection interface is divided into two forces as the angle increases: one still acting perpendicular to the contact interface and the other starting to act parallel to the contact interface. Of these forces, the one perpendicular to the contact interface decreases, while the parallel one increases. That is, while the perpendicular force for a 3-degree angle is 49.93 N, it decreases to 49.81 N for 5 degrees and 49.63 N for 7 degrees. In contrast, the force parallel to the contact interface becomes 2.62, 4.36, and 6.09 N for 3, 5, and 7 degrees, respectively.

In this study, it was observed that as the number of loading cycles increases, the wear area on the polyethylene (PE) insert expands and progressively shifts toward the posterior region, influenced by the anterior-posterior (AP) tibial slope angle. While this phenomenon is not prominently evident at lower cycle counts, such as 100 thousand and 1 million, it becomes considerably more pronounced at higher cycles, specifically at 20 million and 30 million.

This effect can be attributed to the design characteristics of the knee implant used in this study, which follows the cruciate-sacrificing total knee replacement model. In this configuration, as the femoral component undergoes flexion, it eventually contacts the posterior cruciate-sacrificing protrusion on the PE insert at a certain flexion angle. This interaction leads to concentrated wear in this specific posterior region, making it a critical factor in long-term implant performance.

The wear amount distributions according to the number of cycles, drawn with the data obtained from the simulations performed in this study, show qualitative similarity with the experimental studies conducted by Kawanabe et al. (2000). This situation also reveals that correct results were obtained depending on the selected wear model. Additionally, the wear amount distributions show qualitative similarity up to 15 thousand cycles with the numerical study conducted by Zhang et al. (2017), although the loading inputs are different. In contrast, differently, in this study, wear continues to increase even though the slope decreases as the number of cycles increases.

The wear area on the PE insert and its change with the number of cycles, obtained as a result of this study, are also consistent with the change in wear areas according to the number of cycles on the insert, which Zhang et al. (2017) obtained by using a wear model from the literature

4. Results

Through finite element analysis with loading data validated by cadaveric experiments, the posterior tibial slope angle was found to have a significant influence on both contact pressure and wear progression during flexion. Unlike previous similar studies, it was observed that wear accumulation continues to increase as the number of cycles grows, reinforcing the argument that dynamic loading variations—alongside flexion—alter wear behavior on the polyethylene (PE) insert.

The posterior tibial slope angle plays a critical role in determining both the load distribution at the contact interface in knee implant assembly and the wear characteristics of the insert. Notably, as the number of cycles increases, a slight reduction in wear is observed. This phenomenon is attributed to the vertical loading force, initially applied perpendicularly to the PE insert-femoral component interface at a 0-degree assembly (taken as 50 N in this study). As the assembly angle changes, this force is decomposed into perpendicular and parallel components relative to the contact interface. With increasing assembly angle, the parallel force component intensifies, whereas the perpendicular component diminishes. Consequently, the reduction in wear associated with higher posterior slope angles suggests that a greater slope may be advantageous for knee implants. However, despite its apparent benefits, an increased slope also amplifies the parallel force acting on the interface, promoting sliding even under static conditions.

To refine the understanding of posterior tibial slope dynamics, further experimental and numerical investigations are warranted. These studies should explore the static and dynamic effects of posterior slope variations in conjunction with directional and force orientation changes at the interface, flexion mechanics, anterior-posterior (AP) translation, internal-external (IE) rotation, and other contributing factors.

5. Acknowledgments

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