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Research Article

Investigation of Material Effects in Knee Prosthesis Design Using Finite Element Method

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Abstract

Aim: Total knee arthroplasty (TKA) is an effective orthopedic intervention for patients experiencing significant pain and reduced mobility due to advanced joint degeneration. One of the most critical determinants of TKA success is the mechanical and biological properties of the implant materials used. The Finite Element Method (FEM) serves as a powerful engineering tool for modeling and analyzing the mechanical behavior of prosthetic components in detail. This study aimed to investigate the mechanical effects of different material combinations used in knee prosthesis design through FEM analyses.

Material and Method: The mechanical behavior of three commonly used material combinations in knee prostheses—CoCr–UHMWPE, Ti–UHMWPE, and CoCr–Ti—was comparatively analyzed using the Finite Element Method (FEM). The geometry used in the FEM analysis was based on an anatomical knee model derived from computed tomography (CT) data. The 3D geometry was imported into ANSYS Mechanical APDL software, and adaptive meshing was applied to critical regions such as the femur–tibia contact area. The resulting models consisted of approximately 150,000 to 300,000 elements.

Results: Combinations containing CoCr exhibit lower stress concentrations. The Ti–UHMWPE combination exhibits the highest deformation at 0.93 mm, while the CoCr–Ti combination presents the lowest displacement, reflecting its higher structural rigidity. The comparison between three materials indicates that the CoCr–UHMWPE combination offers the most balanced performance in terms of stress distribution, deformation, and contact pressure.

Conclusion: The central finding of this study is that the CoCr–UHMWPE combination may represent the most optimal structure in terms of mechanical load distribution, contact stability, and deformation control in knee prosthesis applications. Although the Ti–UHMWPE configuration provides flexibility advantages, it must be cautiously evaluated for long-term structural stability. The CoCr–Ti configuration, while highly rigid, was shown to carry a potential risk of local stress-induced micro-damage.

Keywords: Total knee arthroplasty, finite element method, knee prosthesis

INTRODUCTION

Total knee arthroplasty (TKA) is an effective orthopedic intervention for patients experiencing significant pain and reduced mobility due to advanced joint degeneration. In recent years, there has been a notable increase in the number of TKA procedures performed worldwide, driven by an aging population, rising obesity rates, and a growing demand for active lifestyles (1).

One of the most critical determinants of TKA success is the mechanical and biological properties of the implant materials used. Parameters such as elastic modulus, stiffness, fatigue resistance, and biocompatibility have a direct impact on implant stability in the short term, as well as on long-term risks such as wear and loosening (2).

The most commonly used materials in knee prostheses include cobalt-chromium alloy (CoCr), titanium alloy (Ti-6Al-4V), and ultra-high-molecular-weight polyethylene (UHMWPE). Each of these materials offers unique advantages and limitations in terms of load distribution, contact pressure, and wear resistance (3).

At this point, the Finite Element Method (FEM) serves as a powerful engineering tool for modeling and analyzing the mechanical behavior of prosthetic components in detail. FEM enables precise evaluation of contact surfaces,

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stress concentrations, and deformation regions. These analyses provide critical insights into prosthesis design and material selection (4).

In this study, the mechanical effects of different material combinations used in knee prosthesis design are investigated through FEM analyses. The study evaluates how material selection affects load transmission, contact pressures, and long-term performance (5).

MATERIAL AND METHOD

In this study, the mechanical behavior of three commonly used material combinations in knee prostheses—CoCr–UHMWPE, Ti–UHMWPE, and CoCr–Ti—was comparatively analyzed using the FEM. The aim was to investigate the effects of these materials on contact pressure, stress distribution, and deformation characteristics (1). Since this study is based on FEM simulations and does not involve human or animal subjects, ethical approval was not required.

Prosthesis Model and Geometry Development

The geometry of the knee prosthesis used in the analysis was based on a high-resolution anatomical knee structure obtained from computed tomography (CT) data. Based on the bone morphology of the real human knee, the femur and tibia bones were carefully isolated and segmented in the axial plane. The volumetric data was transferred to the CAD modeling software SolidWorks, where the femoral and tibial components were reconstructed in accordance with the clinical implant dimensions and anatomy. During modeling, the focus of the analysis was on load-bearing behavior; therefore, soft tissue components such as the meniscus, anterior cruciate ligament (ACL), posterior cruciate ligament (PCL) and collateral ligaments were excluded. This approach allowed the load transfer and contact mechanics analyses to be evaluated more clearly. This parametric model was optimized for both dimensional accuracy and suitability for numerical analysis (6).

Meshing and Numerical Modeling

The obtained three-dimensional CAD models were transferred to the ANSYS Mechanical APDL software environment, where finite element analyses were carried out. In order to achieve high accuracy in numerical analysis, an adaptive meshing strategy was applied, especially in critical areas with high stress and deformation potential, such as the femur-tibia contact zone. In these areas, element sizes were reduced to a minimum of 0.5 mm, and edge density was increased to improve the accuracy of contact mechanics and stress analysis results. In regions of the model that are considered less critical, a sparser mesh structure was preferred to optimize the computation time and make efficient use of system resources (Figure 1).

As a result, the resulting finite element models are structured to contain approximately 150,000 to 300,000 three-dimensional elements. This mesh structure allows both high-resolution regional analysis and numerically accurate modeling of global loading conditions. In addition, element types and shape functions were determined in accordance with the type of analysis, and nonlinear contact definitions and convergence control were provided in contact areas (3).

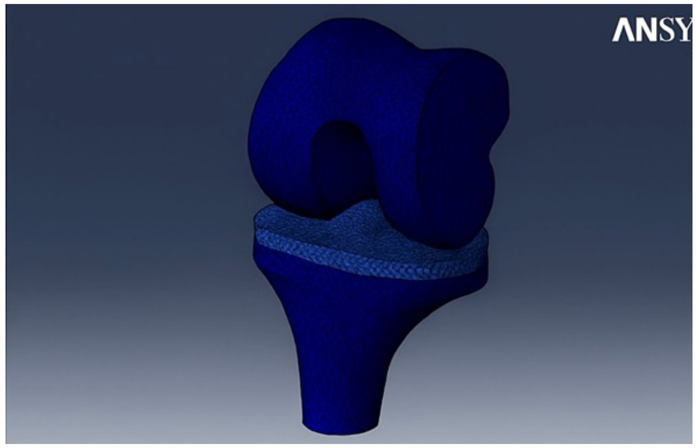

Figure 1. Meshing and numerical modeling

Material Properties

All materials used are modeled as isotropic and linear elastic. Mechanics All material models used in this study are defined assuming isotropic and linear elastic behavior, as is commonly preferred in finite element analysis. This approach provides an acceptable level of structural accuracy along with computational efficiency. The modulus of elasticity (E) and Poisson's ratio (v) of each material are presented in Table 1 below:

Table 1. Elastic Modulus (E) and son's Ratio (v) of the materials

Material	Elastic Modulus (E)	Poisson's Ratio (v)
CoCr Alloy	210 GPa	0.30
Ti-6Al-4V	110 GPa	0.33
UHMWPE	1.0 GPa	0.46

CoCr was preferred for load-bearing components that require rigidity due to its high elastic modulus. Ti-6Al-4V alloy stands out with its relatively lower stiffness and high biocompatibility, which offers an advantage in terms of deformation tolerance, especially in young and active patient groups.

UHMWPE was used as the tibial femur interface component and assumed a load absorbing role at the contact surfaces with its high energy absorbing capacity. In addition, the time-dependent creep behavior of this material was included in the FEM analysis with the definition of viscoelastic material to improve model accuracy. In this way, the long-term deformation trends of the polymer layer were reflected more realistically (2).

Loading and Boundary Conditions

In the finite element analysis, the loading conditions applied to the knee prosthesis system were structured to model the scenario closest to physiological reality. Accordingly, the loading condition was defined to represent a one-legged stance and a vertical force in the range of approximately 1800-2100 N was applied. This value is based on load-bearing scenarios assumed to be approximately 2.5-3.0 times body weight and represents the most critical loading phase of the clinical gait cycle.

In the model, the proximal surface of the femur is fully anchored with a fixed boundary condition (fixed support). In this way, load transfer is aimed to be achieved only through the tibial component. The tibial component is free-fitted from its lower surface to a rigid and frictionless plane, thus creating a contact situation similar to natural load transfer.

Nonlinear frictional contact interaction is defined on the contact surfaces between the two components. Accordingly, the contact behavior was modeled with the penalty method in FEM analysis and the friction coefficient μ=0.04 was assigned to improve the physical accuracy of the contact. This value was determined based on the average friction coefficients of metal-polymer interfacial contacts reported in the literature (7).

This modeling approach provided accurate and precise determination of both contact pressure and stress-strain distribution, allowing for a more realistic analysis of the behavior of prosthetic components under clinical loading scenarios.

Evaluation of Output Parameters

In this study, the analyses performed on the finite element model of each material combination were evaluated with respect to structural parameters that are considered clinically critical. The output parameters analyzed include the following criteria, which play a decisive role in terms of both load-bearing capacity and long-term implant stability:

- **Von Mises stress values:** The maximum and average Von Mises stresses were evaluated to analyze the distribution of structural stiffness and stress concentration zones. In particular, these values were used to identify potential microcrack initiation zones.
- **Maximum contact pressure and contact area:** The maximum pressure values and the width of the contact areas on the load transmission surfaces between two prosthetic components were analyzed for wear tendency and risk of superficial damage. The width of the surface area was considered as a parameter that directly affects the homogeneity of the load distribution.
- **Tibial component deformation:** The maximum displacement of the tibial component under applied load was evaluated in terms of structural stability and compatibility of the implant. High deformation indicates a potential risk of loosening and micro-wear.
- **Displacement and creep potential in the UHMWPE layer:** In particular, the time-dependent deformation behavior of the UHMWPE layer, represented by viscoelastic modeling, was investigated; short-term elastic displacement as well as long-term creep tendency were included in the evaluation.

All analyses were carried out separately for each material combination and the results were interpreted visually and numerically in detail for the load carrying behavior, stress concentrations and deformation zones. In this way, the advantages and potential limitations of each combination are presented comparatively (4).

RESULTS

In this study, the mechanical effects of different material combinations used in knee prostheses were evaluated using Finite Element Analysis (FEM). The outputs obtained were analyzed in terms of stress distribution, contact pressure, displacement magnitude, and deformation profiles. Each parameter was interpreted in relation to the biomechanical performance of the respective material.

Analysis and Interpretation

The results of the stress analysis revealed that the material combinations showed significant differences in terms of mechanical compliance levels. The CoCr-UHMWPE combination showed the lowest levels of both maximum (22.1 MPa) and average (15.4 MPa) Von Mises stress values. The homogeneous stress distribution observed in this combination ensures a more even distribution of the load on the contact surface and prevents stress concentrations.

In contrast, the Ti-UHMWPE and CoCr-Ti combinations showed localized stress accumulation, especially in the contact zones, due to the effect of elastic modulus differences. Ti-UHMWPE produced a more diffuse but irregular stress distribution due to its lower modulus of elasticity, while the high stiffness contrast in the CoCr-Ti combination led to superficial but dense stress concentrations (Table 2).

Table 2. von mises stress distribution according to material combinations

Material combination	Max. von mises stress (MPa)	Average stress (MPa)	Stress distribution property
CoCr–UHMWPE	22.1	15.4	Homogenous, low density
Ti–UHMWPE	25.3	17.2	Widespread, high local stress zones
CoCr–Ti	27.5	18.1	Superficial, localized stress accumulation

These results show that the tensile performance of prosthetic components is closely related not only to the stiffness of the material used but also to the elastic compatibility between the two materials (3).

Analysis and Interpretation

Considering the contact and deformation parameters, the CoCr-UHMWPE combination stands out for having the largest contact area (112 mm²) and one of the lowest contact pressures (22.1 MPa). This structure allows the load to be distributed over a larger area and homogeneously over the prosthesis contact surface, reducing the risk of superficial wear and local stress concentration.

In contrast, the Ti-UHMWPE combination showed a high deformation tendency (0.93 mm) due to the low elastic modulus. This is considered a disadvantage that may lead to long-term degradation of the UHMWPE layer under dynamic loading, such as creep and permanent deformation.

Although the CoCr-Ti combination has the lowest displacement value (0.66 mm), it carries the risk of stress accumulation and micro-wear on the surface due to the high contact pressure (27.5 MPa) and limited contact area (94 mm²). This shows that rigid structures can increase stress concentration while limiting deformation (1,4).

In conclusion, contact and deformation parameters are important determinants of clinical longevity and mechanical durability, and material selection should be made in favor of combinations that optimize these parameters (Table 3).

Table 3. Contact area, pressure and deformation comparison

Material combination	Max. contact pressure (MPa)	Contact area (mm²)	Max. displacement (mm)	Interpretation
CoCr–UHMWPE	22.1	112	0.71	Moderate level, stable
Ti–UHMWPE	25.3	98	0.93	High and elastic deformation
CoCr–Ti	27.5	94	0.66	Lowest deformation, rigid structure

Analysis and Interpretation

Qualitative evaluation of the clinical performance shows that the CoCr-UHMWPE combination exhibits a superior profile in overall stability. This combination offers a prosthetic structure that can provide long-term success, especially in middle-aged and active patients, thanks to the balanced combination of wear resistance, homogeneity of load distribution, and structural stability.

On the other hand, although the Ti-UHMWPE combination offers increased flexibility due to its lower elastic modulus, this feature may lead to decreased structural stability and increased deformation tendency. Therefore, it is recommended to use this combination in young individuals with light body mass, with careful patient selection.

The CoCr-Ti combination, on the other hand, has the highest structural rigidity and, when combined with high wear resistance, may be preferred, especially in patients exposed to high physiologic loads. However, this combination needs to be carefully evaluated due to its limited load distribution and potential stress accumulation (Table 4).

Table 4. Qualitative evaluation in terms of clinical performance

Material combination	Abrasion resistance	Load distribution	Structural stability	Clinical suitability profile
CoCr–UHMWPE	High	Balanced	Good	Optimal choice for middle-aged and active individuals
Ti–UHMWPE	Medium	Medium	Low	Cautious use recommended for young and mobile individuals with light body mass
CoCr–Ti	High	Low	Very high	Preferable in cases requiring high structural rigidity

This qualitative analysis aims to holistically evaluate not only biomechanical data but also factors that directly influence clinical decisions, such as patient profile, functional expectations, and implant longevity (6,7).

DISCUSSION

In this study, the biomechanical behavior of three different material pairs, namely CoCr-UHMWPE, Ti-UHMWPE, and CoCr-Ti, in knee prostheses was comparatively analyzed using the FEM. The numerical analyses revealed that the material combination plays an important role not only in structural strength but also in mechanical parameters such as contact pressure distribution, Von Mises stress profile, and deformation capacity, which directly affect the functional performance of the prosthesis (1,3,8).

Interpretation of Mechanical Performance

The interaction of mechanical parameters is considered to be an important factor directly affecting clinical performance. The CoCr-UHMWPE combination, with its rigidity and energy-absorbing character, allows the load to spread over a wider surface, thus creating homogeneous stress distribution in the contact area and reducing the potential for wear (3,6,9). This structure has the potential to offer long-term structural stability, especially for prostheses subjected to high repetitive loading in the knee joint.

On the other hand, the high deformation (0.93 mm) observed in the Ti-UHMWPE combination, although offering the advantage of flexibility in the short term, should be carefully evaluated as it may cause mechanical deterioration such as creep and microscopic crack formation in the UHMWPE layer in the long term (2,9,10). Although the biocompatible nature of titanium offers a favorable feature, especially in young and active patients, mechanical imbalances may increase the possibility of revision.

Although the CoCr-Ti combination maintains structural rigidity thanks to its low deformation tendency, its high contact pressure (27.5 MPa) and limited contact area

(94 mm²) create localized stress accumulation on the surface, which increases the risk of superficial wear and loosening at the implant-bone interface (4,11). As reported in the literature, such combinations are more susceptible to micro-abrasions during prolonged use under overload.

Therefore, material selection should be based not only on mechanical performance criteria but also on patient profile, activity level, and long-term clinical expectations. The interaction between the stress distribution and deformation profile of material combinations is critical to prolonging prosthesis life and reducing the risk of complications.

Consistency with Literature and Clinical Implications

The findings obtained in this study are highly consistent with the existing literature and confirm the decisive influence of material selection in knee prosthesis design on biomechanical performance. It has been emphasized in various studies that parameters such as stress accumulation, deformation and contact area observed by FEM analyses play a critical role in implant life and clinical stability.

Loi et al. showed that local stress concentrations may adversely affect implant performance and cause microfracture and loosening in their analyses performed with individual-specific FEM models (12). Similarly, Arab et al. stated that mechanical imbalances that may occur at the prosthesis-bone interface in high contact pressure situations threaten long-term implant stability (13).

Maiti and Kumar numerically investigated the deformation and wear trends in the contact zones of CoCr and Ti alloys with UHMWPE under cyclic loading scenarios and analyzed in detail the effects of different combinations on load transfer (8). These results are in direct agreement with the deformation levels observed in our study.

Bhandarkar and Dhatrak reported that the structural stiffness of Ti-6Al-4V alloy may lead to a high risk of deformation if not optimized together with the implant geometry (10). This suggests that titanium-based components should be carefully selected, especially in young and active patient groups. Furthermore, Kang et al. emphasized that the type of tibial insert material directly affects the contact pressure distribution and is an important parameter for prosthesis fit (14).

Finally, the inclusion of the viscoelastic behavior of the UHMWPE layer in FEM analyses provides the opportunity to model the permanent shape changes that occur over time in a more realistic way and increases the accuracy of predictions related to prosthesis life (2,4). This approach allows evaluation of not only the immediate mechanical response but also the long-term biomechanical stability.

Limitations and Future Directions

This study was conducted using the finite element method to comparatively evaluate the biomechanical performance of different prosthetic materials used in hip arthroplasty. However, some limitations inherent to the nature of the model should be taken into consideration.

Firstly, our analyses were conducted under static loading conditions. In real life, the forces applied to the joint have a dynamic structure that changes over time and includes multi-axial components. Therefore, the loading scenario used in the model does not fully represent all mechanical loads in daily life. In future studies, more complex models that simulate dynamic and multi-axial forces are planned to be included.

Secondly, soft tissue structures (ligaments, capsule, muscle forces, etc.) were not included in this study. It is known that these structures make significant contributions to joint stability and load transfer. Factors that directly affect prosthesis design, such as whether the ACL is preserved or not, have not been evaluated in this context. However, detailed soft tissue modeling that includes such parameters should be addressed in greater depth in a separate study.

Additionally, the fact that different liner or insert designs were not comparatively evaluated in this study can be considered another limitation, particularly in terms of changes in contact stresses. In deformation-sensitive materials such as UHMWPE, the effect of insert geometry and thickness on prosthesis performance is significant, and this topic constitutes an important focus for future studies.

Finally, this study modeled only a single loading position (e.g., single-leg stance). However, different joint positions encountered in daily life, such as squatting or climbing stairs, may also have significant biomechanical effects on the prosthesis. Integrating these scenarios into future models would further enhance the clinical validity of the results.

All these issues should be carefully considered when interpreting the study. However, these limitations do not invalidate the main objective of the current study or the comparative results it presents. The relevant points are planned to be addressed in detail in advanced studies involving more comprehensive and dynamic modeling.

CONCLUSION

This study comparatively analyzed the biomechanical performance of three different material combinations commonly used in total knee arthroplasty-CoCr-UHMWPE, Ti-UHMWPE and CoCr-Ti-using the FEM. The evaluation was not limited to classical mechanical parameters; it also comprehensively examined parameters that directly affect clinical outcomes, such as load transfer, contact pressure, deformation capacity, and long-term structural stability.

The results of the analysis revealed that the CoCr-UHMWPE combination was the most advantageous structure in terms of mechanical stability. This combination, with its low maximum Von Mises stress (22.1 MPa), large contact area (112 mm²) and limited deformation (0.71 mm), allowed the load to be distributed more homogeneously among the prosthetic components. This offers clinically significant advantages in terms of wear resistance and the potential for long-lasting use of the prosthesis (3,4).

The Ti-UHMWPE combination showed the highest deformation trend (0.93 mm) due to its high modulus of elasticity. This deformation profile, together with the osteointegration capacity and low specific gravity of the Ti alloy, makes it a highly biomechanically compatible alternative for young and active individuals. However, it should be taken into consideration that risks such as creep formation and microscopic wear on the UHMWPE layer may occur in long-term use (2,7).

Although the CoCr-Ti combination limits the level of deformation due to high structural rigidity, the maximum Von Mises stress reaching 27.5 MPa and the narrow contact area (94 mm²) created high superficial stress accumulation, which increased the risk of local microcrack formation and implant loosening (11).

Overall, the CoCr-UHMWPE combination stands out as the most stable and reliable structural profile in terms of load-bearing balance, deformation control and contact stability in knee replacement applications. Although the Ti-UHMWPE combination stands out with its flexibility and biocompatibility advantages, it should be evaluated more carefully in terms of long-term structural stability. The CoCr-Ti combination, on the other hand, supports mechanical durability with its high stiffness, but carries the risk of microscopic damage due to local stress concentration.

In conclusion, the choice of material for knee replacement should not be limited to mechanical capability alone, but should be evaluated holistically with factors such as patient-specific clinical needs, activity levels and biological interactions. In the future, patient-specific FEM modeling, integration of functional gradient materials and personalized implant designs compatible with 3D manufacturing technologies will play a decisive role in increasing prosthesis longevity and surgical success rates.

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Ethical approval: *Investigation of Material Effects in Knee Prosthesis Design Using Finite Element Method (FEM) since Finite Element Method is used in this publication, ethical approval is not required.*

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