TOPOLOGY OPTIMIZATION AND MECHANICAL PROPERTIES STUDIES ON TOTAL KNEE REPLACEMENT (TKR) USING FINITE ELEMENT SIMULATION METHOD

Muhammad Faris Abd Manap[1]*, Puteri Nur Bahyah Zainuddin[1], Nur Faiqa Ismail[2], Ahmad Faiz Zubair[1], Siti Nur Amalina Halidi[1], Hazimi Ismail[1]

[1]Mechanical Engineering Studies, College of Engineering, Universiti Teknologi MARA, Cawangan Pulau Pinang, Kampus Permatang Pauh, Penang, Malaysia.

[2]Faculty of Information Sciences and Engineering, Management and Science University, Shah Alam, Malaysia

*Corresponding email: muhammadfaris@uitm.edu.my

Article history
Received
23rd April 2023
Revised
19th October 2023
Accepted
6th November 2023
Published
1st December 2023

ABSTRACT

This study aims to propose lower material consumption of Total Knee Replacement (TKR), by employing Topology Optimization (TO). The objective is to propose a new knee implant design via Topology Optimization. Additionally, this study aims to calculate optimum cost-effective materials for the tibial and femoral components of the knee implant while maintaining the desired mechanical properties. SolidWorks and ANSYS Workbench software are used as tools in this study. Initially, the knee implant design was created using SolidWorks, followed by analysis and topology optimization using ANSYS Workbench. The method involves comparing the mechanical properties before and after optimization and calculating the amount of material saved through the optimization process. According to the findings, optimization may result in a reduction in material consumption of up to 23.96% with a difference of less than 5% in terms of the mechanical characteristics of the original design and the newly optimized design.

Keywords: *TKR, optimization, parametric study, knee design, mechanical properties*

1.0 INTRODUCTION

The knee joint is an important part of the human body because it is the location where two or more bones meet to form a joint that enables mobility. It is portrayed as the place where two long bones in the leg meet, and it is supported by a complex network of muscles, ligaments, and tendons (see Figure 1). These structures are important contributors to the knee's stability as well as its functioning. In addition, the bones that make up the knee are shielded from impact by a layer of cartilage that also serves the function of a shock absorber[1, 2].

Knee implants, also referred to as Knee Arthroplasty (KA) or Total Knee Replacement (TKR), are a surgical procedure used to replace a patient's knee joint. This treatment is particularly effective in relieving pain and restoring function for individuals with severe arthritis. Different types of arthritis can impact the knee joint, including osteoarthritis, rheumatoid arthritis, and traumatic arthritis[3]. Osteoarthritis, a degenerative joint disease that commonly affects older adults, causes the deterioration of joint cartilage and adjacent bone in the knee. Rheumatoid arthritis leads to inflammation of the synovial membrane, resulting in excessive synovial fluid, pain, and stiffness. Traumatic arthritis, on the other hand, arises from knee injuries that damage the knee's cartilage[4].

 DOI: https://doi.org/10.11113/jm.v46.484

The development of knee implants began in the early 1900s, and by 1977, Frederick Buechel had fully developed the knee implant. Since then, knee implants have been widely used and have become a standard surgical practice for total knee replacements. According to the latest available data, approximately 600,000 total knee replacements are performed annually in the United States alone[5, 6]. This indicates that knee replacement surgery is now a common procedure carried out in many healthcare institutions.

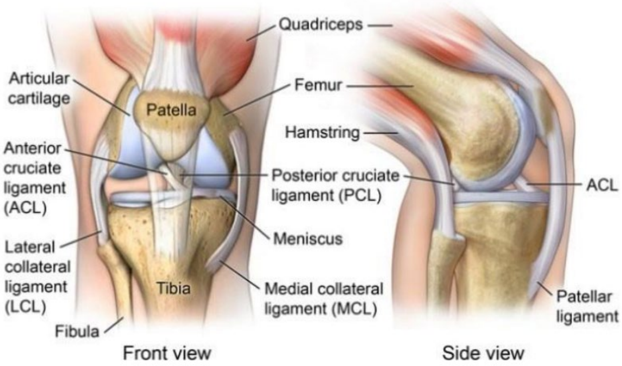

Figure 1: View of knee joint in human body[1].

1.1 Knee Implant Design

There are three primary design options for TKR as shown in Figure 2: Posterior-Stabilized, Cruciate-Retaining, and Bicruciate-Retaining designs. In the Posterior-Stabilized design, the cruciate ligaments are replaced by certain implant components. The tibial component has an elevated surface with an internal post that fits into a femoral component's cam. This design aims to prevent excessive forward movement of the thighbone during knee bending. Some Posterior-Stabilized designs even include an extra-large post that replaces the collateral ligaments. In contrast, the Cruciate-Retaining design maintains the Posterior Cruciate Ligament (PCL) but removes the Anterior Cruciate Ligament (ACL). This design lacks the center post and cam mechanism. It is suitable for patients with a healthy PCL that can continue providing support to the knee joint despite an ACL injury[7].

Lastly, Bicruciate-Retaining designs preserve both the ACL and PCL during total knee replacement. The goal of this design is to replicate the behavior and feel of a natural knee by retaining both ligaments. However, Bicruciate-Retaining components are relatively new, and there is currently limited high-quality research available to demonstrate their specific advantages[8].

It is worth noting that there is currently no significance impact whether the Posterior-Stabilized design offers superior longevity or better outcomes compared to the Cruciate-Retaining design[9]. Short term and middle term follow-up indicated both design's survivorship were at same level[10].

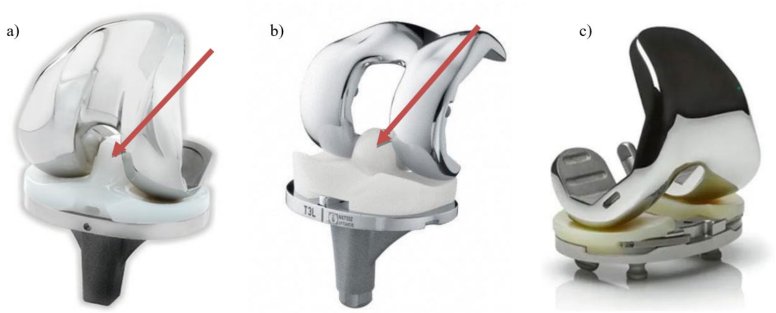

Figure 2: Primary design of TKR: a) Posterior-Stabilized, b) Cruciate-Retaining and c) Bicruciate-Retaining.

DOI: https://doi.org/10.11113/jm.v46.484

1.2 Materials in TKR

The selection of materials utilised for the femoral, tibial, and patellar components of the implant is very important to the overall outcome of total knee replacement surgery (TKR). Throughout the years, a variety of materials have been utilised, each of which possesses its own set of benefits and drawbacks. A examination of the relevant literature suggests that the materials cobalt-chromium alloy, titanium alloy, and polyethylene are the ones that are utilised for TKR the most frequently[11]. One of the primary challenges associated with TKR materials is wear and fatigue. Polyethylene, a popular choice for bearing surfaces, can experience wear over time, leading to particle generation and subsequent inflammation[12]. This wear debris-induced inflammation can result in osteolysis and implant loosening, jeopardizing the long-term success of the procedure[13]. Efforts have been made to enhance the wear resistance of polyethylene through cross-linking and alternative materials, but issues such as fracture and squeaking noises have been reported yet still preferred materials compared to contemporary materials[11,12].

Infection is yet another serious problem that might arise while working with TKR materials. Infections can arise after surgery despite the careful measures that are taken, which can result in the failure of an implant and the requirement for revision surgery. Patients suffering from rheumatoid arthritis had a greater chance of requiring a revision total knee replacement due to an infection than those suffering from osteoarthritis[16, 17]. Younger age is associated with an increased risk of early prosthesis failure following primary TKR for osteoarthritis[18]. Radiolucent lines below the tibial component of a TKR can result from poor cement injection into cancellous bone[19]. Patients aged 55 years and younger have an increased risk of failure following revision TKR[20].

In addition, the materials used in TKR need to have adequate mechanical stability so that they can withstand the stresses that are placed on the knee joint. There are concerns regarding metal hypersensitivity and the possibility of unfavourable responses occurring in some individuals, despite the fact that cobalt-chromium and titanium alloys have amazing strength and longevity. A mismatch in the stiffness of the implant and the bone that is close to it can also produce stress shielding, which can eventually lead to bone resorption and loosening of the implant over time[21, 22].

In conclusion, the design of the TKR as well as the materials used in it play an important part in the success of the process as well as its durability. Even though there have been breakthroughs made to address problems like as wear, infection, and mechanical stability, there are still concerns that need to be addressed. As a result, this research was carried out in order to execute new design with a reduced consumption of materials, which would enable for greater progress to be made towards TKR development.

2.0 METHODOLOGY

2.1 Design of Knee Implant

The development of the implant as shown in Figure 3 involved a meticulous integration of various components, that assembled to form a cohesive whole. The design inspiration for this model originated from two key sources: the well-established Fixed-Bearing Implant and the innovative Bicruciate-Retaining Design (BRD). The purpose of this research was to develop a knee implant that, for patients, provides increased stability and functioning, as well as long-term efficacy. This was accomplished by combining the positive aspects and benefits of both procedures. This approach utilises the knowledge gained through putting ideas through their paces in the past while also taking into account the most recent advances in technology. As a direct consequence of this, it paves the way for individuals to regain their mobility and take pleasure in an improved quality of life.

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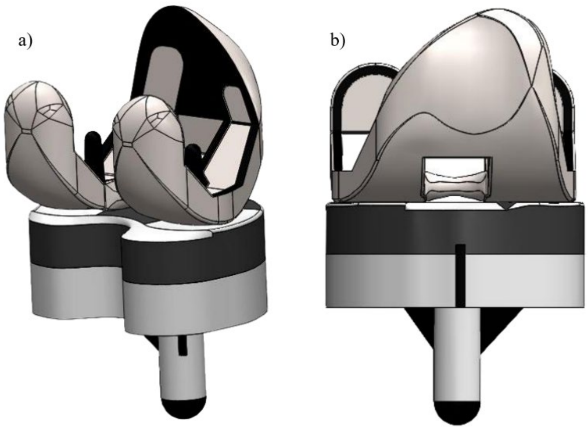

Figure 3: Development of new design TKR with innovative BRD design.

2.2 Materials, boundary conditions and optimization

All the materials in the FE model were modelled as homogenous, isotropic and linear elastic except the polyethylene tibial spacer and patella component which was modelled as non-linear elastic-plastic with the plastic stress-stain constitutive relationship. The mechanical properties of the materials are shown in Table 1. The tibial main component was considered as rigid material to reduce computational time. Mesh sensitivity studies were carried out at the contact condition of femoral and tibial components in order to optimize computational efficiency. The knee implant model is meshed with model contains 19,801 elements and 34,992 nodes, and the shape of the element is a tetrahedron.

Table 1: Material properties[6].

Material	Young's Modulus (GPa)	Poisson's ratio
Femoral Component	220	0.3
Tibial Component	120	0.3
Patella Component	0.9	0.5

The loading condition and force exerted on the simulation based on three type of common movement of daily living activites. Details of the loading condition shown in Table 2. Rigid part was exerted on tibial component labelled A and loading force exerted labelled as B as shown in Figure 4. In this study, it is important to note that the body weight mentioned is based on average data from previous research. Incorporating findings from multiple studies helps establish a broader understanding of body weight trends and provides a more comprehensive perspective.

Table 2: Loading condition in FE analysis.

Types of movement	Equation of loading condition
Normal/standing	Weight of Human Body x 9.8 m/s^2
Walking	Weight of Human Body x 2.8 x 9.8 m/s^2
Jogging	Weight of Human Body x 3.6 x 9.8 m/s^2

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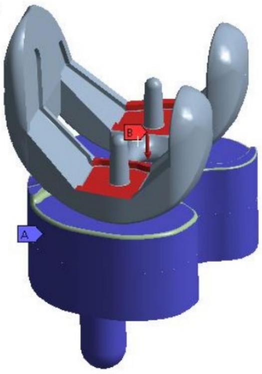

Figure 4: Loading condition and boundary conditions. (A) for fixed support and (B) loading condition.

Establishing the algorithm within the response constraint, which enables the required percentage of material retention in the knee implant to be specified, is the primary emphasis of this project. In order to obtain the necessary level of optimization in the design, numerous iterations need to be carried out in order to establish the percentage that is most appropriate. To determine the best proportion for the optimization objective, a comprehensive investigation into the available possibilities and conduct at least five separate tests. In this particular case, the ultimate decision for the design's final percentage was determined to be 99%. The optimized knee implant model is presented in Figure 5 which shows that optimization occurred at brownish area of femoral component. However, it is crucial to ensure that the design maintains a smooth shape to facilitate its manufacturability and shape retention.

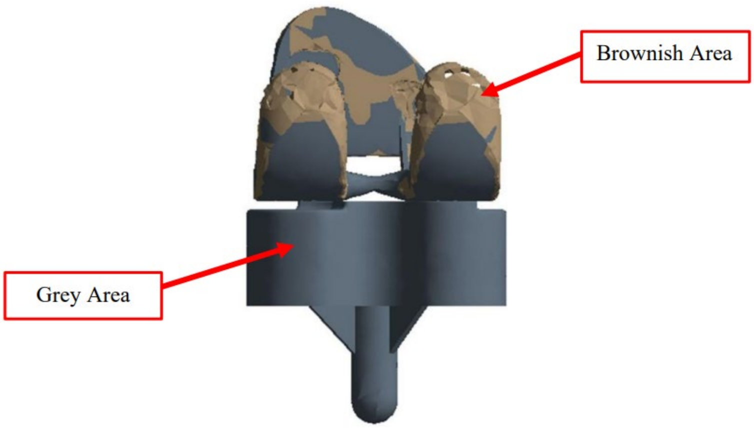

Figure 5: Optimization in FEA: Optimization occurred at femoral component labelled as brownish area.

3.0 RESULTS AND DISCUSSION

3.1 Redesign after optimization

Redesigning the femoral component of a TKR after optimization in finite element analysis (FEA) is a crucial step in enhancing the performance and longevity of the implant. In the context of TKR, FEA helps in evaluating the stresses, strains, and potential failure points in the femoral component when subjected to realistic loading scenarios. In this study, the optimization mainly occurred only at femoral components, and it is vital to redesign the femoral component after optimization as it is essential to translate the improved design into a manufacturable and clinically viable product. The

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process involved using parametric modeling features to adjust geometric parameters, create or modify surfaces, and performed Boolean operations to add or subtract features at the femoral component and it shown in Figure 6.

Figure 6: Optimization in FEA: Optimization occurred at femoral component labelled as brownish area.

3.2 FEA mechanical properties

Figure 7 shows the total deformation of TKR at three different loading conditions. At normal/standing condition, walking condition and jogging condition, the maximum total deformation recorded at 0.0309 mm, 0.0899 mm, and 0.2428 mm, respectively. These findings demonstrate the direct correlation between loading conditions and the extent of total deformation in TKR, with higher levels of activity leading to increased deformation. The data emphasizes the need for careful consideration of loading conditions and their potential impact on the performance and longevity of TKR implants.

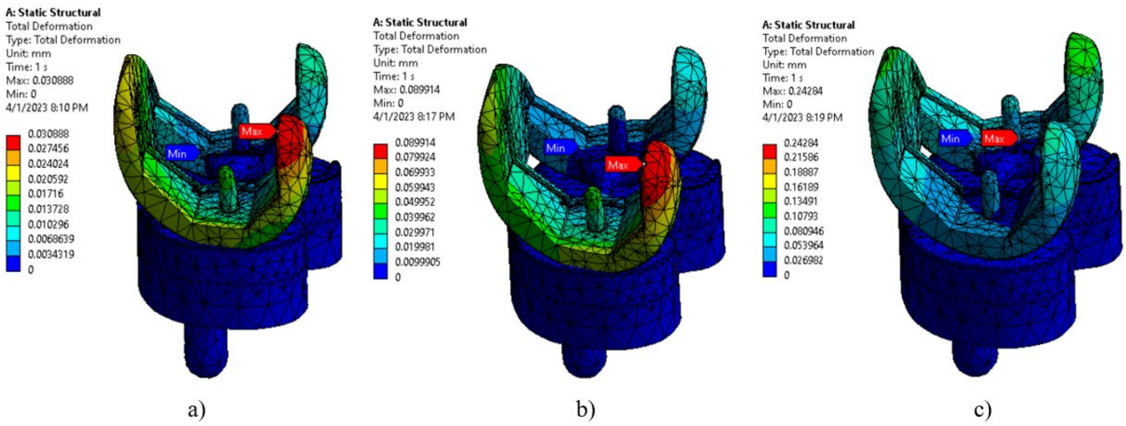
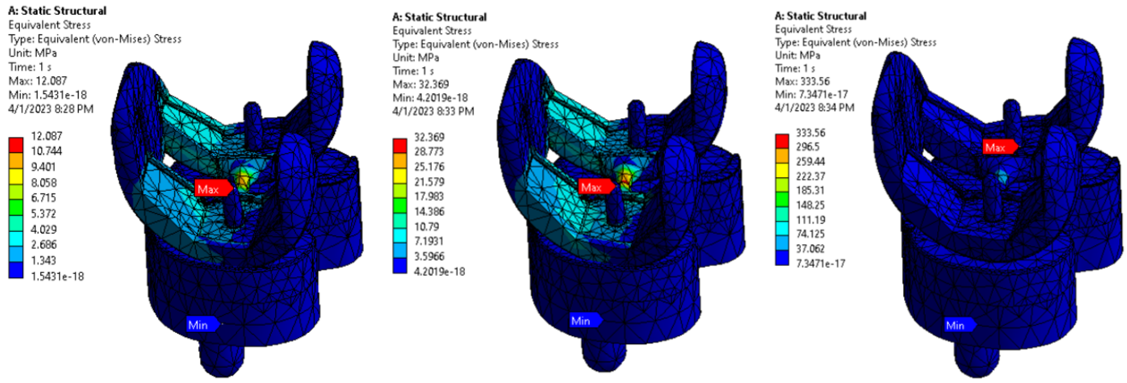


Figure 7: Total deformation at three different loading conditions.

Meanwhile, Figure 8 shows the Von-Mises stress which the normal/standing condition, walking condition and jogging condition, the maximum Von-Mises Stress recorded at 12.087 MPa, 32.369 MPa and 333.56 MPa, respectively. This significant increase in stress during jogging is primarily due to the higher impact forces and greater intensity of jogging compared to normal standing and walking. Jogging involves rapid and forceful movements that subject the TKR to

DOI: https://doi.org/10.11113/jm.v46.484

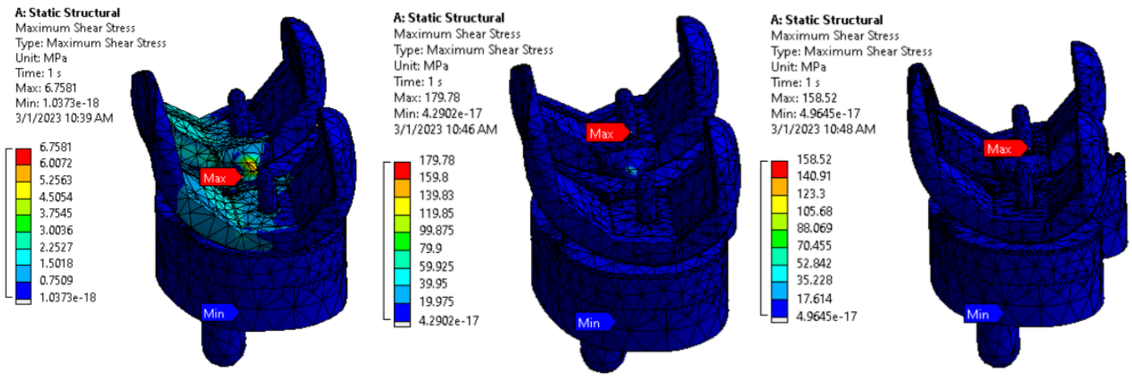
elevated loads, resulting in increased stress concentrations. Furthermore, it is important to note that the normal/standing condition, in contrast to walking, does not involve the dynamic nature of movement. Previous research has consistently highlighted the influence of knee joint dynamics on the distribution of loading within the knee joint.



a) b) c)

Figure 8: Von-Mises stress at three different loading conditions.

Figure 9 shows the shear stress that a little bit different output compared to total deformation and Von-Mises's stress. During normal/standing condition, walking condition and jogging condition, the maximum shear stress recorded at 6.758 MPa, 179.78 MPa and 158.52 MPa, respectively. During walking, the knee joint experiences cyclic loading due to the alternating stance and swing phases. This cyclic loading creates dynamic shear forces that can lead to higher shear stress levels. On the other hand, during jogging, the increased intensity and higher impact forces lead to more dominant compressive forces compared to shear forces. Jogging involves rapid and forceful movements, causing higher vertical ground reaction forces and increased compression on the knee joint. Consequently, the compressive forces tend to dominate over the shearing forces, resulting in relatively lower shear stress levels compared to walking. The assumption agrees with previous research state that short duration of ground contact make it impossible the load per unit distance (PUD) higher in jogging and the impulse joint contact force always greater for running than walking[23–25].



a) b) c)

Figure 9: Maximum shear stress at three different loading conditions.

 DOI: https://doi.org/10.11113/jm.v46.484

Topology optimization occurred at those three conditions and the results indicate to achieve less than 5% mechanical properties difference 'before and after optimization', the mass of femoral component can be reduced at maximum of 23.96%. The maximum mass reduction can be achieved during jogging conditions. Figure 10 shows the original design versus optimization design comparison of mechanical properties.

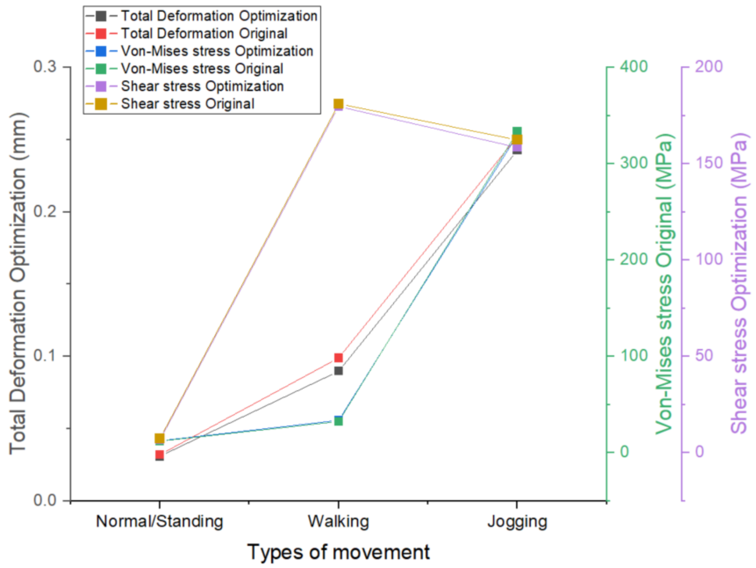


Figure 10: Comparison before and after optimization. Capped at 5% difference, the maximum reduction of new design can be achieved at 23.96%.

4.0 CONCLUSION

In conclusion, this study highlights the direct relationship between loading conditions and the total deformation, Von-Mises stress, and shear stress in total knee replacement (TKR) implants. When compared to normal/standing state and walking, higher levels of activity, and notably running, result in greater deformation, stress, and shear stress. running in particular causes this rise. Jogging causes the TKR to be exposed to larger impact pressures, which in turn leads to increased stress concentrations. Higher shear stress levels are produced as a result of walking due to the cyclic loading and dynamic shear forces involved. The results of a topology optimization study revealed that the mass of the femoral component may be decreased by up to 23.96% with a loss in the component's mechanical characteristics of less than 5%. These findings highlight how important it is to take into consideration the loading circumstances and optimize the design of the TKR in order to improve performance and longevity.

ACKNOWLEDGMENTS

I would like to express my heartfelt gratitude to my family for their unwavering support throughout this project. I am also deeply grateful to my final year project students, for their dedication and contributions to the study. Their enthusiasm, hard work, and collaborative spirit have enriched the research process. Additionally, I extend my thanks to my advisors, colleagues, and friends for their guidance and support.

DOI: https://doi.org/10.11113/jm.v46.484

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