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Research paper

Design and Analysis of High Flexion Femoral Component for Total Knee Arthroplasty (TKA)

Mohammad Hanafi Seman[1], Solehuddin Shuib[1]*, Mohd Afzan bin Mohd Anuar [1], and Amran Ahmed Shokri[2]

[1] *Faculty of Mechanical Engineering, Universiti Teknologi MARA,40450 Shah Alam, Selangor*
[2]*School of Science Health, Universiti Sains Malaysia, 16150 Kubang Kerian, Kelantan*
**Corresponding author E-mail:solehuddin2455@salam.uitm.edu.my*

Abstract

In the early development of TKA, disability of traditional prosthetic knee to consistently reach 115-degree angle raised concerns about functional limitations for demanding high flexion patients. The need for high flexion at 120 degrees in certain patients especially in some ethnic population that requires high flexion for various social and religious activities has been proven by clinical experience. This study was carried out through a static structural analysis of implanted knee underwent deep flexion motion using ANSYS R18. Flexion angles of 0, 90, 135 and 165 degrees with different net force based on a percentage of body weight were applied on the prosthetic knee model. The von Mises stress, shear stress, contact pressure and total deformation at tibial insert were observed and compared to find the optimal design for further optimization. The optimization includes increasing the maximum thickness of polyethylene tibial insert, increasing the conformity between femoral and tibial insert, also changing the post-cam contact features by using flat on flat, flat on a curve, and curve on a curve. Increasing the average conformity of tibiofemoral interface has successfully reduced the von Mises stress, shear stress and contact pressure about 24.4%, 23%, and 40.9%, respectively.

Keywords: *Total Knee Arthroplasty; Total Knee Replacement; Deep flexion; femoral component*

1. Introduction

The knee can be defined as the middle muscle and bone joint of the leg that allows complex movement of the leg [1]. Knee joint consist of three essential complex muscle and bone which is thigh bone (femur), the shin bone (tibia) and joined it together with kneecap (patella) and the fibula [2]. A thin layer of articular cartilage covers the surrounding surface of the knee bones and acts as weigh bearing to support movement mechanism of the entire human body [2]. On the contrary, the complexity of the mechanism and component of the knee joint making it vulnerable to acute injuries and arthritic problems [3].

The knee injury is one of the most leading reasons people often see their doctors for medical assistance, with a total of 10.4 million peoples [4]. The variation of injuries including fracture, dislocations and ligament tears [4]. Torn of the anterior cruciate ligament, the injury that often occurred in high demand sports activities such as football and basketball is one of the most significant types of knee injury. Athletes tend to do fast change of movement also jumping with incorrect landing, can cause half of the injuries to the anterior cruciate ligament, alongside damages to other joint muscles and bones including articular cartilage, meniscus, or other ligaments [4].

Arthritis also one of the considerable type of knee injuries aside from anterior cruciate ligament tear. Osteoarthritis, one of the types of arthritis which are a problem either cause by aging, injury or disease and cause the cartilage to wear and tear away [2].

Total knee arthroplasty is one of the most prevalent common plus reliable methods to cure knee arthritis problems. This is the only remaining alternative to relieve pain and to restore function to an arthritic knee when other treatments such as weight loss, exercise or physical therapy along with medicines and injections failed to overcome the arthritic knee problem [5]. Estimation around 4.7 millions of Americans, with 64% of women and 36% of men have already undergone total knee replacement surgery to replace their arthritic-related problem knee, according to the prevalence study of Mayo Clinic in 2014 [6]. First TKA replacement surgery in Malaysia was in 1970 [7]. 16 years later, a few numbers of TKA surgery has been done in University Hospital Kuala Lumpur and the demand for TKA services rising year by year along with technological and surgical advances [7].

Total knee replacements (TKR) are one of the most common orthopedic surgical procedures performed each year with approximately 250,000 Americans undergo total knee replacement surgery[9]. This treatment was the last option to relieve pain and to restore function to an arthritic knee when other treatments (weight loss, exercise/physical therapy, medicines, and injections) have failed to relieve arthritis-associated knee pain [9]. The traditional prosthetic knee was unable to reach the demand of patients to consistently reach 115-degree angle [10]. The need for high flexion at 120 degrees in certain patients especially in some ethnic population living, especially for Indian, Middle Eastern, and Japanese cultures that requires high social for various social and religious activities has been proved by clinical experience [10],[11]. Deep flexion is arbitrarily defined as the movement of the knee joint to achieve flexion greater than 120 degrees [12].

Fig. 1: ‘Seiza’, formal sitting posture for Japanese [13]

While the majority of modern TKA designs provide pain relief and improved walking ability, patients often do not achieve satisfactory flexion, especially in Asian countries [14]. The desire for the improved function has encouraged innovation in prosthetic design, resulting in a new generation of “high-flexion” knee replacements. Implant design features must be considered, as is present in many implants, results in early impingement of the tibial implant on the femur preventing further flexion [15]. Also, it is important to consider the magnitude of the loads at the knee in the treatment of patients that commonly perform deep flexion during activities of daily living [16].

Deep flexion TKR is arbitrarily defined as a knee that achieves flexion greater than 120 [17]. The need for deep flexion is essential for activities of daily living, especially for Indian, Middle Eastern, and Japanese culture [18]. It is important to consider the magnitude of the loads at the knee in the treatment of patients that commonly perform deep flexion during activities of daily living. Furthermore, dynamic loading in deep flexion is another important consideration in the evaluation and design of total knee arthroplasty (TKA. For example, Japanese requires 150 degrees of flexion for proper sitting (Seiza) and Muslim praying position (Sujud, Julus)[19]. While the majority of modern TKA designs provide pain relief and improved walking ability, patients often do not achieve satisfactory flexion, especially in Asian countries [20]. The desire for the improved function has encouraged innovation in prosthetic design, resulting in a new generation of “high-flexion” knee replacements. To achieve the significant of this project needs to be understanding of normal knee kinematics including the concept of femoral rollback and the need for physiologic posterior stability. From that the goal of TKR surgery also can achieve while maintaining a balanced, stable and also functional knee [21].

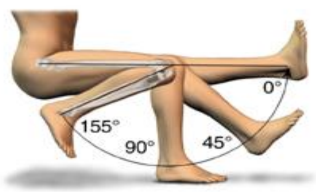


Fig. 2: Schematic diagram of flexion angle [22]

In the present day, various researchers cooperate with doctors, surgeons, and engineers are still working on the enhancement of TKR surgery as well as to improve overall lifespan and performance of the knee implant. The continuous advancement to develop in terms of new operation and procedure techniques, as well as design and material of the knee implant, as it may enrich the overall performance of TKA surgery and most important to get rid the essential of reoperations.

2. Materials and Method

In this study, the knee implant design used for analysis was modeled in prior study [23]. The design modification was performed based on NextGen Legacy® LPS Flex Mobile Bearing, a knee implant produced by Zimmer Incorporated in the year 2006. This phase focused to analyse the knee implant design using ANSYS R18.0 software.

2.1. Finite element analysis of previous design [23]

Table 1: Geometry variation of selected TKA’s designs

Design Modification 1	Femoral component	UHMWPE Tibial
Modification 1	Flat with a 2mm chamfer	Flat curve
Modification 2	-	Flat
Modification 3	Flat	Flat

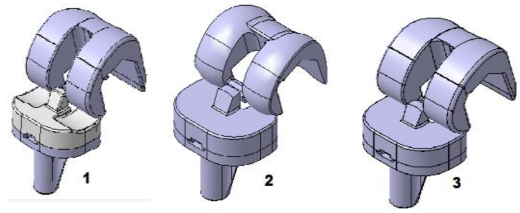


Fig. 3: Modification of previous design [23]

The 3D model of knee implant was developed using CATIA v5 CAD software and imported to ANSYS R18.0 software for finite element analysis. The design features of femoral component and tibial insert for the corresponding modifications are shown in Table 1. Fig. 2 shows the 3D models of knee implants from three different modifications. Cobalt – Chromium Alloy was assigned for femoral and tibial component and Ultra-High-Molecular Polyethylene (UHMWPE) was assigned for the tibial insert. The material properties are shown in Table 2.

Table 2: Material properties for femoral component, tibial insert and tibial component.[24]

Part	Selected material	Young’s Modulus, E (MPa)	Poisson Ratio, v
Femoral	Cobalt Chromium Alloy	210,000	0.29
Tibial insert	Ultra-High Molecular Weight Polyethylene (UHMWPE)	690	0.46
Tibia	Cobalt Chromium Alloy	210,000	0.29

The knee implant finite element models was constructed through a meshing set with adaptive size function, course relevance centre and 1.20 mm element size. The minimum edge length is 4.8195e-002 mm. In this analysis, four different angles of flexion were used. These angles was selected based on the most common daily activities done by Asian. The four angles of flexion were 0, 90, 135 and 165 degree to represent standing, squatting, kneeling and sitting on feet position, respectively.

The location of applied force plays an important role on how it will affect the distributed forces and contact pressure around the femoral implant and dependent on the angle of flexion used. The boundary condition was set via fixed support feature at the base of the tibial tray. Then, the loading force was applied vertically downward in the z-axis. The weight of 66.5 kg (equivalent to 652.365 N) has been considered to be applied during this analysis. This average weight (range 49-80kg) was chosen based on 100 patients with osteoarthritis who underwent knee replacement surgery in Malaysia [25]. Every position will have different net force produced in conjunction with the percentage of body weight [26] to replicate knee load during different physical activities. Table 3 illustrates the knee joint position during different activities and Table 4 shows the net vertical force applied on the knee joint at different knee flexion angles.

Table 3: Knee joint position to replicate different patient's activity.

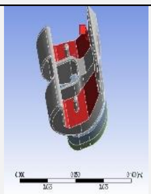
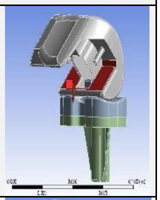
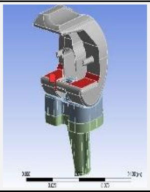
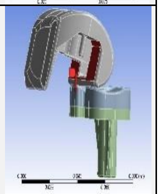
Angle (°)	Activity	Loading position	Angle (°)	Activity	Loading position
0	Stand		135	Squat	
90	Kneel		165	Sit on feet	

Table 4: The net force applied with different flexion angle [26].

Angle flexion (°)	0	90	135	165
Knee vertical force	0.5 BW = 326.183N	1.2 BW = 782.838N	5.3 BW = 3457.535N	6 BW = 3914.190N

2.2. Design Optimisation

Design optimisation has been done using best-selected design according to the static structural analysis results. This design undergoes further optimisation to decrease the possibility of contact pressure, shear stress, especially during deep flexion.

2.2.1 Tibial Insert Thickness

Design optimization was done by increasing the UHMWPE tibial insert from its original 14 mm to 16 mm, 17 mm, and 18 mm thickness, respectively. The sketch of the insert design remained similar, however it was then was pad into 16 mm, 17 mm and 18 mm. Note that the height of tibial post was remained constant. This phase was done to identify the effect of thickness on shear stress, total deformation and also contact pressure, especially at high flexion. Fig. 4 shows the minimum thickness of tibial insert in anterior view and lateral view of UHMWPE tibial insert.

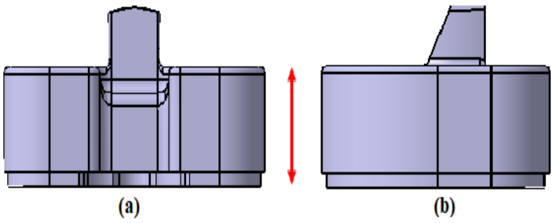


Fig. 4: The minimum thickness of tibial insert labeled with a red double arrow in (a) anterior view and (b) lateral view of UHMWPE tibial insert.

2.2.2 Average Conformity

This phase of optimisation was done by varying the average conformity values of TKA's designs. Conformity can be defined as the ratio of the radius of curvature of the femoral component to that the of the tibial polyethylene component and may be described in the sagittal and frontal plane [27]. Fig. 5 shows the radius of curvature of tibial condyle in frontal and sagittal views. Based on the definition of conformity value, RF/RT, the radius of tibial (RT) sagittal and frontal view was varied, while the radius of femoral (RF) in frontal and sagittal view was kept constant to obtain different conformity values. Table 5 shows the radius measurement of femoral condyle and tibial condyle, and the corresponding conformity values in both sagittal and frontal planes.

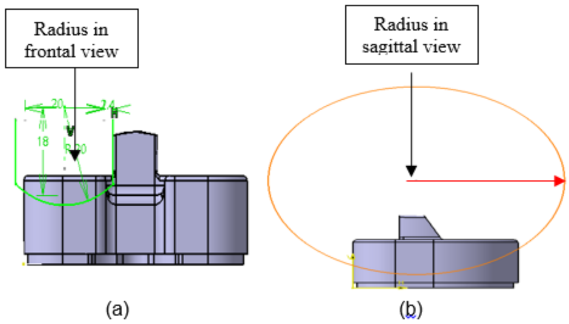


Fig. 5: (a) Radius of Tibial in frontal view (RTF) and (b) Radius of Tibial in sagittal view (RTS)

Table 5: The radius measurement and conformity values of the femoral and tibial insert in both sagittal and frontal plane

Model No	Radius of Femoral (mm)		Radius of Tibial (mm)		Conformity Values		Average conformity
	Sagittal	Frontal	Sagittal	Frontal	Sagittal	Frontal	
1	30	16	35	20	0.86	0.80	0.83
2	30	16	36	19	0.88	0.84	0.86
3	30	16	37.5	18.5	0.90	0.86	0.88

3. Results and Discussion

This study proposes tibiofemoral conformity to optimise the knee implant design. Fig. 6 shows the contact pressure at tibial insert versus angle of flexion for 0.83, 0.86 and 0.88 conformity values. It can be observed that the contact pressure increased with flexion angle. During knee flexion, tibiofemoral contact shifted from centre to posterior part of both medial and lateral condyles. Contact area decreased during such motion, led to increase in contact pressure apart from attribution of greater knee load during high flexion activity. Post-cam engagement of posterior-stabilized knee implant starts at 60 to 90 degree of flexion angle. Post-cam contact area is relatively smaller than tibiofemoral condylar contact area. This geometrical impact has also attributed to higher contact pressure during high flexion activities.

From Fig. 6, it can be seen during 165 degrees of flexion, peak contact pressure for 0.83 and 0.86 average conformity occurred in the posterior- medial region. For 0.88 average conformity, the peak contact pressure in the posterior-lateral region. Also, with the increase of average conformity, resulting in a decrease of contact pressure. This study is in agreement with the previous study by other researchers [28,29], whereas when average conformity increased from 0.83 to 0.88, the contact pressure in high flexion reduced from 53.854 MPa to 43.716 MPa. 14.14% reduction of contact pressure occurred when the average conformity increased from 0.83 to 0.86, and decrement of 5.465% of contact pressure happened when the average conformity increased from 0.86 to 0.88.

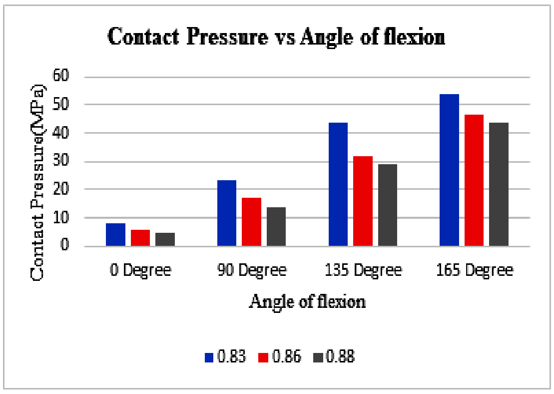


Fig. 6: Contact pressure (MPa) versus angle of flexion for 0.83, 0.86 and 0.88 conformity values

From Table 6 to Table 9, comparison of performance between original modification 3 and optimized modification 3 was reported. It can be found that via optimization, stress, and deformation of the knee implant in high flexion was successfully reduced. Total deformation reduced from 0798 mm to 0.352 mm. Equivalent von Mises reduced 75.313 MPa into 56.972 MPa, while contact pressure reduced from 73.974 to 43.716 MPa. Shear stress also exhibited a reduction from 37.913 to 29.185. Average conformity of 0.88 contributes to 55.9% reduction of total deformation, 24.4% reduction in von Mises stress, 40.9% for contact pressure and 23% for shear stress.

Table 6: Comparison performance between the original and optimised modification 3 based on total deformation and equivalent von Mises stress

Angle of flexion (degree)	Total Deformation (mm)		Equivalent Von Mises stress(MPa)	
	Original Modification 3	Optimised Modification 3	Original Modification 3	Optimised Modification 3
0	0.021	0.008	4.790	5.481
90	0.003	0.031	11.906	19.141
135	0.134	0.117	54.369	58.276
165	0.798	**0.352**	75.313	**56.972**

Table 7: Percentage of difference between the original and optimised modification 3 based on total deformation and equivalent von Mises stress

Angle of flexion (degree)	Total Deformation		Equivalent Von Mises stress	
	Percentage of Difference(%)		Percentage of Difference(%)	
0	61.9		14.4	
90	33.3		60.8	
135	12.7		7.2	
165	55.9		24.4	

Table 8: Comparison performance between the original and optimised modification 3 based on contact pressure and shear stress

Angle of flexion (degree)	Contact Pressure(MPa)		Shear stress	
	Original Modification 3	Optimised Modification 3	Original Modification 3	Optimised Modification 3
0	3.086	4.685	1.808	1.322
90	6.388	13.627	3.072	3.965
135	61.149	28.771	15.791	18.693
165	73.974	**43.716**	37.913	**29.185**

Table 9: Percentage of difference between the original and optimised modification 3 based on contact pressure and shear stress

Angle of flexion (degree)	Contact Pressure		Shear stress(MPa)	
	Percentage of Difference(%)		Percentage of Difference(%)	
0	51.8		26.9	
90	53.1		29.1	
135	52.9		7.5	
165	40.9		23.0	

The results of present study confirm the findings by prior researchers. Previous finite element studies have reported that with proper alignment of the component, stress can be reduced with the increased of average conformity [30]. Previous research also has proven that decreased in conformity may lead to high contact stresses at tibial insert that can exceed the yield strength of polyethylene [31].

4. Conclusion

The present work aims to optimize a knee implant design that able to extend the flexion angle up to 165^{o}. From the finite element analysis, the knee implant design has been improved. The design improvement has successfully reduced the stress induced at UHMWPE tibial insert. This study proves that the deep flexion up to 165 degree for knee implant is still feasible with the optimisation at the critical part of the implant which directly involves in high flexion motion.

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