Design for Additive Manufacturing and Finite Element Analysis for High Flexion Total Knee Replacement (TKR)

Solehuddin Shuib, Mohammad Arsyad Azemi, Iffa Binti Mohd Arrif, Najwa Syakirah Hamizan*
Faculty of Mechanical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia.
**solehuddin2455@uitm.edu.my*

ABSTRACT

The patient from the Asian region always demanded a fully functional knee implant, which implied a high-flexion range of motion. Most of their daily life activities utilized the deep knee flexion which flexed until 165° such as the Japanese proper sitting style and Muslim prayer position. The problem of the study is extending the range of motion or achieving the high flexion of total knee replacement as the traditional total knee replacement was incapable to achieve more than 115°. Hence, the purpose of this study is to achieve a modified design of a knee implant that can flex up to 165° by carried out a static structural analysis in the ANSYS R16. There are 0°, 90°, 135°, and 165° angles of flexion with a different net force based on the percentage of body weight implemented on the knee implant. The analysis includes total deformation, Von Mises stress, shear stress, and contact pressure on knee implant were observed and compared to find better modification design. The total deformation had been decreased by about 69% at 0° flexion, 58.5% at 90° flexion, 90.93% at 135° flexion. The contact pressure also had been decreased by about 99.2%, 22.2%, 99.98% at angle flexion of 0, 90, and 135, respectively. The same declination happened to von Mises stress at about 85.05%, 9.52%, and 88.04% at the same angle of 0, 90, and 135, respectively.

Keywords: *Total knee replacement; High flexion; Finite element analysis; Additive manufacturing*

ISSN 1823-5514, eISSN 2550-164X

Received for review: 2020-11-02
Accepted for publication: 2021-02-19
Published: 2021-04-15

Introduction

The human knee joint is some of the most complex joints in the human body that can be divided into soft tissues and body structure. The soft tissues consist of tendons, menisci, muscles, and articular cartilages. While the bony structure includes the femur, tibia, fibula, and patella [1]. The knee joint bearing remarkably high loads as mostly human body weight are supported by it to do active movement such as walking, sitting, running, and kneeling for daily activities. Injury and damage to knee joints are bound to happen because of an accident and playing sports that can cause fractures, dislocations, and posterior cruciate ligament tears. Besides that, there is also disease due to inflammation of the knee joint namely arthritis. If nonsurgical treatment such as taking medications and walking using supports are no longer bearable, total knee replacement surgery should be considered [2].

Total knee replacement (TKR) is to replace a knee joint with artificial material by conducting a surgical procedure. This surgery and post-treatment are needed to relieve pain and to restore knee functionality. Squatting and kneeling are common activities that require normal flexion beyond 90°. As the development of surgical technique, implant designs, and available biomaterials have improved through the years, patients who undergo total knee replacement can achieve more than 100° of knee flexion and sometimes able to do squatting and kneeling [3]. However, the extent of the range of motion for deep flexion is required in young and active individuals in Asian countries. Besides, mostly Asian and Middle Eastern countries are required to bend their knee up to 165° for deep flexion to do their cultural and religious activities [4][5]. For instance, in Japanese culture, Seiza-sitting is a traditional practice of sitting in attending a tea ceremony. While for the Muslim religion, several positions required deep flexion to perform prayer.

Nevertheless, additive manufacturing (3D printing) is necessary to develop a knee joint with deep flexion as it is cost-effective and time-efficient to produce low volume and complex 3D implants [6]. This recent technology can assist in developing deep flexion of the knee joint with several modifications of designs and analysis. Besides that, additive manufacturing also helps to guide orthopedic surgeons to understand and plan their approach before beginning the operations as it can produce bone models rapidly [6].

Therefore, a suitable design of total knee replacement should be considered to fabricate and assist by additive manufacturing as well as to ensure the knee implant is fully functional in flexing to different angles. The main objective was to achieve a modified design of deep flexion of total knee replacement by implementing finite element analysis and fabricate the prototype of the 3D implant by using additive manufacturing such as fused deposition modeling (FDM).

Materials and Methods

A few types of knee implant designs were collected using the Pugh chart to acknowledge their range of motion referred to in Table 1 before started with the design modifications.

Table 1: Pugh chart

Description			Cruciate Retaining (CR)	Posterior Stabilized (PS)	Mobile Bearing
Criteria	Weight	Datum	Design 1	Design 2	Design 3
Range of Motion	3	0	+	+	+
Stability	2	0	+	+	-
Load Transfer	1	0	+	+	0
Biocompatibility	1	0	0	0	0
Wear Resistance	1	0	-	-	0
Ease of surgery	2	0	0	+	0
Risk of injury	2	0	-	-	0
+			6	8	3
0			2	1	5
-			3	3	2
Net Score			3	5	1

Posterior Stabilized was chosen because it scored the highest compared to other designs. As well as contains an increased range of motion, a more stable component interface, and less technically demanding procedure [7]. The design of this project is modeled by using average dimensions of Chinese male that represent Asian knee male's community from Bing Yue et al. [8] study, that consists of femoral measurement and tibial measurement.

Design modifications

There were three designs to be analyzed consist of the first design was based on the standard total knee replacement that exists in the market as shown in Figure 1(1). The second and third designs were modified to achieve 165° flexion as shown in Figure 1(2) and Figure 1(3) respectively. These modifications were based on NexGen Legacy LPS-Flex Knee produced by Zimmer Incorporated in the year 2016 [9].

The second modification was an increase in cam height. The greater jump height is to prevent tibiofemoral disassociation during flexion from 120° to 155°. In some posterior stabilized knees, as the knee goes into deeper flexion, the cam on the femoral component begins to move superiorly on the spine of the tibial articular surface. To address this, the shape of the cam on the LPS-Flex Femoral Component has been modified to contact the spine more inferiorly and thereby provide a greater jump height at flexion angles greater than 130°.

The third modification was the anterior flange of the femoral component has a larger deeper cut out to provide increased conformity for patella-femoral tracking and the anterior lip of the polyethene has a cut out for the patellar tendon. The difference between second and third design was the rotation in the tibial platform can significantly reduce contact stresses compare to fix the tibial platform. Furthermore, a study shows that there is a limited axial rotation during a setup motion, thereby giving advantages to mobile-bearing knee prostheses as it can be functional as an actual knee.

Figure 1: Three designs of total knee replacement.

Design analysis

These designs were modelled using SolidWorks 2017 software and imported to ANSYS R16.0 software. Titanium alloy was assigned for the femoral and tibial component. Ultra-High-Molecular Weight Polyethylene (UHMWPE) is the material for the tibial insert. The properties of these materials are shown in Table 2.

Table 2: Properties of material

Material	Poisson Ratio	Young Modulus (MPa)
Titanium Alloy	0.36	96000
Polyethylene	0.42	1100

Afterwards, the knee implant undergoes meshing set with adaptive size function, course relevance centre and element size of 1.50 mm as shown in Figure 2.

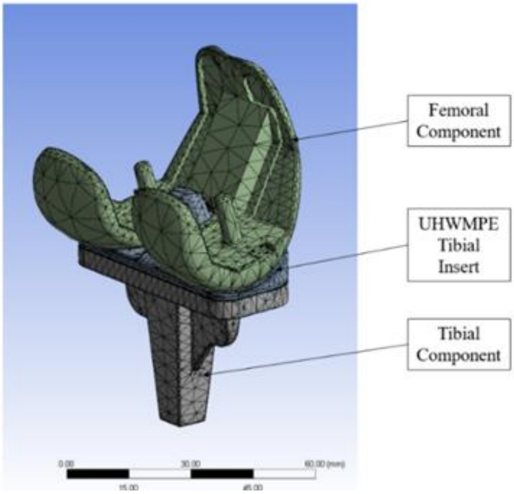


Figure 2: Meshing of the finite element model.

In this analysis, four different angles of flexion were used. The chosen angle is based on the most common daily activities done by Asian. The four angles of flexion are 0°, 90°, 135° and 165° of flexion that represent for standing, squatting, kneeling and sitting on feet position respectively. Each of these positions was applied with the force of certain magnitude.

The location of the applied force plays an important role in how it will affect the distributed forces and contact pressure around the femoral implant, and it is dependent on the angle of flexion used. The boundary condition is set as a fixed support feature at the base of the tibial tray. Then, the loading force applied vertically downward on the z-axis. The weight of 66.5 kg which equivalent to 652.365 N has been considered to apply during this analysis. This average weight (range 49-80 kg) is based on 100 patients with osteoarthritis who underwent knee replacement surgery in Malaysia [10]. Every position will have different net force produced in conjunction with the percentage of body weight [3]. Table 3 illustrates the position of the knee joint for different positions and Table 4 shows the net force applied on the knee joint with different flexion angle.

Table 3: Loading condition for each position

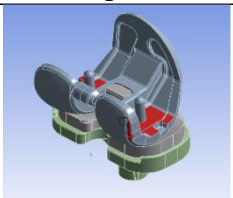
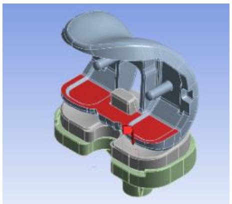
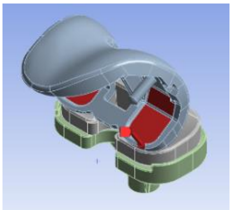
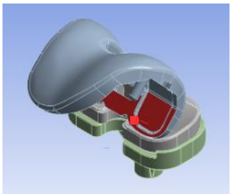
Angle (°)	Position	Loading of force
0	Stand	
90	Kneel	
135	Squat	
165	Sit on feet	

Table 4: The net force applied with different flexion angle

Angle (°)	0	90	135	165
Net force (N)	0.5×65.5kg = 326.18 N	1.2×65.5kg = 782.84 N	5.3×65.5kg = 3475.54 N	6.0×65.5kg = 3914.19 N

Design for additive manufacturing

Fused deposition modelling (FDM) was chosen to produce a prototype as this additive manufacturing is low-cost prototyping that considered more in form and fit rather than functionality. Moreover, FDM extrudes a thermoplastic one layer at a time onto a build plate. However, printed large parts can lead to large variations in temperature across the build platform as different areas of the part cool at different rates of internal stress [11]. This can cause the model printed to deform and leads to warping or shrinkage. The dimensional tolerance was determined to avoid shrinkage which is about ±5 mm.

The chosen 3D FDM machine is Flashforge Guider II as shown in Figure 3. Its uniqueness is the closed surrounding box which allows the temperature to control more efficiently. The slicing software for Flashforge is called FlashPrint. This software is used to convert a 3D object model to specific instructions for the printer. In the slicing process, many additional features need to be determined. One of them is enabled to generate support when the model overhangs greater than 45°. Other features such as infill density and layer thickness affect the strength of the printed part [12]. Moreover, controlling the printing speed can manipulate the time but the quality will be affected too. Adhesion parameter such as brim, raft and skirt is used to prevent warping and helps in bed adhesion. Therefore, the total knee replacement must be strong enough without sacrificing the quality of the surface. Table 5 shows the features and parameters used in the slicer.

Figure 3: Flashforge Guider II [13].

Table 5: Slicer features and parameters

Features	Parameters
Infill density	30%
Infill pattern	Hexagon
Filament material	PLA
Printing speed	50%
Type of adhesion	Brim
Enable support	Enable when exceeding 45°
Layer height	0.2 mm
Printing time	9 hours 54 minutes
Estimated weight	112.81 g

Results and Discussion

This study proposes to achieve a modified design for deep flexion total knee replacement which can flex up to 165° by using finite element analysis. The results of the analysis are total deformation, Von Mises stress, shear stress in XY, and contact pressure. Total deformation can be defined as a change in length or shape depends on the type of material when the forces applied to the object. This parameter is used to show any change for femoral and tibial insert parts with two different materials when the forces were applied. Table 6 shows the analysis of total deformation for original design 1, and modification design 2 and design 3. The modification can be seen increases whenever the angle goes to deeper flexion. Thus, when the angle is deeper into flexion, the area decreases too. When the area is small, the deformation becomes bigger.

Table 6: Result analysis of total deformation (mm)

Angle (°)	Original design 1	Modification design 2	Modification design 3
0	0.007	0.0020443	0.043817
90	0.119	0.28785	0.4229
135	7.011	0.63615	3.9646
165	Cannot flex	2.55520	6.5570

The Von mises stress is a yielding criterion, widely used for metals and other ductile materials. It used to predict the materials yielding under loading applied to determine parameters such as Young’s Modulus, yield strength, ultimate strength, elongation at break and Poisson's ratio. It states that yielding will occur in a body if the stress components that affect it exceed the criterion [14]. Therefore, if the stress of Von Mises exceeds the basic tension yield limit stress, it is predicted that the material yields. Table 7 shows the analysis of Von Mises stress for original design 1, and modification design 2 and design 3.

Table 7: Result analysis of Von Mises stress (MPa)

Angle (°)	Original design 1	Modification design 2	Modification design 3
0	6.87	1.03	4.54
90	34.91	31.59	22.75
135	612.01	73.17	64.45
165	Cannot flex	206.20	180.80

Table 8: Yield strength of the materials

Material	Yield Strength (MPa)
Titanium Alloy	930
Polyethylene	25

Table 8 shows the yield strength for titanium alloy and polyethylene materials. When it reached 90°, the polyethylene starts to yield refer to Table 7. To what extend it will yield is based on the the total deformation values in Table 6. The titanium alloy's yield strength is far stronger, therefore no deformation occurred at the tibial and femoral components.

Table 9: Result analysis of shear stress in XY (MPa)

Angle (°)	Original design 1	Modification design 2	Modification design 3
0	1.11	0.42	2.058
90	9.08	10.26	10.024
135	95.44	26.66	14.583
165	Cannot flex	28398.00	64.794

Table 9 shows the analysis of shear stress in the XY plane for original design 1, and modification design 2 and design 3. Shear stress can be referred to as a force applied to tend to cause deformation to the object by slippage along planes parallel to the imposed stress. The infected areas show that they become smaller when the angle reaches deeper flexion. Hence, the shear stresses are increases because the contact area is inversely proportional to the shear stress.

Table 10: Result of analysis of contact pressure (MPa)

Angle (°)	Original design 1	Modification design 2	Modification design 3
0	67.60	0.55	6.11
90	33.74	43.37	32.42
135	375000.00	90.30	136.36
165	Cannot flex	791.47	452.72

Table 10 shows the analysis of contact pressure for original design 1, and modification design 2 and design 3. The contact pressure created when two objects touch with force applied over the surface of the object. Hence, the higher the angle of flexion, the higher the values of deformation, stresses and pressure. These happen because, at 165° flexion, the surface area of femoral intact to the tibial insert is very small, thus produces very high pressure. Moreover, it obeys Pascal's law refer in Equation (1).

$$Pressure = \frac{Force}{Area} \tag{1}$$

As mentioned before, standard knee replacement (design 1) cannot achieve high flexion due to its design. Furthermore, at flexion angle of 135°, design 1 produces the highest values in total deformation = 7.011 mm, Von mises stress = 612.01 MPa, shear stress = 95.44 MPa and contact pressure = 37500 MPa. These happen due to short posterior femoral condyles or small contact area. It proves that the large posterior femoral condyles provide more contact area, hence reduces the deformation, stresses and pressure. Table 11 shows the percentage difference between the original design 1 and modification design 2. Majority of the values on the modification design 2 are lower than the original design 1.

Table 11: Percentage difference between original design 1 and modification design 2

Angle (°)	Total Deformation (%)	Von Mises Stress (%)	Contact Pressure (%)
0	69	85.05	99.2
90	58.5	9.52	22.2
135	90.93	88.04	99.98

Table 12: Percentage difference between modification design 2 and design 3

Angle (°)	Total Deformation (%)	Von Mises Stress (%)	Contact Pressure (%)
0	95	77.39	91.02
90	31.9	27.97	25.25
135	83.95	11.93	33.78
165	61.03	12.32	42.8

Table 12 shows the percentage difference for modification design 2 and design 3. Between design 2 and design 3, there are some tight competition but the differences between these two designs are unconstrained and constrained tibial platform. Moreover, results for design 3 are much better in most cases when comparing with design 1. However, comparing to design 1 and design 2, both results are divided into two sides and distributes equally with each other. The project was carried out in static analysis, so when comparing unconstrained and constrained tibial platform, it is more relevant to apply dynamic analysis since it involves movement in cylindrical motion. Also, there are many studies about comparing fix bearing and rotating bearing prosthesis that shows rotating bearing prosthesis increases the contact area, reduces load and improve in the motion of the knee [15][16][17]. Therefore, it is safe to say that design 3 is more practical and applicable than design 2 since design 3 constrain the rotation about 5° to 10°.

To achieve high flexion knee motion, some risks are suspected to happen such as post-fracture tibial inserts and polyethylene wear will increase whenever an overload occurs during high flexion knee motion [18]. Hence, carefully follow up of the patients are needed before more complications happen. The objective of this project can be achieved as it is to study the feasibility of high flexion knee using finite element analysis. However, the study has a few limitations which are first, the study was the only simulation and not in-real situation case. Secondly, the analysis considers only a few boundary conditions that are limited to software capability [19]. Lastly, the analysis was done in static analysis whereas dynamic analysis is more practical. Therefore, further analysis needs to be done by considering real knee simulation, more boundary conditions and to implement the dynamic analysis.

Figure 4 shows from the left design 1, design 2 and design 3 printed using fused deposition modelling (FDM) which is Flashforge Guider II. The print settings from Table 5 produces fine TKR parts. They have a particularly good dimensional accuracy and high-quality surface. Post-processing such as rubbing with sandpaper is needed to remove the strings and smoothen some rough areas. The supports need to be removed by using scalpel and chisel. This method of additive manufacturing has the advantage of manufacturing objects with complex free form geometry, which is impossible using traditional methods of subtractive manufacturing [20][21]. In short, 3D printed patient-specific implant (PSI) is possible to be fabricated using FDM.

Figure 4: 3D printed of TKR using FDM.

Conclusion

This study aims to achieve a modified design of total knee replacement that able to extend the angle of flexion up to 165°. By implementing finite element analysis, the modified design of knee implant has been improved. The modified design has reduced total deformation, stresses and pressure successfully from the original design. This study proves that high flexion up to 165° of total knee replacement is still applicable and feasible by modifying the design at the crucial part of the knee implant.

Acknowledgement

This work is supported by the Strategic Research Partnership (SRP) under Research Grant 100-RMC 5/3/SRP PRI (022/2020).

References

[1] R. Vaishya, V. Vijay, A. Vaish, and A. K. Agarwal, "Computed tomography based 3D printed patient specific blocks for total knee replacement.," *J. Clin. Orthop. trauma*, vol. 9, no. 3, pp. 254–259, 2018.

[2] M. H. Seman, S. Shuib, M. Afzan, and A. A. Shokri, "Design and Analysis of High Flexion Femoral Component for Total Knee Arthroplasty (TKA)," *Int. Journal of Engineering and Technology*, vol. 7, no. October, pp. 381–385, 2018.

[3] T. Nagura, C. O. Dyrby, E. J. Alexander, and T. P. Andriacchi, "Mechanical loads on the knee joint during deep flexion," *Am. Soc. Mech. Eng. Bioeng. Div. BED*, vol. 50, pp. 393–394, 2001.

[4] Y. Niki, Y. Takeda, K. Udagawa, H. Enomoto, Y. Toyama, and Y. Suda, "Is greater than 145 ° of deep knee flexion under weight-bearing conditions safe after total knee arthroplasty ?," *Bone joint Journal*, no. March, pp. 782–787, 2010.

[5] J. A. McClelland, J. A. Feller, H. B. Menz, and K. E. Webster, "Patients with total knee arthroplasty do not use all of their available range of knee flexion during functional activities," *Clin. Biomech.*, vol. 43, pp. 74–78, 2017.

[6] G. G. Jones, S. Clarke, M. Jaere, and J. Cobb, "3D printing and unicompartmental knee arthroplasty," *EFORT Open Rev.*, vol. 3, no. 5, pp. 248–253, 2018.

[7] F. R. Kolisek *et al.*, "Posterior-stabilized versus posterior cruciate ligament-retaining total knee arthroplasty.," *Iowa Orthop. J.*, vol. 29, pp. 23–27, 2009.

[8] B. Yue, K. M. Varadarajan, S. Ai, T. Tang, H. E. Rubash, and G. Li, "Differences of Knee Anthropometry Between Chinese and White Men and Women," *J. Arthroplasty*, vol. 26, no. 1, pp. 124–130, Jan. 2011.

[9] G. Guild III, MD and S. Labib, MD, "Range of Motion In High Flexion Total Knee Arthroplasty vs. Standard Posterior Stabilized Total Knee Arthroplasty A Prospective, Randomized Study," *Reconstr. Rev.*, vol. 3, no. 1, 2013.

[10] A. H. Z, M. O, and G. Ruslan, "Total Knee Replacement: 12 Years Retrospective Review and Experience," *Malaysian Orthop. J.*, vol. 5, no. 1, pp. 34–39, 2011.

[11] "Dimensional accuracy of 3D printed parts | 3D Hubs." [Online].

Available: https://www.3dhubs.com/knowledge-base/dimensional-accuracy-3d-printed-parts/. [Accessed: 16-Jun-2020].

[12] J. Fernandes, A. M. Deus, L. Reis, M. F. Vaz, and M. Leite, "Study of the influence of 3D printing parameters on the mechanical properties of PLA," *Proc. Int. Conf. Prog. Addit. Manuf.*, vol. 2018-May, no. August, pp. 547–552, 2018.

[13] "Guider IIs - FlashForge." [Online]. Available: https://www.flashforge.com/product-detail/11. [Accessed: 28-Oct-2020].

[14] H. Altenbach, "Book Review: Armenàkas, A. E., Advanced Mechanics of Materials and Applied Elasticity," *J. Appl. Mathematics Mech.*, no. 86(9), pp. 681–681, 2006.

[15] E. H. Garling, B. L. Kaptein, R. G. H. H. Nelissen, and E. R. Valstar, "Limited rotation of the mobile-bearing in a rotating platform total knee prosthesis," *J. Biomech.*, vol. 40, no. SUPPL. 1, 2007.

[16] G. Solarino, M. Carrozzo, G. Vicenti, and B. Moretti, "Joints Long-term outcome of low contact stress total knee arthroplasty with different mobile-bearing designs," *Joint*, vol. 2, no. 3, pp. 109–114, 2014.

[17] A. Causero, P. Di Benedetto, A. Beltrame, R. Gisonni, V. Cainero, and M. Pagano, "Design evolution in total knee replacement: which is the future?," *Acta Biomed.*, vol. 85, pp. 5–19, 2014.

[18] J. Victor, J. K. P. Mueller, R. D. Komistek, A. Sharma, M. C. Nadaud, and J. Bellemans, "In vivo kinematics after a cruciate-substituting TKA," *Clin. Orthop. Relat. Res.*, vol. 468, no. 3, pp. 807–814, 2010.

[19] C. K. Cheng *et al.*, "Biomechanical considerations in the design of high-flexion total knee replacements," *Sci. World J.*, vol. 2014, 2014.

[20] M. J. Rowe and M. Crane, "3D-printed patient-specific applications," *Orthop. Res. Rev.*, no. August, pp. 57–66, 2008.

[21] M. Javaid and A. Haleem, "Additive manufacturing applications in medical cases: A literature based review," *Alexandria J. Med.*, vol. 54, no. 4, pp. 411–422, 2018.