International Journal of Technology 12(6) 1312-1322 (2021)
Received August 2021 / Revised October 2021 / Accepted December 2021

International Journal of Technology

http://ijtech.eng.ui.ac.id

Evaluation of the Contact Area in Total Knee Arthroplasty Designed for Deep Knee Flexion

Joko Triwardono[1,2], Sugeng Supriadi[1*], Yudan Whulanza[1], Agung Shamsuddin Saragih[1], Deva Ariana Novalianita[1], Muhammad Satrio Utomo[2], Ika Kartika[2]

[1]*Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus Ui Depok, Depok 16424, Indonesia*
[2]*National Research and Innovation Agency, Banten 15314, Indonesia*

Abstract. Total knee arthroplasty (TKA) implants are becoming an interesting subject in implant design research and development activities due to their complexity. They should be able to facilitate knee movement while supporting body weight during daily usage. Meanwhile, incidents such as hyperflexion in TKA implants outside their designated configuration can lead to subluxation and dislocation in this study, a polyethylene component of a posterior-stabilized right knee joint implant was developed to facilitate a high range of motion (ROM). Finite element analysis (FEA) was used to analyze the contact area on the polyethylene component. FEA was used to simulate weight-bearing conditions at 0°, 30°, 60°, 90°, 120°, and 150° of knee flexion. The modified polyethylene component resulted in better performance in terms of contact area, especially at 120° of knee flexion. The two dominant contact areas on the polyethylene component were 733 mm^2 at 0° of knee flexion and 576 mm^2 at 120° of knee flexion. Furthermore, the current design of the polyethylene component can maintain a contact area of 65 mm^2 at 150° of knee flexion. The current design is expected to accommodate deep knee flexion movement in daily activities and reduce the possibility of subluxation and dislocation at the polyethylene component during deep knee flexion. In addition, a large contact area can reduce the potential wear on or fracture of the polyethylene component. Finally, the result of FEA was validated using a simulator of knee kinematic motion; there was no indication of subluxation and dislocation at any degree of knee flexion.

Keywords: Dislocation; Finite element analysis; Hyperflexion; Polyethylene; Subluxation; Total knee arthroplasty

1. Introduction

Fiber- Knee replacement surgery or total knee arthroplasty (TKA) for the treatment of chronic degenerative pathologies of the knee has been a successful method for 60 years. During this period, the collaboration between surgeons and engineers has resulted in many developments in prosthesis design (Karczewski et al., 2021). For example, the first TKA allowed a single degree of freedom, but now TKA offers multiple degrees of freedom (Murray, 1928). Almost all TKAs performed in the United States and Europe have a range of motion (ROM) of 120° for knee flexion. This satisfies the inhabitants of the West, as it accommodates the range of motion required for most of their daily activities. However, this

*Corresponding author's email: sugeng@eng.ui.ac.id, Tel.: +62-81218270800
doi: 10.14716/ijtech.v12i6.5193

is not true for people in East Asia and the Middle East, whose sociocultural background varies greatly, as does their normal range of joint motion. This therapy is frequently refused because the resulting ROM is restricted (Villar et al., 1989). Squatting is used to perform activities on the toilet or just to rest, and it can easily be done for hours (Ahlberg et al., 1988). A cross-legged sitting posture is popular in many regions of Asia for eating on the floor as well as for informal activities such as chatting. Furthermore, kneeling is a popular practice among Muslims during prayer as well as among Japanese people during traditional rituals. For example, it has been reported that Saudi men have a knee flexion difference of more than 15° compared to Scandinavians (Hefzy et al., 1998). Most of the population in the Middle East routinely bend their knees to 165°. At prayer, most Muslims kneel with their limbs fully extended (between 150° and 165°) and with the shaft of the heel erect, reaching the posterior surface of the upper thigh. Since most commercial TKAs available today are not designed to achieve knee flexion of more than 120°, commercial TKAs do not meet the needs of patients in predominantly Muslim countries and Asian countries who practice traditional kneeling and sitting poses. In addition, differences in morphometry data between populations around the globe require a specific implant design for each population (Utomo et al., 2019). Hyperflexion outside the design configuration of implants are can lead to subluxations and dislocations (Li et al., 2004).

According to Thiele et al. (2015), some causes for revising the design of total knee arthroplasty are aseptic loosening (34.7%), instability (18.5%), and polyethylene wear (18.5%) (Thiele et al., 2015). These failure mechanisms have been associated with thin polyethylene (Pijls et al., 2012; Massin, 2016; Garceau et al., 2020; Presti et al., 2020; Crawford et al., 2021; Tzanetis et al., 2021). Polyethylene wear may result in osteolysis and the subsequent loosening of the components (Pijls et al., 2012; Massin, 2016). A significant amount of contact stress in the posterior post region might explain polyethylene wear and fracture in posterior-stabilized (PS) TKA (Nor Izmin et al., 2020; Garceau et al., 2020; Crawford et al., 2021; Tzanetis et al., 2021). Therefore, it is necessary to be prepared for patient management following possible knee implant failure.

Finite element analysis (FEA) is a versatile tool for studying the contact area during the design of the polyethylene component (Ahmad et al., 2020). Evaluation by FEA of the contact area on the polyethylene component, particularly in the posterior region of the post, may assist in avoiding issues that develop after TKA. In previous studies (Ishikawa et al., 2015; Tanaka et al., 2016; Zhang et al., 2017; Azam et al., 2018; Kang et al., 2018; Tanaka et al., 2018), an FEA of weight-bearing deep knee flexion was performed for 0° to 120° of knee flexion. In this study, FEA was performed for 0° to 150° of knee flexion.

In this study, the polyethylene component of posterior-stabilized right knee joint prostheses was developed from the benchmark product. Benchmarking is a systematic method or process of measuring product performance by comparing it with products from other companies that are considered the best in the same industry. Vanguard Posterior Stabilized Knee Zimmer Biomet was used as benchmark in this study. FEA was used to measure the contact area on the polyethylene component. We hypothesized that the geometric modification of the polyethylene component could improve the contact area and increase the distribution of contact stress; this may reduce subluxation and dislocation at the polyethylene during deep knee flexion and minimize the risk of implant failure.

2. Methods

2.1. Geometry and Numerical Setup

Existing three-dimensional (3D) benchmark models were used to construct the polyethylene component of the knee joint prosthesis. A 3D-scanner was used to gather point and line data that was then imported into Mimics (version 22.0, Materialize, Leuven, Belgium) software for modification. The benchmark's post, medial, and lateral surface curvatures were processed and imported to be developed using the Solidworks 2020 program, as shown by the flowchart of the method in Figure 1.

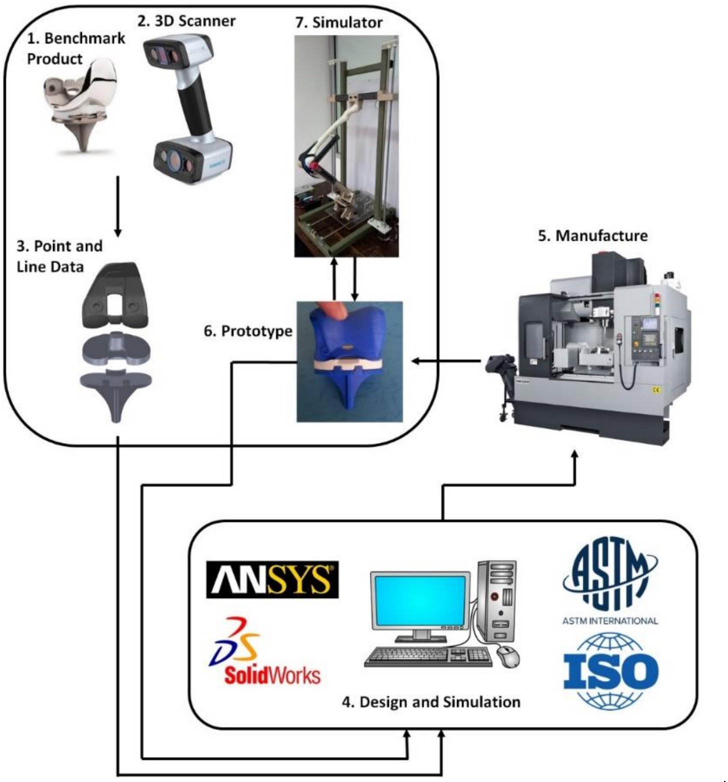

Figure 1 The flowchart of the method

Initially, the post, medial, and lateral surface curvature geometry was obtained from the benchmark, as shown in Figure 2. The polyethylene was modified to create a design that increased the contact area at knee flexion beyond 90°. The polyethylene post was transformed from a rectangle to a cylinder 17.4 mm in diameter, and the posterior post was rounded to an 8 mm radius, as shown in Figure 3. The goal was to increase the contact area between the posterior post and the cam femur when flexion was greater than 90°.

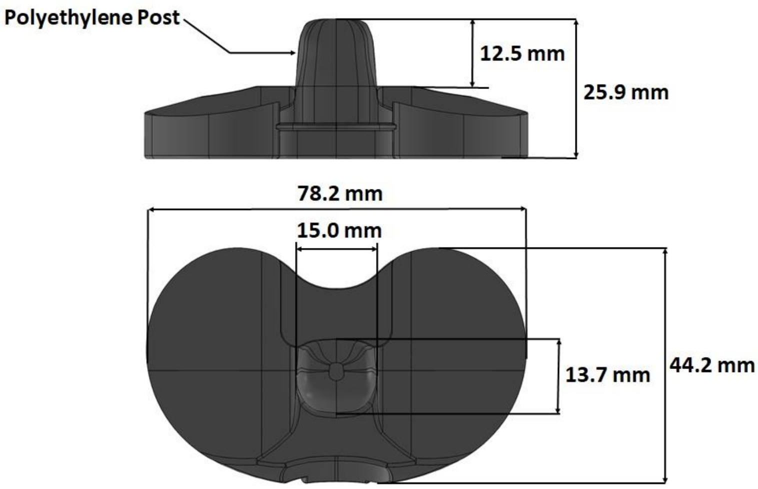

Figure 2 Schematic diagram of the geometr of the benchmark polyethylene model

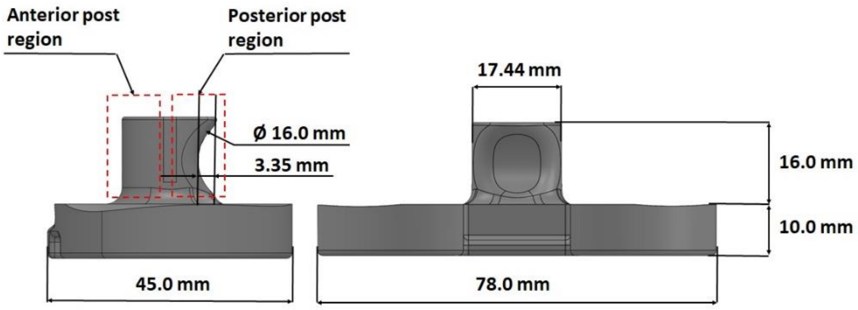

Figure 3 Schematic diagram of the geometry of the modified polyethylene model

FEA was used to simulate the behavior of the polyethylene component under mechanical force for a bent knee. The femoral component and the tibia component were positioned perpendicular to the mechanical axis of the knee. The distal anatomical axis of the femur was aligned with the femoral component (Kuriyama et al., 2014). It was determined that the posterior slope was zero when the component was oriented to the anterior anatomical plane of the tibia (sagittal alignment), as shown in Figure 4. The femoral epicondylar axis and the anteroposterior tibial axis were used to perform the neutral rotational alignments of the femoral and tibial components, respectively.

In the FEA simulation parameters, a continuous vertical force on the femoral component equal to a bodyweight of 80 kg was transformed into a 4-kN (five times the bodyweight) stress on the knee's bicondylar joint (Kuriyama et al., 2014; Ishikawa et al., 2015; Tanaka et al., 2016; Tanaka et al., 2018). The Ansys Workbench was used to perform the FEA simulations. Both the polyethylene and the femoral component were designed as rigid bodies. The femoral component's Young's modulus was set at 78 GPa, which is comparable with data for an stainless steel 316L alloy (Sulong et al., 2016). The polyethylene component was made as described in previous research (Kurtz et al., 1999). It was made of Ultra High Molecular Weight Polyethylene (UHMWPE), a nonlinear elastoplastic material American Standard Testing Material (ASTM) D 4020, with an average molecular weight greater than 3.1 million g/mol. Poisson's ratio was calculated to be 0.46. The first mesh sensitivity study was conducted in a polyethylene model with an mesh element size of 1.0 mm.

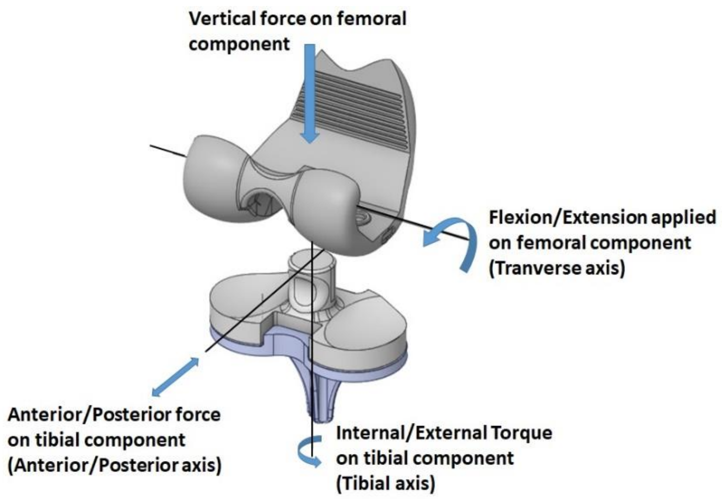

Figure 4 The mechanical arrangement for the knee simulator machine

The femoral component and polyethylene mesh were created using a 10-node quadratic tetrahedral mesh. The produced mesh had 16,448 femoral condyle nodes and

14,557 polyethylene nodes, 8,837 elements for the femoral condyle and 8,132 elements for polyethylene. FEA was used to simulate weight-bearing deep knee bend measurements at 0°, 30°, 60°, 90°, 120°, and 150° of knee flexion. The contact area was calculated by dividing the continuous vertical force on the femoral component by the average von Mises stress on the polyethylene surface. Visual observation validated the results of the simulation performed by the simulator of the knee's kinematic motion.

2.2. Validation of the Experimental Setup

The results of the FEA were validated using a simulator of the knee's kinematic motion (Walker et al., 1997). This tool simulated motion on three axes of movement and one axis of rotation, as illustrated in Figure 5. The X axis, for the rotation of the tibia, had a rotation range of ±15°. The Y axis was for the anterior posterior movement of the tibial component. The Z axis was for the transverse movement of the femoral component. The W axis was for the medial lateral movement of the femoral component.

The modified knee implant prototype was made using a 3D-printer machine attached to the femur bone and tibia bone, which duplicated the adult right leg bones. Photograph was taken at angles of 30°, 60°, 90°, 120°, and 150° and yielded medial views, lateral views, and posterior views.

Figure 5 The simulator of the knee's kinematic motion

3. Results

3.1. FEA Results

The FEA results for the tibiofemoral joint are shown in Figure 6 and Table 1. The largest contact area on the polyethylene was 733 mm^2 at 0° of knee flexion and 576 mm^2 when the knee was bent at 120°. The minimum contact area on the polyethylene was 65 mm^2 at 150° of knee flexion. The maximum of average contact stress on the polyethylene was 30.5 MPa at 150° of knee flexion. The minimum average contact stress on the polyethylene was 2.7 MPa when the knee was straight and 3.4 MPa at 120° of knee flexion. The contact area on the polyethylene was greatest at 0° of knee flexion and it decreased as knee flexion increased. The contact area on the polyethylene was inversely proportional to the average contact stress on the polyethylene. The average contact stress on the polyethylene was increasing from 0° to 150° of knee flexion.

The posterior post region contacted the femoral cam during knee bends at 60° to 150° of knee flexion. At approximately 60°, the posterior post region contacted the femoral cam. At 90° of knee flexion, the contact area of the posterior post region was at its largest. At 30°

of knee flexion, the contact area of the anterior post region was minimal, as shown in Figure 6. There is no contact in the anterior post region during any flexion variation.

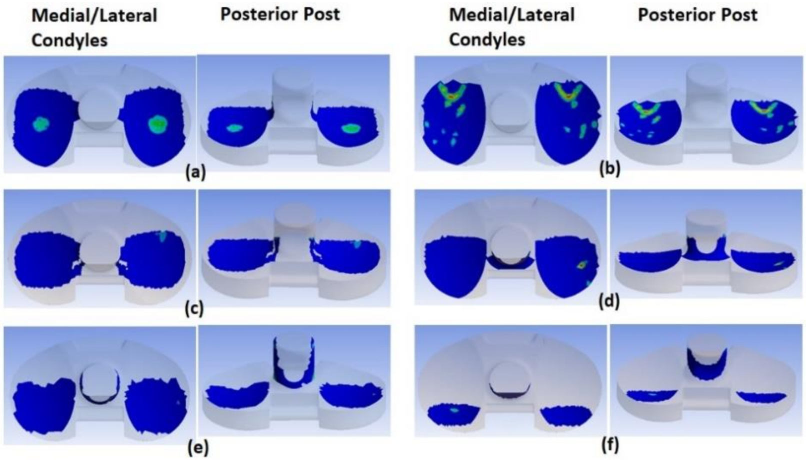

Figure 6 The simulated on the polyethylene component under variations in flexion: (a) 0°, (b) 30°, (c) 60°, (d) 90°, (e) 120°, and (f) 150°

Table 1 The contact areas from the calculation of the average contact stress (in MPa) on the polyethylene component under variations in flexion from 0° to 150°

	0°	30°	60°	90°	120°	150°
Average Stress (MPa)	2.72	9.16	3.91	4.26	3.47	30.55
Contact Area (mm^2)	733	218	510	469	576	65

Table 1 shows that, at 150° of knee flexion, contact areas of greater than 60 mm^2 were measured at the polyethylene when a 4-kN force was applied. These results indicate that by using the present designs of TKA, significant contact on the polyethylene at 150° knee flexion may occur because the modified polyethylene component is expected to accommodate high flexion in daily activities and reduce the possibility of subluxations and dislocations at the polyethylene during deep knee flexion. A larger contact area can reduce potential wear on or fracture of the polyethylene. However, the contact area at the polyethylene is largest at 120° knee flexion.

3.2. Validation

At 30° of flexion using the kinematic motion simulator, there was no contact on the posterior post region.

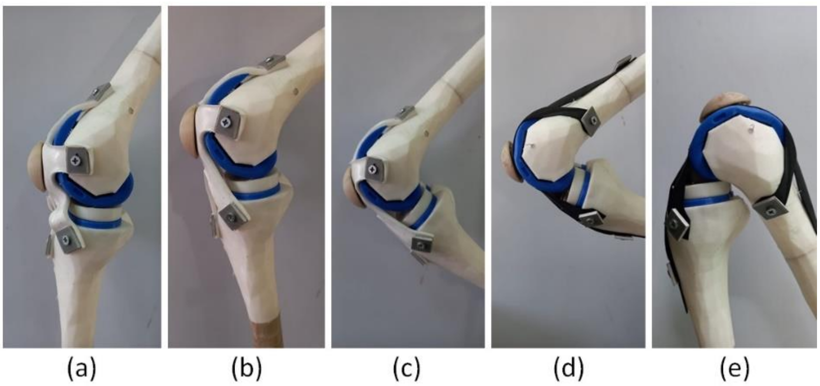

Figure 7 Photographs medial views of the simulated kinematic motion of the knee: (a) 30°; (b) 60°; (c) 90°; (d) 120°; and (e) 150°

Starting at the angle of 60°, there was contact in a small area on the posterior post region. This accorded with previous FEA results. From the photographs in the medial and lateral views it was clear that the polyethylene always contact with the femoral condyle during 30° to 150° of flexion. However, as the flexion angle increased, the contact area became smaller. From photographs did not indicate any subluxation or dislocation. This was also in accordance with previous FEA results.

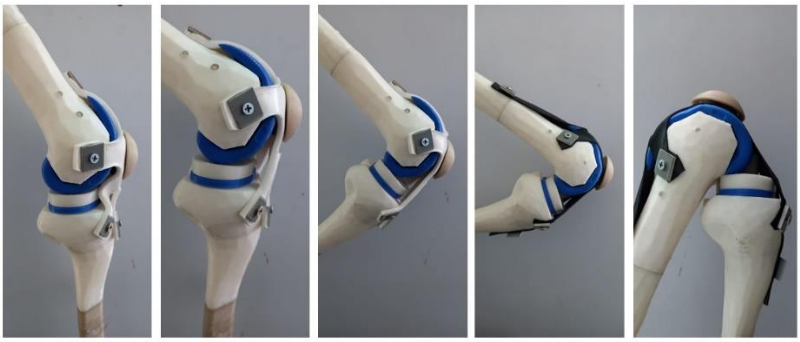

Figure 8 Photographs lateral views of the simulated kinematic motion of the knee: (a) 30°; (b) 60°; (c) 90°; (d) 120°; and (e) 150°

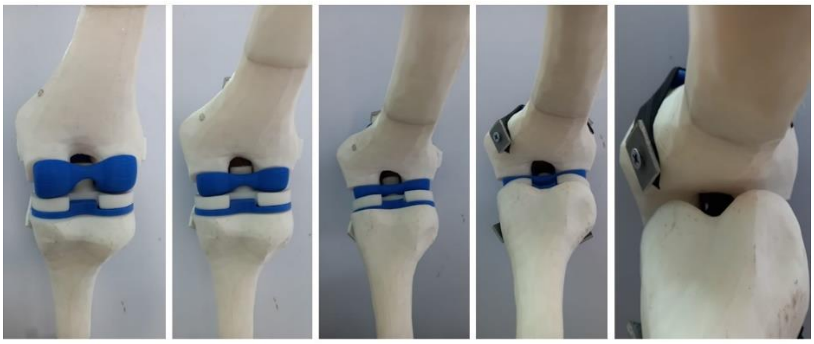

Figure 9 Photographs posterior views of the simulated kinematic motion of the knee: (a) 30°; (b) 60°; (c) 90°; (d) 120°; and (e) 150°

4. Discussion

The current results were compared to the results of previous studies (Tanaka et al., 2016). For the FEA result using polyethylene, the largest contact areas were 329 mm^2 at 0° of knee flexion and 146 mm^2 at 120° with the knee bent (Tanaka et al., 2016).

Table 2 The contact areas (in mm^2) on the polyethylene component during 0° to 150° of knee flexion from a comparable study by Tanaka et al. (2016) and the current study

		0°	30°	60°	90°	120°	150°
Tanaka et al. (2016)	Under maximum contact stress on the medial and lateral condyles, and on the ball	329	125	108	118	146	-
Current Study	Under average contact pressure on the polyethylene	733	218	510	469	576	65

In the current study, the largest contact areas were 733 mm^2 at 0° of knee flexion and 576 mm^2 at 120° with the knee bent. In previous studies, the contact area on the polyethylene was minimal at 60° of knee flexion. Meanwhile, in the current study, the contact area on the polyethylene was minimal at 150° of knee flexion. In the current study, the contact area was largest at 0° of knee flexion and decreased with increasing knee flexion. At approximately 90° of knee flexion, the posterior post region of the polyethylene began to come into contact with the femoral cam through the post-cam mechanism (Tanaka et al., 2016). This differs from the current results obtained, namely that the posterior post region of the polyethylene contacted the femoral cam at about 60° and that post-cam contact increases the contact area on knee flexion, as presented in Table 2.

According to Nakamura et al. (2015), In computer simulation research, the anteroposterior translation and geometric center of the femoral component were measured using the medial and lateral contact tool. Contact tools are important for evaluating the contact area and the contact stress (Nakamura et al., 2015) because a small contact area and a high contact stress are thought to induce significant problems such as polyethylene insert wear and fracture or severe post wear (Puloski, 2000; Reay et al., 2001; Mauerhan, 2003; Clarke et al., 2004; Casey et al., 2007).

In the current study, the contact area on the polyethylene was minimal at 150° knee flexion. This should be of particular concern because insufficient contact area might induce wear and fracture of polyethylene. The mean contact stress for arthroplasties is inversely proportional to the contact area. The contact area on the polyethylene component significantly increased during deep knee flexion. Many factors influence the site of the contact between the post and cam, including the form of the cam, the position of the attachment of the cam to the femoral component, and the curvature of the posterior femoral condyles (Utomo et al., 2020). The modification on polyethylene post feature is advantageous for reducing excessive tension at the bone-implant contact and preventing post fracture. In the current study, the design's curved shape of the polyethylene post increased the contact area during deep flexion.

The FEA was conducted under the assumption that all force was applied to the tibiofemoral articular surface and to the post's polyethylene component. In our study, a relative force of 4 kN (Walker et al., 1997; Kuriyama et al., 2014; Azam et al., 2018) was applied. Despite this limitation, our research has provided vital information about the tibiofemoral joint and the post-cam mechanism. The design of the polyethylene component resulted in an increase in the contact area; this is expected to accommodate high flexion in daily activities and reduce the risk of subluxations and dislocations during deep knee flexion.

5. Conclusions

The modification of the polyethylene component of the TKA implant resulted in an increase in the contact area; this is expected to accommodate deep knee flexion (ROM > 120°) in daily activities and reduce the risk of subluxations and dislocations. The FEA result was validated using a simulator of the kinematic motion of the knee; no subluxation or dislocation. It is now necessary to learn more about how to perform geometrical optimization so as to increase the distribution of contact stress and to minimize the risk of mechanical implant failure.

Acknowledgements

The author would like to thank the Indonesian Institute of Sciences (LIPI) for its financial support through a 2019 scientific scholarship (SK Number: B-4919/SU.3/HK.01/V/2019) and the TI-Bio Laboratory of the University of Indonesia, Depok, Indonesia, for providing all the facilities for this research. This research was funded by the University of Indonesia through the PUTI Saintekes 2020 program (NKB-4964/UN2.RST/HKP.05.00/2020).

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