Computational Model for Mechanics of Total Knee Replacement: Effect of Tibial Rotation during Deep Flexion in Relation to Post-Cam Design

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Abstract: The requirement of deep kneeling is common among Asians e.g. Seiza and kneeling during prayer. In this study, the sensitivity of stress in toral knee replacement (TKR) post to tibial rotation during deep flexion was analysed and its relation to design of post-cam articulation was investigated. Three dimensional (3D) finite element models of two designs of clinically used posterior stabilized (PS) type total knee arthroplasty were constructed using their computational aided drawing (CAD) data. Loaded deep flexional motion from 0 to 135 degree in neutral, 10° and 15° of tibial rotation was adapted using finite element model to characterize the effects of knee kinematics on the stress states of ultra-high molecular weight polyethylene (UHMWPE) tibial inserts and relation to post-cam design. Peak equivalent stresses in post at neutral, 10° and 15° tibial rotation were 65.22 MPa, 108.97 MPa and 134.50 MPa respectively, for Superflex, and 47.16 MPa, 45.69 MPa and 47.67 MPa respectively, for NRG. The result shows that the variation of maximum equivalent stress at different flexion angle and tibial rotation were caused by the post-cam contact geometry in sagittal plane and axial plane, respectively. Stress state of Superflex tibial post was found to be more sensitive to tibial rotation as compared to NRG. Modification on the post design based on post-cam radius of curvature ratio in both axial and sagittal has eliminated the sharp edge and provided larger contact area, hence reduce edge loading and high stress concentration area in Scorpio NRG. Stress in Scorpio NRG tibial post was found to be less sensitive to tibial rotation.

Key words: Deep flexion, finite element analysis, post-cam design, tibial rotation.

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1. Introduction

In the recent years, due to the change of diet habits of elderly population, number of patients with osteoarthritis has been increasing every year. In most cases, total knee replacement (TKR) operation has been chosen as the last and most promising solution. In the United States, more than 400,000 TKR procedures have been carried out in 2003 and as reported in previous paper the number is predicted to increase exponentially within the next 30 years [1]. Quality of life of the patients who are suffered with severe osteoarthritis is found to be improved after being applied with total knee arthroplasty (TKA) procedure [2]. Posterior-stabilized (PS) type TKA was designed in such way to avoid posterior subluxation of tibia by means of post-cam mechanism to replace the function of posterior cruciate ligament while allowing natural femoral rollback [3]. In TKA implant design, durability and kinematics are two essential factors that must be taken into account. Design of TKA implant including the interfaces articulation, contact geometry and relative alignment between components with combination of surrounding soft tissues will determine the kinematics of the implant that leads to the durability of the UHMWPE tibial insert in terms of the stress states within the component [4], [5]. Via design alterations, function of TKA has been improved however for Asian daily activities, deep flexion has become main concern. For example, Japanese requires 150 degree of flexion for kneeling on tatami mat [2].

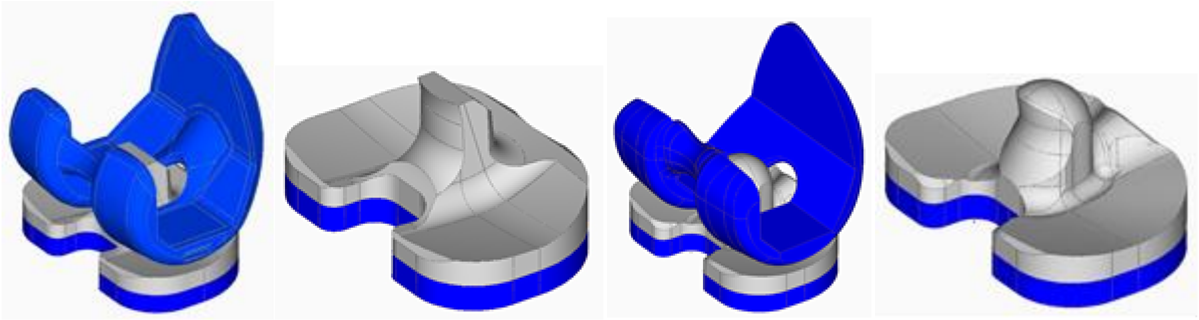
It is essential to well understand the stress state in polyethylene tibial insert during such kinematics as the tibial insert wear and failure due to post-cam contact under deep flexion has become crucial problem in PS type TKA. Three dimensional finite element analysis has been found to be a powerful tool in assessing the three dimensional stress distribution of implant knee system. In numerous investigations, normal walking gait was utilized as the input motion to quantify the kinematics and durability of TKR implant [4], [6]-[13]. Work done by Halloran *et al*. to develop and verify experimentally an explicit finite element (FE) TKR model that include articulations of tibio-femoral and patello-femoral [8]. The results have shown a good kinematic conformity between simulation and experimental measurement using Stanmore knee simulator in terms of anterior-posterior displacements and internal external rotations. In durability analysis, they have exhibited the effect of mesh size and rigidity of FE models on contact pressure and contact area. Meanwhile, Godest *et al*. have used explicit dynamic FE analyses to develop dynamic models of tibial insert–femoral articulations that able to determine the knee kinematics and contact mechanics simultaneously during dynamic-loading-controlled walking gait cycle conditions [4]. In other study, explicit finite element simulation has been utilized to study the effect of different medial:lateral loading ratio on the kinematics and stresses produced by TKR during normal gait cycle [13]. It was found that the von Mises stress and contact stress significantly affected by the small offsets of the vertical loading. The larger maximum von Mises stress was exhibited by the unicondylar loading (95:5 of medial:lateral loading ratio) as compared to bicondylar loading (50:50) with 4-6 MPa difference along the gait. The results however, have shown that the kinematics of TKR is less sensitive to the small changes of eccentric loading.

Kinetics analysis (force and pressure) of artificial knee joint undergo deep flexion motion was conducted to determine the effect of such kinematics to the performance of TKR in quite number of studies [2], [14]-[16]. Innocento *et al*. applied a numerical sensitivity analysis to investigate the effect anatomical factors: medial and lateral collateral ligaments location, patella tendon length; and component alignment: proximal-distal patellar orientation, patellar tilting and tibial component arrangement, for various types of knee implant on the patello-femoral and tibio-femoral articulations contact forces [15]. The knee joint was subjected with 10 seconds loaded (200 N) deep squatting between 0° to 120°. Tibio-femoral contact force was found to be sensitive to the anterio-posterior displacement of medial collateral position with respect to femur and tibia. In different research, stress analysis of TKA undergoes three high flexion activities: stairs climbing, standing from a chair and standing from a double-leg kneeing was conducted [16]. Three different flexion angles: 60°, 90° and 135°; with femoral loads of 20% to 450% body weight acting inferiorly and posteriorly to represent those three different conditions of human activity. Huang *et al*. applied 500-N shear stress at 60°, 90°, 120° and 150° flexion to study the effect of post-cam design on the stress state of PS tibial post [14]. However, these studies only applied simple loading condition on the knee joint without taking into account in vivo data of deep flexional motion.

The effect tibial rotation on the stress state of TKR is less pronounced by the researchers. Previous study shows that tibial rotation at the highest flexion varies among different patients. Ueo *et al*. carried out an evaluation on the patients internal rotation who able to knee (seiza) after undergoing TKR operations [17]. The evaluation was performed to 30 knees from 23 patients and the outcome showed that the internal tibial rotation was ranging from 0.8° to 26.7° with average 14.3° at full flexion. Research by Kanekasu *et al.* reported that the largest angle of tibial rotation acquired from 18 post-TKR patients was 17° at 137° flexion [18]. Kinematics characterization has been conducted also on intact knee joint. Nakagawa *et al.* performed a kinematics study on 20 Japanese subjects using MRI and found that there was a 13° of tibial rotation when the knee moved from 133° to 162° flexion [19]. There are a few attempts have been done to study the kinetics of TKR (force & pressure) undergo deep flexion motion combine with tibial rotation [3], [14]. However, these studies only investigate deep flexion with neutral and 10° tibial rotation and most of them do not discuss further the influence of tibial rotation on the stress distribution of tibial insert and relation to post-cam design. In this study, two FE models of clinically used TKR, Stryker's Scorpio Superflex and Scorpio Non-Restrictive Geometry (NRG), respectively having different post-cam design were constructed. The models were subjected with dynamic loaded knee flexion between 0 to 135° and tibial rotation of 0°, 10° and 15° to analyze the sensitivity of stress in TKR post to tibial rotation and deep flexion.

2. Method and Analysis

There are two types of PS type knee prosthesis with different post-cam design have been analyzed. FE models were developed from the 3-D CAD data of both designs of prosthesis. The stiffness of femoral and tibial components is much higher in comparison to tibial insert, thus they have been treated as rigid bodies. The tibial insert was made of ultra-high molecular weight polyethylene (UHMWPE) and assumed to be elastic-plastic material.



(a)

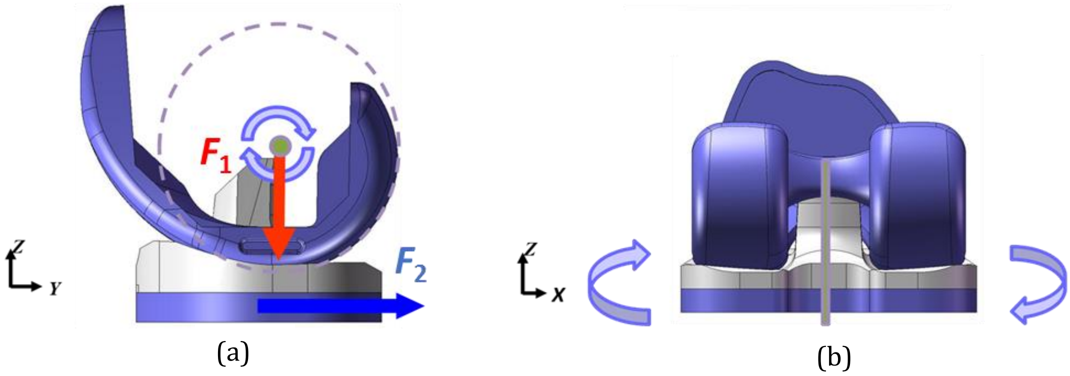
(b)

Fig. 1. CAD models of knee prosthesis (a) SuperFlex; and (b) NRG.

In Superflex and NRG, 143153 and 121538 split 4-node tetrahedron finite elements, respectively were utilized to represent the femoral component, tibial component and tibial insert. Fig. 1 shows the CAD model of both TKRs. The FE models were validated by comparing the peak contact stress, mean contact stress and contact area with the results obtained in previous study whereby a 500-N compressive posterior load was applied to the tibial component against the femoral part [3]. In natural healthy knee joint, the effect of friction is almost negligible in dissimilarity to TKA motions that can be unsmooth [6]. Therefore, the coefficient of friction of 0.04 between femoral component and tibial insert was selected to be consistent with previous research [4], [8]. In actual TKA knee, flexing motion of femoral and tibial components are strongly influenced by the ligaments and muscles surrounding the knee, at the same instant balancing the reaction and frictional forces generated on the condylar and post surfaces of tibial insert. In the present models, two pairs of nonlinear springs were positioned anteriorly and posteriorly to the tibial insert to represent the action of those ligaments [12]. The nonlinear force-displacement relation of springs was given by:

$$F = k_1 d^2 + k_2 d = 0.18667 d^2 + 1.3313 d \qquad (1)$$

Where F is force exerted by the spring, d is the displacement of the spring and k_1 and k_2 are the stiffness coefficients of the springs, respectively. To evaluate the model, input loadings and kinematics of normal walking was applied to determine the contact area and contact stress curve during one complete cycle.



(a) (b)

Fig. 2. Boundary conditions of TKA model (a) Sagittal view; and (b) Posterior view.

In the present study, the TKRs were modeled to perform high flexion motion from 0 to 135° with neutral, 10° and 15° tibial rotation. The displacement of femoral component was free in proximodistal axis, and fixed in mediolateral and anteroposterior axis. It was allowed to rotate about its mediolateral axis which was assumed to be coincide with the centre of curvature of the condylar surface of the femoral component. The tibial component was allowed to translate freely in anteroposterior direction and fixed in mediolateral and proximodistal axis. Fig. 2 shows the boundary conditions of the TKR model. At the same instant, load data for rapid deep squatting was applied [20]. The loadings, F_1 and F_2 represent the normal load and shear load sustained by the TKR. The force-flexion angle relation is shown in Fig. 3.

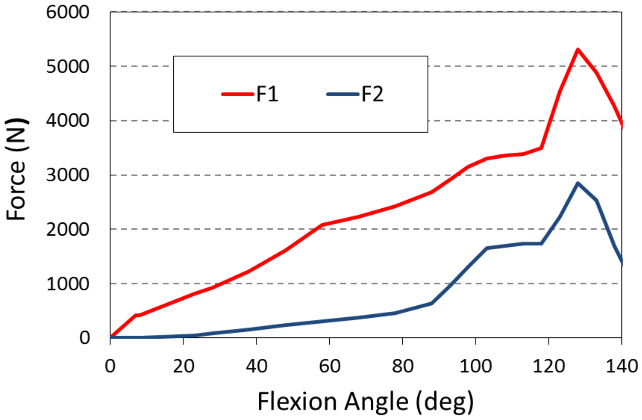


Fig. 3. Force-flexion angle relation of deep squatting.

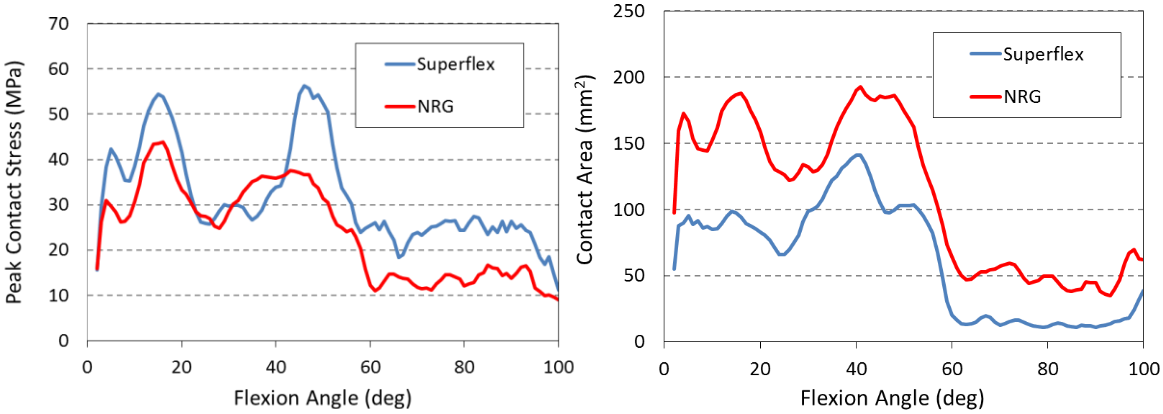
3. Results

3.1. Validation Test

The validation test was carried out for flexion angles of 90° & 120°. Table 1 shows the comparison of peak contact stress, mean contact stress and contact area between present finite element model and result by Nakayama *et al*. [3]. The largest difference of peak contact stress, mean contact stress and contact area between FEM and experimental result by Nakayama *et al*. were 14.5%, 17.1%, 7.9%, respectively showed a good agreement between both results. Due to different size and geometry of TKR design, direct comparison with previous explicit FE models [4], [8], [13] was intricate, however the evaluation test of present explicit FE models exhibited typical trends of maximum contact stress and contact area of normal walking gait as shown in Fig. 4.

Table 1. The comparison of peak contact stress, mean contact area and contact area between present FEM and study by Nakayama *et al.*

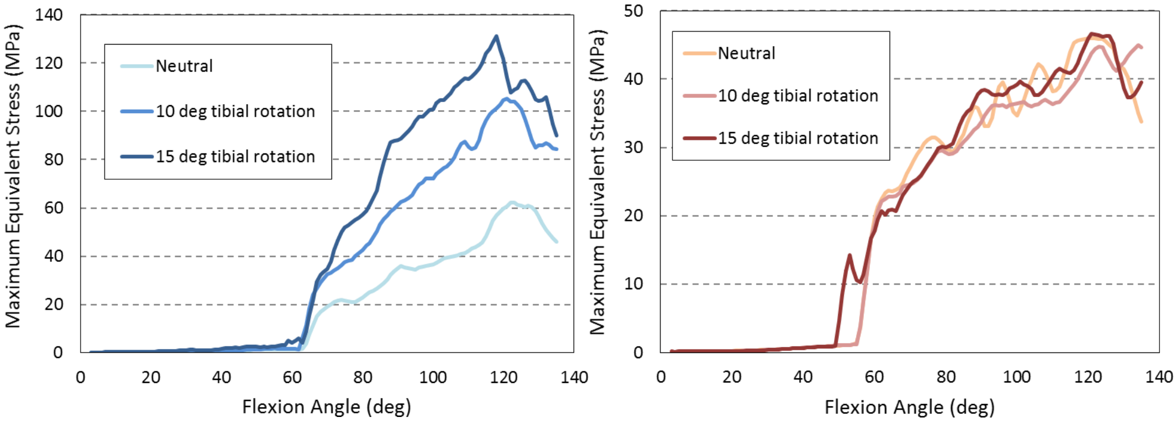
Flexion angle (°)	Peak contact stress (MPa)		Mean contact stress (MPa)		Contact area (mm^2)	
	FEM	Nakayama *et al.*	FEM	Nakayama *et al.*	FEM	Nakayama *et al.*
90	27.3	25.9±1.5	13.0	11.1±0.2	42.6	45.1±2.1
120	27.7	32.4±0.5	12.4	14.8±0.5	38.6	45.1±2.1



(a) (b)

Fig. 4. Tibiofemoral contact analysis during walking gait for both models (a) Peak contact stress; and (b) Contact area.

3.2. Stress States of Tibial Post



(a) (b)

Fig. 5. Maximum equivalent stress history from 0 to 135° flexion with neutral, 10° and 15°tibial rotation (a) Superflex; and (b) NRG.

Fig. 5 (a) and (b) shows the relationship between the maximum equivalent stress and flexion angle for

Superflex and NRG respectively. In this study, only the maximum stress in the post of TKR was discussed as the part expose to failure during high flexion as compared to condylar part. Maximum equivalent stress increased with flexion angle for each model. It can be seen that the maximum equivalent stress increased tremendously at about 60° for both TKRs shows that the post/cam contact occurs initially at this flexion angle. For Superflex, the maximum equivalent stress reached the peak values at about 120° flexion with 60MPa, 110 MPa and 130 MPa for neutral position, 10° and 15° tibial rotation, respectively.

The dependence of peak values of maximum equivalent stress on tibial rotation is shown in Fig. 6. It can be clearly noted that peak equivalent stress in post of NRG remained at about 50 MPa with increasing tibial rotation angle. The result also shows that tibial rotation increased the peak stress in post of Superflex more than 100% between neutral position and 15° tibial rotation. Distribution of equivalent stress on the tibial of both models at 120° of flexion and 9° of tibial angle are shown in Fig. 7.

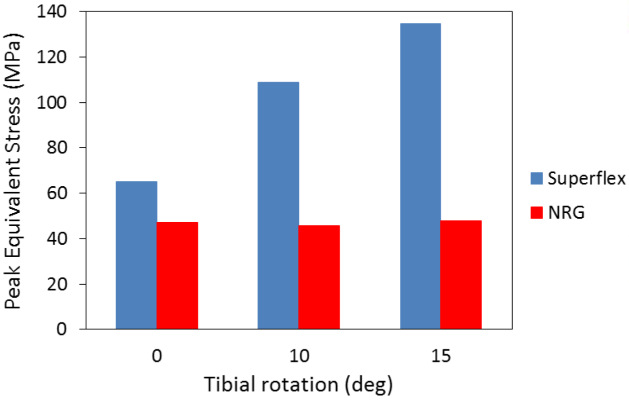


Fig. 6. Peak values of maximum equivalent stress for each type of TKA.

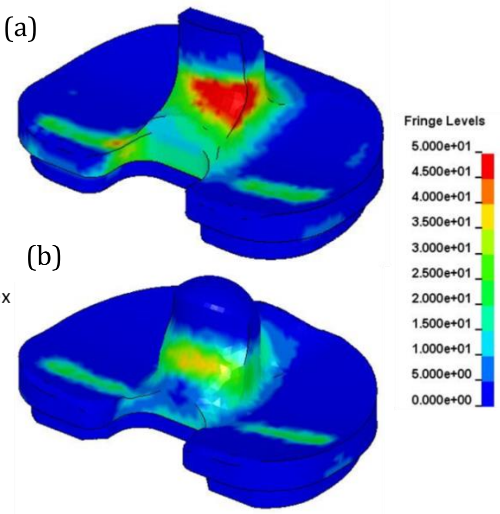


Fig. 7. Distribution of equivalent stress on the tibial insert at 120° of flexion and 9° of tibial angle (a) Superflex; and (b) NRG.

4. Discussions

Kneeling is one of the common activities among Asian especially in Japan, countries around East Asia and Middle East eg. Seiza on tatami, kneeling and squatting during prayer. Previous biomechanical investigations have shown that deep knee flexion generate significantly higher normal and anterior-posterior load in comparison to normal walking [20], [21]. It was approximated that double leg deep squatting generate up to 50.7% body weight net inferior force and 62.8% body weight net posterior load [21] while Dahlkvist *et al*. reported that more than 5 times bodyweight of normal load is applied to tibiofemoral joint surfaces and 2.9 to 3.5 times bodyweight of load acts tangentially during rapid descending [20]. Numerous experimental works have been carried out to study tibial rotation during deep flexion motion [17]-[19], [22]. Kinematics study on intact knee shows that the internal rotation increased with knee flexion up to 11.1° [22] and 17° at 137° flexion for post-TKR knee [18]. Therefore, the combination of such kinetics and kinematics due to high flexion motion is predicted to be main cause of tibial post wear and damage. This hypothesis was proven by the results of the current study, showing that relatively high von Mises stress, exceeding 40 MPa was noticeable at the tibial post for both types of TKA.

Apart from post-cam mechanics, failure of tibial post may also come from other factors such as post location and post geometry [23]. Various studies on influence of post-cam design on the mechanical performance of PS type TKR were reported in previous research [2], [3], [14], [24]-[26]. In general, post-cam design can be categorized into two groups, flat-on-flat and curved-on-curved [3], [14]. In this study, both TKR models are curved-on-curved types of post-cam design however, post of Superflex has larger post-to-cam radius of curvature ratio with sharper edge as compared to NRG in axial plane. Contact between post and cam at neutral tibial rotation started at 62° and 56° for Superflex and NRG respectively due to larger size of NRG post.

Superflex is found more sensitive towards tibial rotation than NRG due to larger edge loading during tibial rotation. The tibial rotation caused the post of tibial simultaneously sustained bending moment and torsional loading [14]. Post of Superflex has a nearly-flat posterior surface with sharp edge at both posteromedial and lateral sides. The post design has been improved by eliminating the sharp edges with rounder shape of posterior surface in NRG. The design modification reduced the edge loading, as the result, stress deviation due to tibial rotation was reduced. Fig. 8(a) and (b) show the stress distribution on tibial post in crossectional area on axial plane for both TKRs at 120° flexion and 9° tibial angle. It can be clearly seen that high stress concentrated around the posteromedial edge of Superflex post, in contrast, small region of stress generated on tibial post near the post-cam contact of NRG.

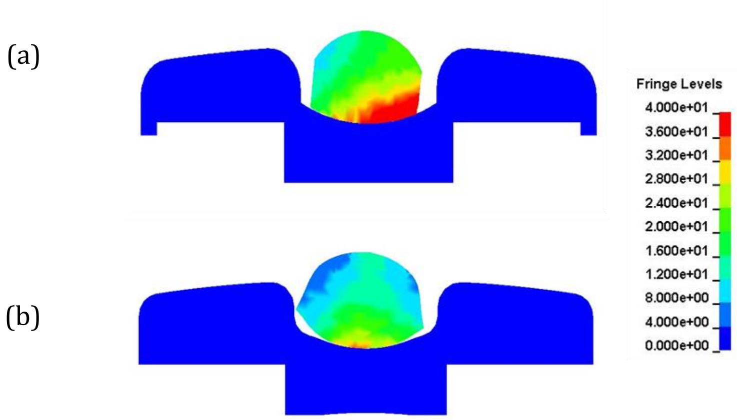


Fig. 8. Crossectional view of post-cam contact in axial plane with stress distribution at 120°flexion angle and 9° tibial angle for (a) Superflex; and (b) NRG.

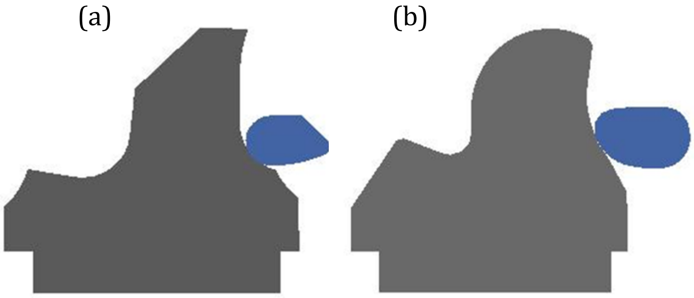


Fig. 9. Crossectional view of post-cam contact in sagittal plane at 90° flexion angle with neutral rotation for (a) Superflex; and (b) NRG.

The results also show obvious variation on equivalent stress at different flexion angles. Post-cam contact of Superflex generated increasing equivalent stress from 60° to 120° flexion, and relatively sudden decreased from 120° to 135° flexion. In sagittal plane, the cam Superflex small radius of curvature at distal surface and increasing sharply at posterodistal surface with relatively flat posteriorly as shown in Fig. 9(a). At 120° flexion, post cam contact happened at the relatively sharp curve on cam created high stress concentration on tibial post. Relatively flat posterior surface of cam reduced the equivalent stress tremendously from 120 ° to 135° of flexion angle. NRG shows almost similar trend from 60° to 120° flexion with lower maximum stress attained, however there was slight decrease at 135 ° of flexion. This observation was due to design of cam which oriented with large radius of curvature on posterodistal and posterior surface as in Fig. 9 (b). At neutral rotation, stress on post of Superflex was lower than NRG up to 100° of flexion angle as shown in Fig. 10, however at larger flexion angle, Superflex exhibited higher stress than NRG. Post-cam contact of Superflex has good conformity at neutral position whereby the post-cam radius of curvature ratio is close to 1 in axial plane (Fig. 9(a)). The relatively flat on the distal surface of Superflex cam provide larger contact area, in contrary, relatively sharp curvature on distal surface of NRG created smaller contact area from 60 to 100° flexion. Therefore, higher stress can be observed on NRG tibial post at these flexion angles.

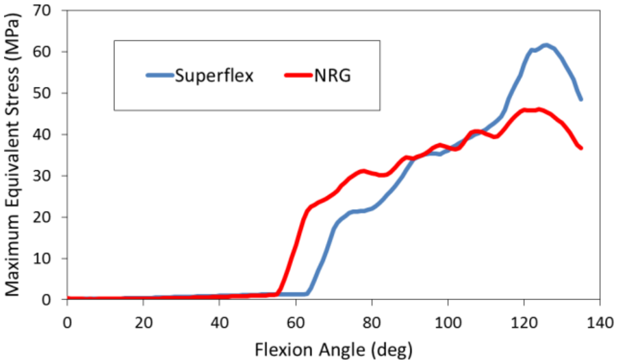


Fig. 10. Maximum equivalent stress history with neutral rotation for both models.

This study has certain limitations. The input loadings applied to the models were measured from normal patients [20] that may vary from patients with TKR. The models were subjected to flexion and tibial rotations which are linearly correlated to each other. In contrast, the higher tibial angle might occur at lower flexion angle during deep squatting. This study used a simplified model whereby two pairs of springs were utilized to represent the reaction of surrounding soft tissues [12]. The position of muscle and ligaments e.g. insertion point and relative location of ligaments on tibial and femur, were not considered in this model. Different relative orientations of ligaments insertion give different mechanical response, thus the kinetics and kinematics of knee joint will be significantly affected [27]. However, we assumed that the explicit FE model used in this study was sufficient to compare those two models of TKR.

5. Conclusion

In conclusion, post-cam design modification has reduced the equivalent stress generated during high flexion with tibial rotation. This study suggests that post-cam contact geometry in axial plane is important to accommodate tibial rotation and post-cam design in sagittal view is essential to accommodate deep flexional motion. The results also show that radius of curvature of tibial post relative to cam of femoral component on both axial plane and sagittal plane give significant effect on the stress state of TKR post. This study could give general guideline on the selection of TKR by surgeon as the range of motion may vary for different patient. Modification on the NRG TKA based on post-cam radius of curvature ratio in both axial and sagittal plane has eliminated sharp edge and provided larger contact area, hence reduce edge loading and high stress concentration area to accommodate lower equivalent stress during deep flexion motion and high tibial rotation. This modification also has made the stress in post of Scorpio NRG less sensitive to tibial rotation.

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