Mechanics of Posterior Stabilized Total Knee Arthroplasty During Daily Activities in Relation to Prosthesis Condylar and Post-cam Design: A Finite Element Study

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ABSTRACT

The mechanic of TKA prosthesis in relation to prosthesis design remains unclear despite of previous extensive research. This study attempts to observe the stress states and contact mechanics of polyethylene (PE) insert of knee prosthesis during common daily activities and their relation with condylar and post-cam design. Knee joint loadings during walking, stair climbing, chair sitting and deep squatting were applied to Scorpio Superflex and Scorpio Non-Restricted Geometry (NRG) knee implants using 6-degree-of-freedom (DOF) displacement-force driven model. Finite element models were developed in FEMAP using tetrahedron elements while motions of knee joint were modelled in LS-DYNA. Design of Superflex serves relatively good conformity but more rotational resistance that leads to surface distortion. NRG, however, has more relaxed geometry without compromising the needs of appropriate conforming articular surfaces. This research demonstrated that PE tibial insert stress conditions are closely associated with condylar and post-cam geometry. Conforming interfaces serve good wear resistance, however provide surface constraint towards motion, which leads to surface distortion.

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Introduction

Total knee arthroplasty (TKA) has been widely accepted as the most promising treatment for final-stage knee arthritis. More than 400,000 TKR procedures were performed in the United States in 2003 and the number was projected to increase exponentially within the next 30 years [1] . Regain the ability to perform normal daily activities may become expectation among TKA patients. Walking, stair climbing and chair sitting/rising are common human activities, and for Asians, deep squatting also becomes crucial part of their life such as *seiza* on *tatami* among Japanese and kneeling in prayer for Muslims. Patient's activities are closely associated with the relationship between flexion angle and joint loads [2] , which in turn produce various stress states and contact mechanics at tibial polyethylene (PE) insert. Hence, correlations among knee kinematics, tibiofemoral load, stress and contact mechanics of knee system will be beneficial for the design and selection of better prosthesis.

Numerous studies have been carried out related to joint mechanics either on intact or implanted knee for various activities. The investigations on TKA mechanics have been carried out through a wide range of approaches including *in vivo* measurements [2–4] using custom-designed instrumented knee implant, sophisticated computational simulation [5–7] and *in vitro* assessment [26]. Knee joint mechanics during physical activities were also extensively studied including mechanics of knee during stair climbing [2–4,8], chair rising [2,3,9] and squatting [2,3,10–14].

Posterior stabilized total knee arthroplasty (PS TKA) prosthesis is designed with the appearance of post-cam mechanism to substitute the degenerative posterior cruciate ligament. The ultimate role of this mechanism is to allow femoral rollback and improve the range of motion of post-operative knee [15]. Introduced more than two decades ago [16], prior reports revealed satisfactory survivorship of PS TKA after long-term follow-up [17–19] . However, there are some important issues in PS TKA addressed in previous report associated with the kinematics and longevity of the implant. As the range of motion becomes a major concern among the patients, durability of the implant is also an essential outcome measure of TKA postoperative knee. Wear of PS TKA insert was observed in prior retrieval studies which involved tibial post wear [20,21] and delaminating articular surface of tibial condylar [22]. Loading at tibiofemoral joint generates contact stress and induces PE distortion. Excessive contact stress is found to be the main cause of splitting particles from the PE insert surface, leads to osteolysis and implant loosening while extreme distortion may result in subsequent implant fracture. Therefore, it is crucial to well understand the contact mechanics and stress states of PE insert under various loading conditions and knee motions and how they correlate to design prosthesis.

Despite of extensive studies have been done as presented above, the mechanic of TKA prosthesis in relation to prosthesis design still remains unclear. Therefore, the ultimate goal of this study is to investigate the effect of prothesis geometrical design on the stress states and contact mechanics of PE insert during various weight bearing activities and high flexion motion using dynamic finite element (FE) analysis.

Methods and Analysis

There were two types of PS TKA knee prostheses investigated namely Scorpio Superflex and Scorpio NRG (Stryker, Allendale, New Jersey, size 3). Fig. 2 shows the geometrical overlap between the Superflex and NRG left knee systems. The geometry of both types of implants was obtained from the manufacturer. Computational aided drawing (CAD) in FEMAP V11.1.2 (Siemens PLM software, Plano, Texas, USA) was used to construct three-dimensional finite element (FE) models employing tetrahedron elements with an average edge length of 1.2 mm. The PE insert was represented by an elastic-plastic material having Young's Modulus of 800 MPa and Poisson's ration of 0.40. The femoral and tibial components were modeled as rigid bodies. Due to significant differences in the bulk modulus of the PE insert and metal femur, soft constraint-based formulation in LS-DYNA (LSTC, Livermore, California, USA) was used to define the contacts of tibio-femoral and insert-tray interfaces. Static and dynamic friction coefficients of 0.04 were selected for metal-on-plastic contacts [5]. Two pairs of non-linear springs were placed on the anterior and posterior sides to model the action of soft tissues around the knee. The force-displacement relationship of the springs was taken from previous literature to simulate a knee with a resected cruciate ligament [23]:

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

Where F is the force applied, d is the spring translation, and k_1 and k_2 are the coefficients of stiffness of the springs.

To simulate the mechanics of the knee, a 6-DOF dynamic model combining displacement and force driven knee joint was developed. The femoral component was constrained so that it displaced in the mediolateral (ML) and anteroposterior (AP) directions, and rotated along the AP and proximodistal (PD) axes, thus resulting in 2-DOF of motion. Fig. 1 shows the AP, ML and PD directions with respect left human knee. The tibial tray was allowed to displace in the AP and ML directions, perform AP rotations to replicate varus-valgus motion, and to rotate in the PD direction to simulate tibial internal-external rotation. Boundary conditions of four activities, normal walking (ISO loading protocol), stair climbing [3], chair sitting [24], and deep squatting [10], were applied. The FE model was validated by comparing the peak contact stress, mean contact stress, and contact area at 90° and 120° of the flexion angle with neutral alignment from computational analysis to the results from previous experimental work on Scorpio Superflex knee system by Nakayama et al. [15].

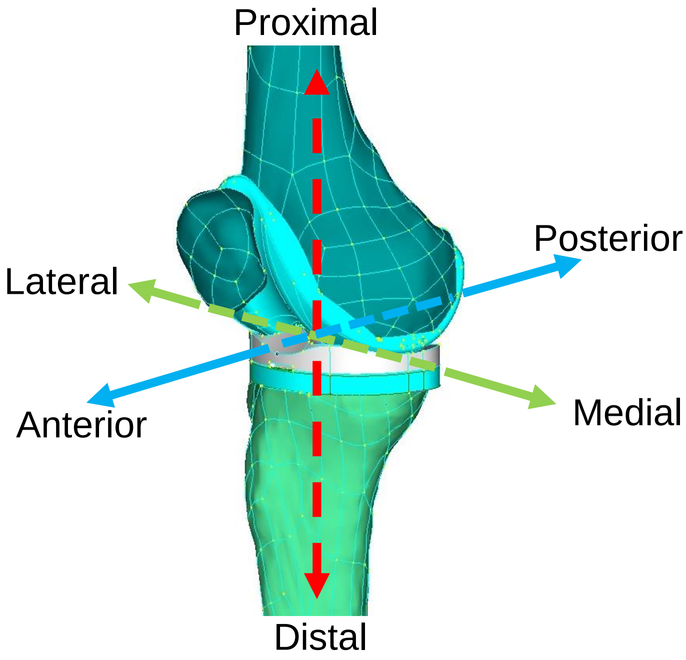

Figure 1: Anteroposterior (AP), mediolateral (ML) and proximodistal (PD) directions with respect to left knee.

Results

Table 1 shows the comparison between the FE model and the experimental work by Nakayama et al. on Scorpio Superflex knee prosthesis. The two results exhibited good agreement, with the largest differences in peak contact stress, mean contact stress, and contact area being 14.5%, 17.1%, and 7.9%, respectively.

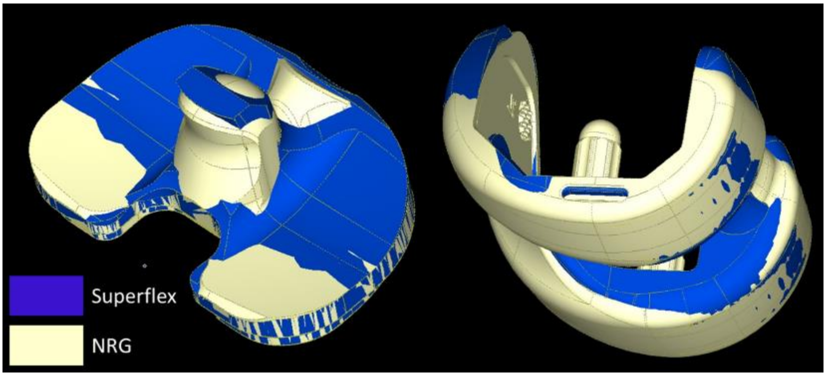

Figure 2: Geometrical overlap between Superflex and NRG (left knee implant).

Almost 100% of tibio-femoral articulations occurred at the condylar interfaces throughout the entire cycles of walking and stair climbing. Fig. 3 and Fig. 4 show the maximum von Mises stress, maximum contact stress, and contact area for both activities as a function of cycle percentage. During walking, the maximum von Mises stress and maximum contact stress ranged from 5 to 25 MPa and from 10 to 58 MPa, respectively. The stance phase of walking generated relatively higher stresses on the PE insert in comparison to the swing phase. The Scorpio Superflex PE insert endured higher contact stress and larger distortion than the Scorpio NRG during the walking gait cycle. During stair climbing, the maximum von Mises stress and maximum contact stress ranged from 8 to 24 MPa and from 12 to 50 MPa, respectively. At 60% of the cycle, the tibio-femoral condylar contacts of Scorpio Superflex generated higher von Mises stress and contact stress compared to Scorpio NRG. The peak values of maximum von Mises stress were 24 MPa and 23 MPa for Superflex and NRG, respectively, while the peak values of contact stress were 50 MPa for Superflex and 42 MPa for NRG knee implants.

Table 1: Comparison of peak contact stress, mean contact stress and contact area with neutral position at 90˚ and 120˚ of flexion angles between FE model and experimental results by Nakayama et al (15)

Flexion Angle (°)	Peak contact stress (MPa)		Mean contact stress (MPa)		Contact area (mm^2)	
	FE model	Nakayama et al	FE model	Nakayama et al	FE model	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

The tibial condyle and post stresses for both designs of knee implants during chair sitting are shown in Fig. 5. In general, von Mises stress and contact stress at the tibial condyle increased with the flexion angle. Post-cam engagement of NRG occurred earlier than Superflex, with the sudden rise of post stress occurring at 60° of flexion in NRG and at 66° in Superflex. Fig. 6 shows the progress of tibial and post stresses during deep squatting. Superflex and NRG tibial condyles showed almost comparable performance in terms of contact mechanics, but NRG was found to be better at resisting distortion as higher von Mises stress was exhibited by Superflex. Post-stress of Superflex was greater than NRG from initial post-cam engagement to 135° of flexion. Fig. 7 shows the maximum von Mises stress distribution in the articular surface of the tibial inserts at 90° and 130° of flexion angle during deep squatting.

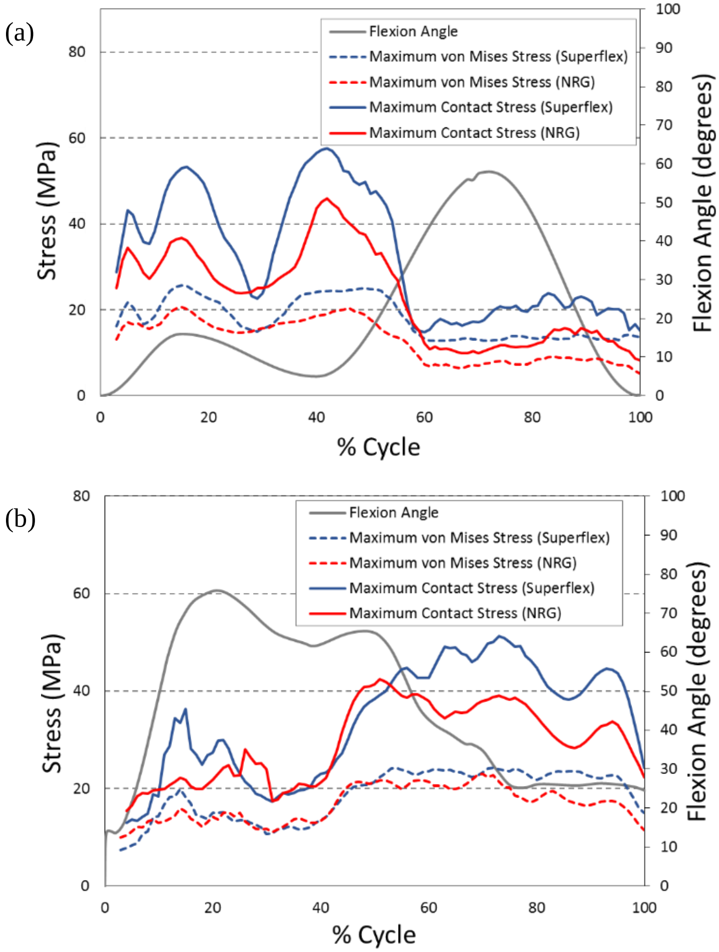

Figure 3: Maximum von Mises stress and maximum contact stress in the function of cycle percentage for: (a) walking, and (b) stair climbing.

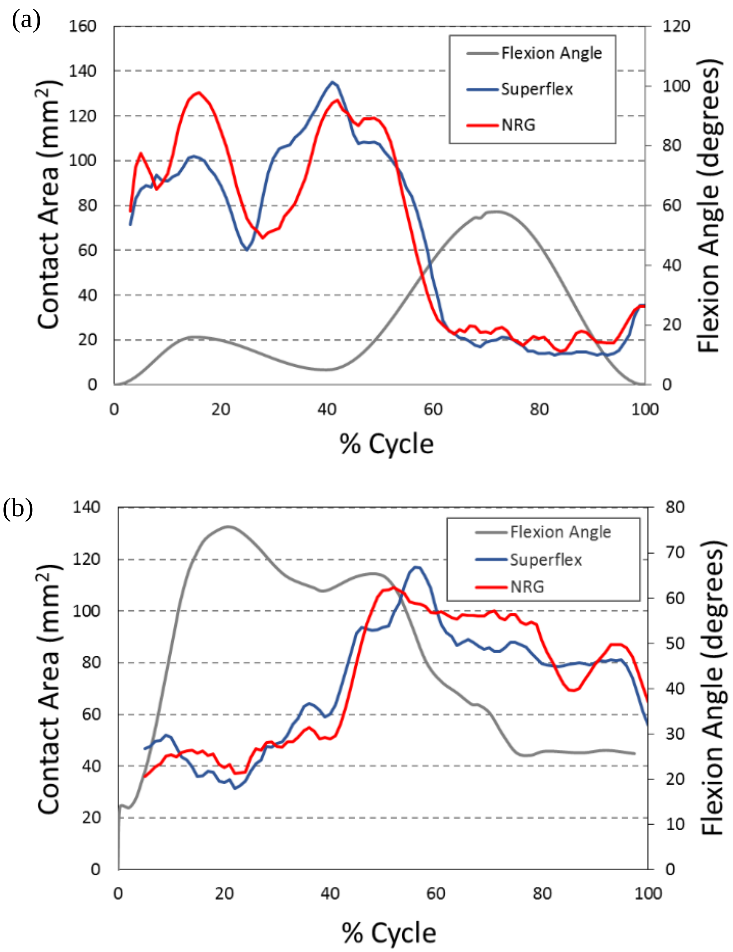

Figure 4: Contact area in the function of cycle percentage for: (a) walking, and (b) stair climbing

Table 2 and Table 3 summarize the comparison of the peak magnitudes of maximum von Mises stress and mean contact stress at different sections of the Scorpio Superflex and Scorpio NRG tibial inserts for all activities. Note the peak values of maximum von Mises stress and mean contact stress at tibial post for both designs during stair climbing activity.

Based on our analysis, a slight post-cam contact was observed at approximately 71° of flexion angle. The short duration of contact resulted in substantially higher stresses on the tibial posts of both types of implants. Overall, the peak magnitudes of stress of Superflex were fairly higher than NRG for all activities.

Table 2: Peak values of maximum von Mises stress for each section of tibial insert in MPa. Higher magnitude obtained by NRG is marked.

	Medial condyle		**Lateral condyle**		**Tibial post**	
	Superflex	NRG	Superflex	NRG	Superflex	NRG
Walking	25.5	21.1	26.2	21.0	-	-
Stair climbing	25.0	20.8	25.4	24.3	15.3	**31.2**
Chair sitting	24.3	23.4	25.0	23.0	31.0	23.6
Deep squatting	45.4	31.9	83.0	31.1	135.0	45.6

Table 3: Peak values of mean contact stress for each section of tibial insert in MPa. Higher magnitude obtained by NRG is marked.

	Medial condyle		**Lateral condyle**		**Tibial post**	
	Superflex	NRG	Superflex	NRG	Superflex	NRG
Walking	26.9	25.3	28.5	22.5	-	-
Stair climbing	23.8	21.9	26.2	24.8	15.6	**67.9**
Chair sitting	29.3	**36.3**	30.1	**32.1**	52.8	52.0
Deep squatting	69.9	42.5	69.7	46.3	97.6	69.6

Discussion

The present study demonstrated that the stress states and contact mechanics at tibial PE insert vary significantly between different geometry of tibiofemoral condylar articulating surfaces and post-cam configuration. Mündermann et al. categorized the daily activities into three major groups based on the loading conditions; high cycle loading, high loading and high flexion loading [2] . Walking falls under first group while stair climbing is clustered under second group. These two weight bearing activities create repetitive compressive and shear force on the tibiofemoral joint with smaller flexion angle ranging from 0 to 70°. Femoral-insert condylar contact mechanics and geometry give an important insight to determine the durability and mobility of the knee prosthesis when performing such activities. High flexion loading is attributed by maximum loads at high flexion with small number of cycles. Chair sitting and deep squatting are categorized in this group. Apart from tibiofemoral condylar articulations, design of post-cam mechanism gives apparently large effect on the performance of knee implant mainly during high flexion activities, even though chair sitting and deep squatting are performed in a small number of frequency and directly correlated to the factor of origin, religion and culture of the patients. The boundary conditions applied in this study were taken from various experimental investigations [3,10,24] , and therefore different subjects involved in different activities. This method, however, did not jeopardize the entire results as the study intended to carry out the mechanics performance characterization and comparison between two different implant designs when performing all activities rather than comparing the mechanics of TKA between different activities.

Tibial insert of Scorpio Superflex has double radii about mediolateral axis with smaller sagittal curvature posteriorly [11] . The post-cam mechanism applies curve-on-curve contact geometry in axial plane with relatively flat surface of cam posteriorly in sagittal plane [15] . NRG knee system has single radius of tibial insert about mediolateral axis and double curvature radii of femoral condyle, which is relatively larger from 0° to 95° and smaller higher flexion radius from 95° to 155° [12,13] . The post-cam mechanism of NRG also has curve-on-curve contact configuration in axial plane, and elliptical shape of cam with larger radius of curvature posteriorly in sagittal plane [14] .

Prosthetic design of tibiofemoral condylar articulating surfaces leads to remarkable effect on the stress conditions of PE insert. This is an important key towards survivorship of knee implant as the tibiofemoral contact primarily lies on this region during high cyclic motion of walking and climbing with relatively smaller flexion angle and tibial axial rotation. In overall, NRG has shown less condyle distortion and contact stress as compared to Superflex. Larger anterior radius of curvature of Superflex provides more constraint to tibial internal rotation, results in higher von Mises stress at tibial condyle. Besides that, this biradial design was found more sensitive towards rate of flexion. Note the sudden increase of stress between 0% and 18% of stair climbing cycle which directly proportionated with the rate of flexion occurred from 20° to 70° of flexion angle (Fig. 3(b)). Femoral condylar of NRG has slightly larger width in mediolateral direction (Fig. 2) has successfully improved the conformity as 70% of the walking and stair climbing cycle, contact area of NRG was larger than Superflex, led to lower contact stress during both activities (Fig. 3). Single anteroposterior radius of curvature of NRG tibial condyle reduces the constraint towards tibial rotation, yet facilitates good conformity from the marginally improved mediolateral width of femoral condyle. This observation demonstrated that contact stress at tibial condylar is more sensitive towards conformity in frontal planes (about anteroposterior axis) than conformity in sagittal planes of TKA prosthesis.

(a)

(b)

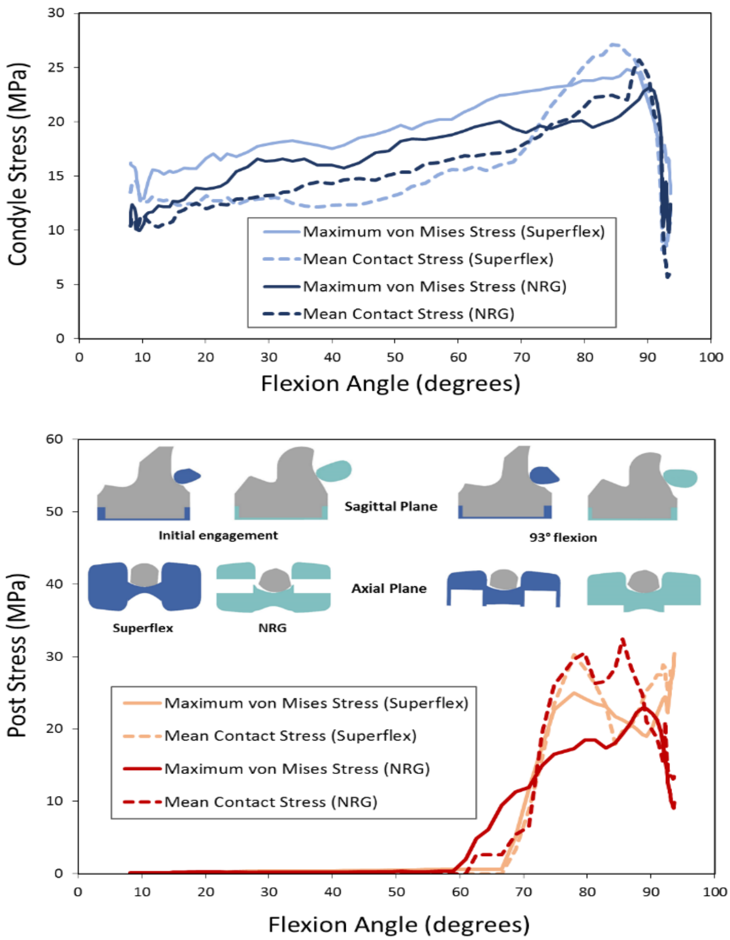

Figure 5: Dependence of maximum von Mises stress and mean contact stress on flexion angle during chair stand-to-sit activity for: (a) tibial condylar, and (b) tibial post (Inset: Cross-sectional view of post-cam engagement in sagittal

plane (top) and axial plane (bottom) at initial engagement and 93° of flexion angle, respectively).

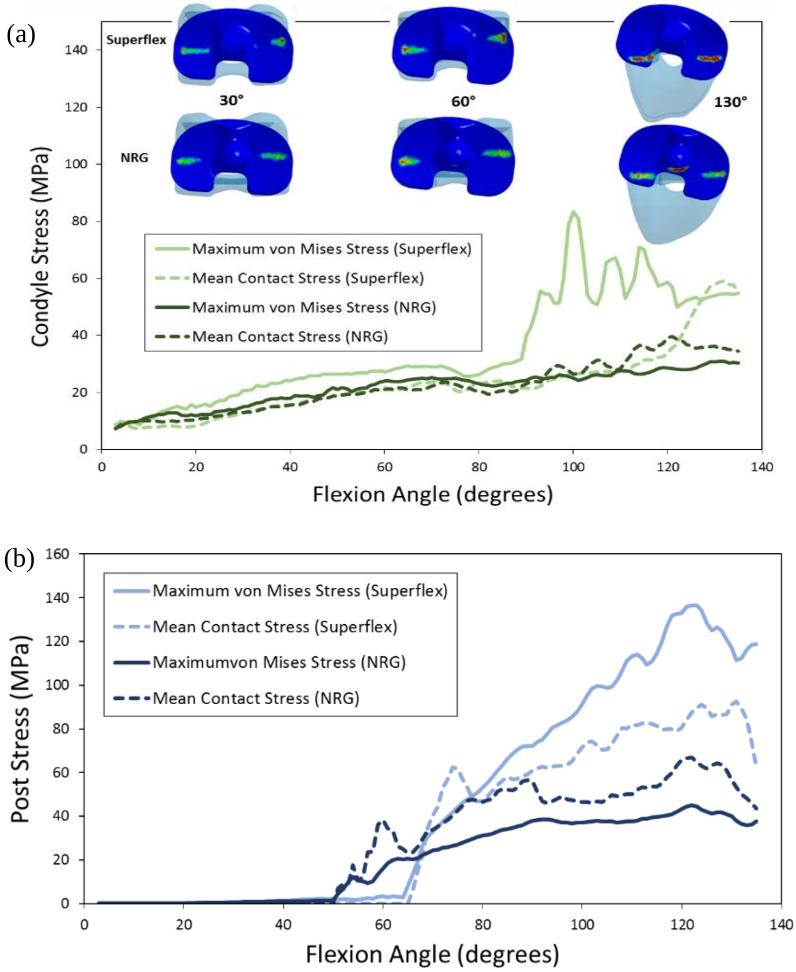

Figure 6: Maximum von Mises stress and mean contact stress during deep squatting at: (a) tibial condylar (Inset: Contour of maximum contact stress at PE insert of Superflex (top) and NRG (bottom) at 30°, 60° and 130° of flexion angle, respectively), and (b) tibial post.

Apart from ability to perform weight bearing activities, high flexion motion, e.g. chair sitting and deep squatting, is also one of the ultimate goals of TKA patients especially among Asian. Prior studies revealed high tibiofemoral loads were generated during deep flexion motion in both intact and post-operative knee. Estimated up to 62.8% body weight of net force during double leg deep squatting [25] , and more than 5 times bodyweight of normal force was computed during rapid deep descending [10], while 2.5 times bodyweight of peak compressive load was measured during chair stand to sit [2] and chair rising [3]. Kinematics studies of knee reported that the axial rotation of tibia increased with knee flexion angle in both physiological knee [26] and implanted knee [11]. The combination of such motion and high tibial loads lead to tibial wear and subsequent damage as proven by the present results, showing that high stress, exceeding the yield of PE was sustained by the tibial insert during high flexion motion.

Post-cam geometry that able to maintain low stress of PE insert is essential as previous case reports and retrieval study revealed severe damage of tibial post [20,21,27,28]. During chair sitting activity, post-cam design configuration of Superflex facilitates better conformity in both sagittal and axial planes, from initial engagement to 87° of flexion angle, which in turn results in lower contact stress, however provides more axial rotational resistance, leads to higher distortion at posterior surface of tibial post (Fig. 5(b)). The result conforms previous experimental work that obtained greater mean contact stress of NRG tibial post than Superflex at 90° of flexion with neutral alignment using comparable size of tibial component (size 5) [14,15]. Mean contact stresses were 11.1 MPa and 15.5 MPa for Superflex and NRG, respectively. Von Mises stress and contact stress of Superflex increased tremendously from 87° to 93° of flexion angle due to the edge loading sustained by significantly small radius at posteromedial surface of tibial post (Fig. 5(b)). This is in agreement with experimental study by Nakayama et al., found that the peak contact stress of Superflex tibial post substantially increased with internal rotation at 90° of flexion [15].

When performing deep squatting motion, higher axial rotation takes place, which in turn increases the edge loading effect at tibial post of Superflex. Puloski et al. carried out a retrieval study on post wear in four different manufacturers of PS TKA knee implant: Howmedica (Kinemax, Kinematic I and II), Zimmer (CCK and Insall-Burstein II), Smith and Nephew Richards (Genesis I and II) and DePuy (AMK and Coordinate) [20]. Post of Genesis I was fractured during the time of revision and they suggested that this was due to relatively high and slender shape of tibial post compared to other retrieved prosthesis post designs. Our results are consistent with this study and hypothesized that apparent high von Mises stress of Superflex tibial post during deep squatting is characterized not only by its small posteromedial post radius, but aslo by its relatively tall and thin shape compared to NRG post geometry. Elimination of the sharp posteromedial edge in NRG post design provides more freedom to the axial rotation of tibial component, which in turn results in lower distortion in comparison to Superflex,. Tamaki et al. assessed the kinematics of NRG knee system and found the tibial component achieved maximum tibial rotation of 15.6° at 140° of knee flexion [13] . In contrast, fluoroscopic analysis by Kanekasu et al. measured only 7° tibial rotation at 140° of flexion with Superflex TKA [11].

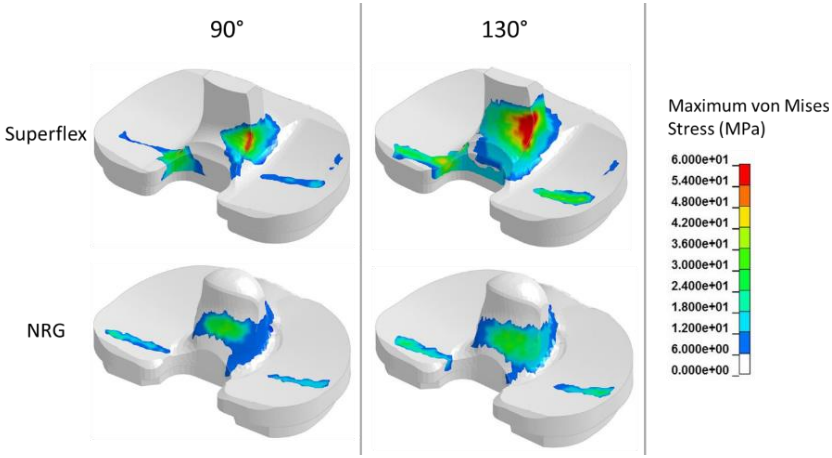

Figure 7: Contour of maximum von Mises stress at tibial insert articular surface for Superflex and NRG TKA implants at 90° and 130° of flexion angle, respectively, during deep squatting motion.

Mechanics of TKA during very high flexion is also attributed by condyle geometry. Appearance of biradial of curvature in anteroposterior direction with relatively higher articular surface anteriorly in Superflex condyle design has become another source of surface constraint, which in turn generate higher von Mises stress. Note the relatively high maximum von Mises stress appeared at anterior side of medial condyle of Superlflex at 90° and 130° of flexion angles as illustrated in Fig. 7. This observation suggests another reason of limited tibial internal rotation of Superflex TKA post-operative patients as discussed earlier. Apart from that, NRG femoral condyle is designed with smaller posterior radius which has successfully reduced the impingement and increased tibial clearance at posterior lateral condyle of PE insert. It can be seen by the relatively higher peak contact stress of Superflex during 130° flexion at posterior tibial condyle as shown in Fig. 6(a). This modification also has lowered the tibial insert distortion, as we observed lower maximum von Mises stress at very high flexion (120° - 135°) obtained by NRG due to less rotational constraint towards flexion motion. This is supported by the *in vivo* evaluation by Klein et al. who compared the range of motion between Superflex and NRG [12]. The average intraoperative knee flexion achieved was 122° for Superflex and 6° greater for NRG. Apart from that, the remarkable higher stress at posterior of Superflex PE condyle during deep flexion as illustrated in Fig. 7 is also characterized by the existence of posterior flange which is reduced in condylar design of NRG.

This study has some limitations. We used a simplified model which combined translation and force-driven knee motion. The action of knee soft tissues was only represented by the existence of two pairs of nonlinear springs which were positioned anteriorly and posteriorly to the tibial component. The ligamentous effect, for instant, position of ligaments insertion point and relative location of ligaments on tibial and femoral bone was not taken into consideration. Muscle driven knee model with better ligamentous effect which includes e.g. medial and lateral collateral ligament models can provide more realistic knee kinetics and kinematics. We assumed, however, the utilized FE model was sufficient to distinguish the performance of two different designs of knee implant as the simulation was performed under similar component alignment, soft-tissue constraint model and loading conditions. Another notable design modification of NRG is the size reduction of femoral anterior flange [13]. This design variable was not taken into account as the dynamic model used in this study excluded the mechanism of knee extensor e.g. quadriceps muscle action.

Conclusions

In conclusion, stress conditions of PE insert are closely related with implant design and at the same time provides insight into TKA knee range of motion. A good knee prosthetic design compromises between good conformity and appropriate motion resistance. Surface conformity must be considered in all planes including sagittal and axial planes for post-cam geometry, and frontal and sagittal planes for condylar design. Conforming interfaces serve good wear resistance, however provide surface constraint towards motion, which leads to surface distortion. Results of present research is beneficial for surgeons in selecting suitable knee implant for their patients as well as giving design guidelines to manufacturers in innovating better knee prosthesis in future.

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