A Photoelastic Study of Contact Stress on the Tibial Insert of Knee Prosthesis at Deep Flexion

by

Ansarullah LAWI^{*}, Keisuke SEKIYA^{*}, Junichiro TAKIGUCHI^{*} and Shunji HIROKAWA^{**}

(Received July 23, 2008)

Abstract

This paper presents the experimental results of photoelasticity for determining the magnitude and distributions of stresses on the polyethylene insert of typical three types of posterior stabilized knee prostheses designed to attain high/deep knee flexion. Three prostheses used in the experiment were a conventional posterior stabilizer knee, Scorpio NRG (Stryker Co., USA), Bisurface knee (Kyocera Inc., Japan) with a unique design with a ball-and-socket joint and CFK (Complete Flexion Knee, Japan Medical Material Co., Japan) which we have developed by further improving the Bi-surface so as to make a complete knee flexion. Epoxy resins were selected to fabricate the tibial insert models. Special equipment was used to apply 2 kg force on the model by setting knee flexion angle at 0°, 30°, 60°, 90° and 120° respectively. After that, the stressed model was sliced in parallel with the sagittal plane and photoelastic fringes in each slice were observed. The results demonstrated that while knee angle was smaller than 90°, shear stress on the lateral slice became highest for Bi-surface, followed CFK and NRG was lowest, indicating NRG has high conformity as to the condylar insert articulation. After knee angle bacame larger than 90°, shear stress on the mid-posterior slice became highest for NRG, followed Bi-surface and CFK was lowest. We may conclude that CFK has optimal configuration at deep knee flexion from a load bearing viewpoint.

Key Words: Knee prosthesis, Photoelasticity, Complete flexion, Post-cam, Ballsocket, Contact stress, FEM, Kinematics

1. Introduction

According to the statistics in 2005¹⁾, one third of the world population necessitate a sedentary sitting on a floor because of their life style or their religion. And the number of patients undergoing total knee arthroplasty (TKA) surgery in Asia and Muslim countries is growing steadily. Yet, one of the major problems to be solved is that the patients loose deep flexion of the knee after TKA. So far, various designs of the artificial knee joint have been proposed in order to attain deep flexion²⁾⁻⁸⁾. Among those developed thus far, *Bi-surface* knee prosthesis (Kyocera Inc., Japan) is of special interest because of its unique design with a ball-and-socket joint which functions not only as a posterior-stabilizing cam but also as a load-bearing surface in deep flexion⁵⁾. Still the maximum flexion angle of Bi-surface knee is up to about 150° and not good enough for performing such a sedentary sitting even with Bi-surface knee, the X-ray studies for their knee joints revealed that the femoral condyles and tibial insert were in separate, indicating a risk of subluxation when standing up. Whether the patient can make a sedentary position or not rests on his/her thigh and calf fatnesses.

Thus we have developed a new type of knee prosthesis by further improving the abovementioned Bi-surface knee so as to enable the patient to make a complete knee flexion as much as 180° and we designated it as *CFK* (Complete Flexion Knee, Japan Medical Material Co., Japan). Our CFK has a ball-and-socket joint as Bi-surface does and its socket part is jutted to the anteriorproximal direction to form a tibial post. The principal objectives of CFK are to avoid an

^{*} Graduate Student, Department of Intelligent Machinery and Systems

^{**} Professor, Department of Mechanical Engineering

impingement between the ball and the posterior hem of the socket by offsetting the ball, to allow internal/external rotation by a spherical bearing structure of a ball-and-socket and a post-and-cam. The spherical bearing structure of the ball-and-socket and the post-and-cam contributes to reduce contact stress as well as to guide the femoral motion relative to the tibia.

Prosthesis has to balance the range of flexion, the intrinsic stability and the durability. Thus our CFK with high stability and mobility has to be further assessed with respect to the durability. Since the durability of an artificial knee joint is mainly attributed to wear of the polyethylene insert, it is essential to focus on determining the magnitude and distributions of stresses on the insert. In Japan, the law does not permit cadaveric studies freely and the specimen can not be harvested as planned. Thus we attempted to perform some alternatives such as an FEM model analysis or a photoelastic analysis.

The FEM analyses have been most extensive for stress analyses in the artificial knee joint, since it can be applicable to the problem of the stress strain levels induced in the internal parts of tibial insert ^{6), 7)}. However, the results of the conventional FEM analyses greatly depend upon the way how to create the meshes. Ramesh et al. ⁸⁾ noted that photoelastic isochromatics can be effectively used to detect the FEM meshing problems. Secondly, the FEM techniques are based on the approximation of nodal displacements (not stresses) via shape functions whereas the formation of photoelastic fringes is governed by the distribution of stresses. Furthermore the stress values introduced from the FEM are the Von Misses stresses; while the wear is mainly attributed to the shear stresses. And thirdly, some experiments are necessary to verify the validity of the results from the FEM and vice versa. For these reasons, we employed a three-dimensional photoelasticity for determining the magnitude and distributions of stresses on the insert using the stress-freezing method.

This study carry out photoelastic experiments to evaluate the stress distributions and contact areas for the polyethylene tibial inserts of the above-mentioned Bi-surface, CFK and one of the contemporary posterior stabilized (PS type) knees.

2. Materials and Methods

2.1 Prostheses

The prostheses used in our study are shown in **Fig.1**. In **Fig.1**, (a) is a contemporary posterior stabilized knee prostheses, Scorpio NRG (Non Restricted Geometry) (Stryker Co., USA). (b) is Bi-surface, and (c) is CFK respectively. All are designed to attain high/deep flexion of a knee.



Fig.1 Overviews of typical three types of posterior stabilized knee prostheses designed to attain high/deep flexion of a knee.

The posterior stabilized knee prostheses are designed to stabilize anterior-posterior knee motion by mechanical interaction between the tibial post and the femoral cam after removal of the Posterior Cruciate Ligament. NRG (**Fig.1**, (a)) is designed for high flexion by allowing sufficient rollback to avoid bony impingement without increased resection. The tibial insert's articulating surface adapts a spherical arc in order to realize greater rotational freedom. Additionally, its post-and-cam configurations help accommodate the rotations on the post⁷⁾.

As already mentioned, the Bi-surface knee prosthesis (**Fig.1** (b)) has a unique ball-and-socket joint in the mid-posterior portion of the femoral and tibial components, which functions as a posterior stabilizing cam mechanism and as a load-bearing surface in flexion. The posterior condylar part of the tibial articular surface (Arrows $\langle --- \rangle$ in **Fig.1** (b)) is flattened in the anterior-posterior direction to provide axial-rotational freedom around the ball-and-socket joint.

CFK (**Fig.1** (c)) is designed so that it has both the advantages of NRG and Bi-surface. As **Fig.1** (c) shows, the ball-and-socket joint and the post-and-cam are virtually the same one. The principal objectives of this knee prosthesis are to avoid an impingement by offsetting the ball position, to allow internal/external rotation by a spherical bearing surface of the ball-socket and post-cam architecture and to avoid subluxation by keeping continuous contact even at the state of complete knee flexion.

Figure 2 shows the articulation modalities of three prostheses according to knee angle. For NRG, the femoral-cam comes into contact with the tibial post at around 60° of flexion. After that, it has three contact points: the medial and lateral condylar surfaces and the post-and-cam surface. The post-and-cam contact is aimed to enhance the roll-back but not to bear the load; the post-and-cam of NRG can not function as a load bearing joint over about 100° of flexion. As for Bi-surface, the femoral-ball comes into contact with the tibial socket at around 80° of flexion. Therefore, when a knee is more than 80° of flexion, it has three contact areas: the medial and lateral condylar surfaces and the ball-and-socket surface. At around 120° of flexion, it has only one contact point namely the ball-and-socket surface. At deep knee flexion (over 130°), the ball-and-socket maintains contact, however, sometimes the ball and the socket separate with each other or cause an impingement between the ball and the posterior hem of the socket; the maximum flexion angle is limited to 150° at most. CFK can maintain a continuous contact from full extension to full flexion starting with the contact between the femoral condyles and the tibial insert, via between the ball and the socket, until between the post and the cam, and vice versa from full flexion to full extension.

knee angle	0°	90°	150°	180°	
NRG	F-T contact*	Dost & Ca	am contact		
Bi-surface	E-T contact*	Ba	all & Socket con	tact	
CFK	F-T contact*	Ball & So		Post & Cam co	ntact

Fig.2 Articulation modalities of three prostheses according to knee angle.

2.2 Photoelastic Experiment

Basic Principle of Photoelasticity

Photoelastic measurement relies on the fact that the model being studied, when under stresses, can split an incident light vector into two components ⁹. The two components develop phase shifts,

and their relative retardation is proportional to the difference between the two principal stress values. When a model is viewed in monochromatic light, the relative retardation is counted as the fringe order. For linear photoelastic material, the difference in the principal strains can be measured by establishing the fringe order as well. This relation is expressed as,

$$N = tf_s(\sigma_1 - \sigma_2) \tag{1}$$

where t is the model thickness and f_s is the material fringe value for strain.

Stress-freezing photoelastic analysis is commonly used for analyzing stress in three-dimensional models. This technique is based on a behavior that is exhibit by polymeric substances when they are heated. When a high polymer is heated to a temperature slightly above its softening point, or its critical temperature (glass-transition temperature), its rigidity, expressed for example by the modulus elasticity, is greatly reduced, although the material retains its elastic behavior. Suppose a model is loaded at this temperature and then the applied loads are retained while the model is cooled to ambient temperature, a state of stress remains "frozen" in the model ¹⁰.

After stress-freezing, the model is sectioned into slices without disturbing the stress field and then the stress in each slice is analyzed using two-dimensional methods. For the analyses of the frozenstress fringe pattern, it is necessary to know the *material fringe value* of the plastics at the stressfreezing temperature ¹¹). For this purpose, a calibration has to be carried out, in which a pure bending is applied to a simple supported beam which is made of the same material as the model (**Fig. 3**).



Fig.3 Method used to support the calibration beam in pure bending.

When such a beam is removed from the oven after stress freezing and viewed in a circular polariscope the central region will contain a frozen pattern of uniformly spaced fringes, parallel to the beam axis (see **Fig. 6**). The stress and fringe order vary linearly from zero at the neutral axis to maximum values at the upper- and lower-beam boundaries. The material fringe value is calculated as follows:

$$f_s = \frac{3Pl_2}{2nd^2} \quad (N / m^2 / fringe) \tag{2}$$

where P = force applied to beam in pure bending (N: Newton), l_2 , = distance (m), N = fringe order at the beam boundary, and d = depth of beam (m).

Once the fringe value of the material is known, it is possible to calculate the maximum shear stress at any point on a slice. From the stress-optic law, it can be shown that

$$\alpha = \frac{1}{f_s} \quad (N/m) \tag{3}$$

$$\frac{\sigma_1 - \sigma_2}{2} = \frac{n}{t\alpha} \quad (N / m^2) \tag{4}$$

where α = photoelastic stress sensitivity (N/m), (σ_1 - σ_2)/2 = maximum shear stress (N/m²), *n* = fringe order at the point in question, f_s = material fringe value (N/m²/fringe/m) and *t* = thickness of slice (m).

Models

Tibial insert models were fabricated by the process illustrated in **Fig. 4**. First, a precision mold of the insert was made in silicone epoxy rubber (KE-RTV, Shinetsu Silicone Co., Japan). The insert was first encased in plasticine, and the plasticine mass was covered with dental plaster. Once the plaster was hard, the mold was split in half. Half the plasticine was removed, exposing half the insert and the mold halves were rejoined. Silicone rubber was poured into the hollow. After the rubber had cured, the procedure was repeated for the other half of the mold. The hardener rubber was cut in half and the insert was removed. The result was a hollow silicone rubber mold of the entire plaster. The two halves of the mold were rejoined, and epoxy monomer for the insert model was prepared by mixing two types of araldite (GY 250 and GY 1252, Ciba Geigy Co., Japan) and hardener (HY 950, Ciba Geigy Co.) at 43°C in the ratio of 1:1:0.2. A vibrator mixer used at each stage to avoid the formation of air bubbles. The mixture was poured into silicone molds and cured for 12 hours at room temperature. To prevent additional stress, the models were all cooled by water during the slicing process¹².



Fig.4 Method used to fabricate the photoelastic models.

A calibration beam with the dimension of 32 x 20 x 6 mm was also fabricated from the same mixture as the models in order to introduce the glass-transition temperature of the model material as well as to introduce the material fringe value for strain. **Figure 5** shows the variations of Young's modulus as a function of temperature. We found that stress-birefringence was elastic with the most ideal situation at 90°C ($\alpha = 37.6$). **Figure 6** shows an example of frozen-stress pattern on the calibration beam showing uniformly spaced fringes.

145



Fig.5 Fringe values vs. temperature for frozen stress.



Fig.6 Frozen-stress pattern on the calibration beam showing uniformly spaced fringes.

Experimental set-up

Figure 7 shows the experimental set-up. A special tool was designed to permit identical simultaneous loading to the model in a temperature-controlled environmental chamber. A universal joint with six degree of freedom was used to set the tibia with arbitral 3D orientations relative to the femur, thereby making knee flexion angles from 0° to 120° . At every angle of knee flexion, a 2 kg load was applied to the tibia from the femur in the direction along the femoral axis.



Fig. 7 Experimental set-up

3. Results

The stress distributions in the insert model were analyzed and compared for two locations of each type, i.e. the mid-posterior side and the lateral side. The mid-posterior side was selected mainly to assess the stress on the post (socket) at higher knee flexion, while the lateral side was selected to asses the stress on the femoral condylar articulating surface of the insert at lower knee flexion. **Figure 8** and **9** show the results from the three prostheses: the isochromatics of model slices in the

mid-posterior and the lateral areas at 0° , 30° , 60° , 90° and 120° of knee flexion respectively. Small arrow indicates stress concentration point.



Fig. 8 Isochromatics of the slices in the mid-posterior side.



Fig. 9 Isochromatics of the slices in the lateral side.

From **Fig.8**, we may summarize the most stressed areas and the maximum stress values in the mid-posterior side for the three prostheses as,

NRG

At 0°, stress is found in back side of tibial model. At 30° and 120°, small fringes are observed. The maximum order of isochromatics is 3.1 at 90°. Stress concentrations are found at 60° and 90°.

Bi-surface

The maximum order of isochromatics is 3.65 at 120°. No stress patterns appeared at 0° or 30°, while at 60°, 90° and 120°, high stress concentrations were found.

CFK

The maximum order of isochromatics is 2 at 120° . No stress concentrations are found at 0° , 30 and 60° .

Also from **Fig.9**, we may also summarize the results in the lateral sides for three prostheses as, *NRG*

The maximum order of isochromatics is 3 at 60°. Stress concentrations move posteriorly according as a knee flexes and then disappear at 120°.

Bi-surface

The maximum order of isochromatics is 3 at 60°. No stress patterns appeared at 90° or 120° CFK

The maximum order of isochromatics is 3 at 60°. No stress concentrations are found at 120°.

Using the relationship between the fringe order and the shear stress values for the same material as the models, we can calculate the maximum shear stress values on the insert model as shown in **Table 1**, which provides the comparison of the maximum shear stresses between the three prostheses.

Figure 10 (a), (b) illustrate the variations of maximum shear stresses for the three prostheses as a function of knee angles. First, by comparing Fig.10 (a) and (b), we find that every prosthesis replace the contact modality from that between the femoral condyles and the tibial insert to that between ball and socket or post and cam after 60° of knee flexion. From Fig.10 (a), we know that the shear stresses of NRG and Bi-surface start to increase from 30° of knee flexion, while that of CFK from 60° . After 60° of knee flexion, Bi-surface keeps constant value while NRG and CFK show an increase. After 90° of knee flexion, the stresses of three prostheses go diverging with each other; Bi-surface again increases, NRG makes rapid decrease and CFK keeps constant value. At 120° of knee flexion, The stress of Bi-surface reaches highest among the three prostheses at that angle indicating the impingement between the ball and the posterior hem of the socket. On the other hand, CFK shows constant stress with moderate value, which indicates the spherical bearing structure between the post and cam works reasonably well.

From **Fig.10** (b), we know that the shear stresses of three prostheses show similar variations through whole range of knee flexion. However precise observation reveals that the variation pattern of NRG is more uniform than those of Bi-surface and CFK. Thus we may say, NRG is best as to the conformity between the femoral condyle and the tibial insert as long as a knee angle is smaller than 90°.

Prosthesis	Knee flexion angle (9	Midposterior side (post-cam)		Lateral side		
		Fringe order	Shear stress (kPa)	Fringe order	Shear stress (kPa)	
NRG	0	0	0	1.39	52.5	
	30	0	0	1.82	60.8	
	60	2.5	70.8	3	71.1	
	90	3.1	91.8	1.39	51.8	
	120	0	0	0	0	
Bi-surface	0	0	0	1.39	54.1	
	30	0	0	1.82	74.1	
	60	3.1	109.2	3	78.2	
	90	3.1	109.2	0	0	
	120	3.65	128.6	0	0	
CFK	0	0	0	1.39	54.1	
	30	0	0	1.22	49.7	
	60	0	0	3	78.2	
	90	1.82	53.9	1.22	37.9	
	120	2	54.9	0	0 149	

Table 1 Shear stress in the midposterior and lateral side of three prostheses.



Fig. 10 Comparison of the maximum shear stresses for the three prostheses as a function of knee angle.

Figure 11 shows the stress distribution patterns on the post-and-cam or the ball-and-socket at 90° of knee flexion. It is clearly seen that the stressed area is much wider for NRG than for others. As for CFK, it should be cautioned that the thickness of stressed area is not enough.



Fig. 11 Stress distribution patterns on the post-and-cam or the ball-and-socket at 90° of knee flexion.

4. Discussion

As a knee prosthesis has been initially developed for the western people, the kinematics or kinetics at high/deep knee flexion has not been seriously taken into consideration for designing it. Recently not only Asian or Arabic people but also the western people began to demand knee prosthesis capable of deep knee flexion because they dissatisfied with loosing the range of knee motion after TKA.

To this respect, many of the conventional PS type prostheses have been remodeled to attain high/deep flexion. The primary concept for this is to round the edge of femoral posterior condyles⁴⁾. While Bi-surface has a unique feature quite different from the conventional PS types. CFK has followed the design concept of Bi-surface. Such a design as Bi-surface or CFK may contribute to improve the prosthetic kinematics however, it is not yet sure whether their kinematic advantage could balance with the durability. The prosthetic durability is mainly attributed to wear which is further attributed the stresses exerted on and in the polyethylene insert. Thus we carried out photoelastic measurements. Since the forces transmitted on a knee joint during lower limb's activities are not well known, we evaluated the stresses on CFK by comparing them with those on other prostheses, i.e. NRG and Bi-surface.

The results from our experiment demonstrated that the stress on the tibio femoral articulating surfaces was relatively low and its variation pattern was uniform for NRG while knee flexion angle was smaller than 90° (Fig.10 (b)). This means the configuration of NRG is well designed for usual activities of lower limb, such as walking. Unfortunatelly however, NRG did not introduce stress on the post and cam when knee angle was larger than 120° (Fig.10 (a)). This is because NRG could not make a knee flexion larger than 120°, indicating subluxiation. For a range of knee flexion between 90° and 120°, stress values on the post and cam were relatively high. This means that the post and cam configurations are not well designed for a weight bearing viewpoint. The stress on the post and cam of CFK showed low and stable values after 90° of knee flexion, demonstrating the advantage that the post and cam have spherical bearing structure. Contraly to our expectation, the Bi-surface's ball and socket marked pretty high stresses. Observation of photoelastic frings reveald that stress concentration was generated due to impingement at the posterior hem of the polyethylene insert. Although it is reported that a patient could achieve full flexion with the Bi-surface knee⁵, it is highly possible that a tibio femoral separation or the above mentioned impingement gave to rise. Although it is a current notion that no prostheses can keep both stability and durability in high flexion, CFK showed stability with low stresses even at deep flexion.

There are limitations in our present study. We only applied the load with the fixed value to the fixed direction, and the measurements were carried out under static condition. In order to overcome these problems, we are planning to develop a real-time photoelastic fringe measurement method instead of the conventional stress freezing method, and also planning to use a robot for a load application equipment.

5. Conclusion

We have performed photoelastic studies to determine the magnitude and distributions of stresses on the polyethylene insert of typical three types of posterior stabilized knee prostheses which had been designed to attain high/deep knee flexion. They were, NRG (a conventional posterior stabilizing prosthesis), Bi-surface (a prosthesis with a unique design in order to attain deep flexion) and CFK (a newly developed prosthesis aiming to make a complete knee flexion).

While knee angle was smaller than 90°, contacts were made on the tibio femoral articulating surfaces. Thus the shear stresses on the lateral slice were mainly investigated. The results demonstrated that NRG has high conformity with lowest stress, CFK was second and Bi-surface was third with highest stress.

After knee angle bacame larger than 90° , contacts were made on the ball-socket or the post-cam portions. Thus the stresses on the mid-posterior slice were mainly investigated. The results demonstrated that CFK has high conformity with lowest stress, Bi-surface was second and NRG was third. Over about 120° of knee flexion, it was found that the post-cam contact could not be maintained for NRG, indicating a subluxiation.

We may conclude that CFK has optimal configuration for deep knee flexion from a load bearing viewpoint. We may also conclude that the photoelastic study would be helpful to complement the results from the FEM analyses.

ACKNOWLEDGMENTS

This research program is supported by the Japanese Government Grand in Aid for General Scientific Research, category B(1) (2008,20300161). The authors express their gratitude to Doctor Takao Hotokebuchi, Professor of Medical School, Saga University for his help for this study.

References

- 1) http://www.adherents.com/Religions_By_Adherents.html
- K.Nakayama, S.Matsuda, H.Miura, et al., Contact Stress At the Post-cam Mechanism in Posterior-Stabilised Total Knee Arthroplasty, The Journal of Bone & Joint Surgey, Vol.87-B, No.4, pp483-488 (2005).
- E.A.Morra and A.S.Greenwald, Polymer Insert Stress in Total Knee Designs During Highflexion Activities: A Finite Element Study, The Journal of Bone & Joint Surgey, Vol.87-B, pp.120-124 (2005).
- H. Huang, J.Y. Su and G. Wang, The Early Results of High-flex Total Knee Arthroplasty: A minimum of 2 Years of Follow-up, The Journal of Arthroplasty, Vol.20, No.5, pp.120-124 (2005).
- M. Akagi, T. Nakamura, Y. Matsusue, T. Ueo, K. Nishijyo and E. Ohnishi, The Bisurface Total Knee Replacement: A Unique Design for Flexion, The Journal of Bone and Joint Surgery, Vol.82-A, No.11, pp.1626-1633 (2000).
- C.Shashishekar and C.S.Ramesh, Finite Element Analysis of Prosthetic Knee Joint Using ANSYS, Biomedicine and Health, Vol.12, pp.65-72 (2007).
- M.Todo, R.Nagamine and S.Yamaguchi, Stress Analysis of PS Type Knee Prostheses under Deep Flexion, Journal of Biomechanical Science and Engineering, Vol.2, No.4, pp.237-245 (2007)
- 8) K.Ramesh and PM.Pathak, Role of Photoelasticity in Evolving Discretization Schemes for FE Analysis, Journal of Experimental Techniques, Vol.23(4), pp.36-38 (1999).
- 9) S.Hirokawa, K.Yamamoto and T.Kawada, A Photoelastic Study of Ligament Strain, IEEE Transactions on Rehabilitation Engineering, Vol.6, No.3, pp.300-308 (1998).
- P.S.Theocaris & E.E.Gdoutos, Matrix Theory of Photoelasticity, Springer Series in Optical Sciences, Vol.11, pp.132-137 (1979).
- 11) B.L.Stewart and R.O.Edwards, Removable Partial Denture Design: A Photoelastic Study, Journal of Biomedical Material Research, Vol.18, pp.979-990 (1984).
- M.Wang, M.Zang and J.Zang, Photoelastic Study of the Effects of Occlusal Morphology on Tooth Apical Stress from Vertical Bite Forces, Journal of Contemporary Dental Practiceournal of Experimental Techniques, Vol.5(1), pp.74-93 (2004).