Variable tibiofemoral articular contact stress in fixed-bearing total knee arthroplasties

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ABSTRACT
Background: Rotational allowance at the tibiofemoral joint would be required during deep flexion. However, the amount of flexion and rotation has not been investigated in modern total knee arthroplasty (TKA) designs. The present study aimed to determine the contact stress in five posterior-stabilized fixed-bearing TKA designs.

Hypothesis: We hypothesized that the contact area and stresses at the tibiofemoral articular surfaces vary according to the type of implant design and tested condition.

Materials and methods: The contact area and mean and peak contact stresses at the tibiofemoral articular surfaces were determined when a compressive load of 1200 N was applied to a NexGen LPS Flex, Scorpio NRG, Genesis II, PFC Sigma, and Foundation implant. Measurements were performed at 0° and 45° flexion with 0°, 5°, 10°, and 15° rotation, and at 90° and 135° flexion with 0°, 5°, 10°, 15°, and 20° rotation.

Results: The LPS Flex showed that the femoral component could not achieve 20° rotation at 135° flexion. The Scorpio NRG showed less than 20 MPa of contact stress at all conditions. The Genesis II showed higher contact stress than 20 MPa at 135° flexion with 20° rotation. The PFC Sigma showed that the femoral component could not achieve >10° rotation at any flexion angle. The Foundation showed more than 20 MPa of contact stress at 90° flexion with 20° rotation and at 135° flexion with 10°, 15°, and 20° rotation.

Discussion: Surgeons should be more aware of the variable contact conditions of the tibiofemoral articular surfaces in individual TKA designs.

Level of evidence: Level IV, basic science study.

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1. Introduction

Total knee arthroplasty (TKA) has become one of the successful orthopedic treatments for improving pain and function in patients with knee osteoarthritis, with great long-term survivorship. As an increasing number of TKAs is being performed on younger and more physically fit patients [1], it is important to optimize contact stress in order to reduce the wear rate and improve long-term survivorship [2,3].

In addition to implant position and soft tissue balance, design characteristics have a direct effect on kinematics during weight-bearing activities including deep knee flexed posture [4]. Although a wide range of tibiofemoral axial rotation would be required during deep flexion (>120°) [5], even knee prostheses of the same type have different allowance of flexion and rotation. Especially in fixed-bearing TKA, the rotational allowance at the tibiofemoral joint is important to prevent deep knee flexion disturbance and/or loading eccentricity at the polyethylene insert. However, no previous study has examined the amount of flexion and rotation without edge loading in modern TKA designs.

The purpose of this study was to evaluate the contact location, area, and stress of the tibiofemoral articular surfaces in five types of fixed-bearing TKA. We sought to answer two specific questions:

• how do the design characteristics affect the contact location, area, and stress at the articular surfaces?
• how do the tibiofemoral flexion and axial rotation increase the contact stress in each TKA design?

We hypothesized that the geometry of the tibiofemoral articular surfaces significantly affect contact conditions, and that some TKA designs show high contact stresses under some tested conditions.

2. Materials and methods

2.1. Materials

Five posterior-stabilized (PS) fixed-bearing TKAs in size-matched femoral components and inserts were analyzed: the NexGen LPS Flex (Zimmer-Biomet, Warsaw, Indiana, USA), the Scorpio NRG (Stryker, Mahwah, New Jersey, USA), the Genesis II (Smith & Nephew, Memphis, USA), the PFC Sigma (Depuy Synthes, Warsaw, IN, USA), and the Foundation (Encore Medical Co., Austin, TX, USA). The curvature of the polyethylene insert was assessed using a profilometer (Mitsutoyo Co., Ltd., Kanagawa, Japan) and computer-aided design software program (SolidWorks 2001Plus SP3.0, SolidWorks Corporation, Massachusetts, USA). The characteristics of the symmetrical polyethylene articular surface in the five TKAs are described as follows (Fig. 1): the LPS Flex has curved surfaces in the coronal plane and a curved surface inclined posteriorly in the sagittal plane. The Scorpio NRG has flat surfaces inclined toward the center in the coronal plane and curved surfaces in the sagittal plane. The Genesis II has concave surfaces in the mid-to-lateral and mid-to-anterior portion and convex surfaces in the central and posterior portion. The PFC Sigma has curved surfaces in both the coronal and sagittal plane. The Foundation has flat surfaces in the mid-to-lateral and mid-to-posterior portion and curved surfaces in the central and anterior portion. Symmetric (LPS Flex, Scorpio NRG, PFC Sigma, and Foundation) and asymmetric (Genesis II) femoral condyles were designed with a multi anteroposterior (AP) radius, a femoral sagittal profile with a smaller radius in 135° of flexion than in extension.

3. Methods

The experimental method used in this study was described previously [6]. All experimentations were performed by mechanical engineers HH, TS, and SI, at Kyushu Sangyo University in 2011. The femoral and tibial components with polyethylene insert were mounted onto a six-degrees-of-freedom (6-DOF) knee simulator...
with parallel-link six-axis servo-hydraulic actuators [7]. An axial compressive load of 1200 N was applied to the femoral component against the tibial component [8,9]. The position of the femoral component in the coronal plane was adjusted so that both the medial and lateral femoral condyles contacted the tibial articular surfaces. A digital electronic pressure sensor (K-scan sensor, Tekscan Inc., Boston, Massachusetts, USA) was placed at the bilateral interfaces between the femoral and tibial polyethylene insert to measure both the contact area and stress.

3.1. Methods of assessment

Measurements were performed at 0°, 45°, 90°, and 135° of flexion of the femoral component, with 0°, 10°, and 15° of internal rotation of the tibial component relative to the femoral component. In terms of 90° and 135° of flexion, 20° of internal rotation of the tibial component relative to the femoral component was additionally evaluated. The applied component flexion angles of 0° to 135°, and the rotation angles of 0° to 20°, were determined according to kinematic data in previous study [5,6]. Spine-cam engagement is designed to work for implant flexion angles above 90° for all of the components. Each measurement was sequentially performed five times. Peak contact stress, defined as the highest stress of all the sensing locations, as well as the mean contact stress and contact area, were automatically calculated using Tekscan software (Tekscan Inc.).

3.2. Statistical analysis

The contact area and stress were compared across angles of flexion within each design and across the implants at each angle of flexion and rotation of the femoral component and internal rotation of the tibial component using analysis of variance and a post-hoc test. The peak contact stress with the tibial insert in neutral position was compared with that in rotation for each design at each angle of flexion. Statistical analysis was performed using JMP Software (Version 11.0; SAS Institute Inc., Cary, NC, USA). All values were expressed as the mean ± standard deviation. Probability values of less than 0.05 were considered to be statistically significant.

4. Results

4.1. Contact location and area

The each contact location and area on the articular surfaces of the polyethylene insert are presented in Fig. 2. The contact location translated posteriorly with flexion in all designs. Due to the constraint of articular surfaces and spine-cam mechanism, the LPS Flex could not rotate up to 20° at 135° of flexion or the PFC Sigma could not flex up to 135° of flexion. In the Scorpio NRG, Genesis II, and Foundation, the lateral contact location translated to the posterior edge of the lateral articular surface at 135° of flexion with 20° of rotation.

The each contact area on the insert is presented in Fig. 3. At 45° and 90° of flexion, the LPS Flex was significantly larger than the other designs. At 0° and 135° of flexion, the Scorpio NRG was significantly larger than the others. The Genesis II decreased with flexion and was significantly smaller than the others at 0° and 135° of flexion. The PFC Sigma was significantly larger than the others at 0° and 90° of flexion, except for the Scorpio NRG at 0° of flexion and the LPS Flex at 90° of flexion, but could not flex up to 135° of flexion. The Foundation was significantly smaller than the others at 45° and 90° of flexion.

4.2. Contact stress

The mean contact stress demonstrated an opposite trend to the contact area (Fig. 4). The LPS Flex was significantly higher than the other designs at 0° of flexion, but significantly lower than the others at 45° and 90° of flexion. The Scorpio NRG was significantly lower
than the others at 0° and 135° of flexion. The Genesis II increased with flexion and was significantly higher than the others at 45° and 135° of flexion. The PFC Sigma was significantly lower than the others at 0° and 90° of flexion, except for the Scorpio NRG at 0° of flexion and the LPS Flex at 90° of flexion, but could not flex up to 135° of flexion. The Foundation showed the highest mean contact stress at 90° of flexion.

The each peak contact stress distribution is presented in Fig. 2 and Tables 1 and 2. The peak contact stress ranged from 8.3 to 17.4 MPa; this range was approximately two times higher than the range of the mean contact stress for each flexion angle (Fig. 5). The LPS Flex was significantly higher than the other designs at 0° of flexion, but was significantly lower than the others at 45° of flexion. The Scorpio NRG was significantly lower than the others at 0° of flexion. The PFC Sigma was significantly lower than the others at 90° of flexion, but could not flex up to 135° of flexion. The Foundation was significantly higher at 45° of flexion, but significantly lower at 135° of flexion compared with the others.

4.3. Effect of rotation of the tibial component

The effects of rotation and TKA design on the peak stress are presented in Figs. 2 and 6 and Tables 1 and 2, respectively. The LPS Flex at 20° of rotation was significantly higher than at 0°, 5°, 10°, and 15° of rotation, approaching 20 MPa, and could not rotate up to 20° at 135° of flexion. The Scorpio NRG could rotate up to 20°
Table 1
The peak contact stress for the five tested designs at 0° of flexion with neutral rotation and 15° of rotation.

<table>
<thead>
<tr>
<th>Design</th>
<th>0° of flexion with neutral rotation (MPa)</th>
<th>0° of flexion with 15° of rotation (MPa)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPS Flex</td>
<td>14.1 ± 0.3b</td>
<td>14.9 ± 0.3b</td>
<td>0.003³</td>
</tr>
<tr>
<td>Scorpio NRG</td>
<td>8.3 ± 0.3b</td>
<td>14.0 ± 0.6</td>
<td>&lt;0.0001⁴</td>
</tr>
<tr>
<td>Genesis II</td>
<td>12.4 ± 0.3bc</td>
<td>15.4 ± 0.1c</td>
<td>&lt;0.0001⁴</td>
</tr>
<tr>
<td>PFC Sigma</td>
<td>13.0 ± 0.1bcd</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Foundation</td>
<td>12.6 ± 0.1c</td>
<td>13.0 ± 1.0b,c</td>
<td>0.45</td>
</tr>
</tbody>
</table>

N/A: not applicable. Level of significance: p < 0.05.

³ Significant difference between neutral rotation and 15° of external rotation.
⁴ Significant difference between LPS Flex and Scorpio NRG/Genesis II/PFC Sigma/Foundation.

Table 2
The peak contact stress for the five tested designs at 135° of flexion with neutral rotation and 20° of rotation.

<table>
<thead>
<tr>
<th>Design</th>
<th>135° of flexion with neutral rotation (MPa)</th>
<th>135° of flexion with 20° of rotation (MPa)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPS Flex</td>
<td>16.1 ± 0.2b</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Scorpio NRG</td>
<td>15.3 ± 0.2bc</td>
<td>16.3 ± 0.4</td>
<td>0.002³</td>
</tr>
<tr>
<td>Genesis II</td>
<td>17.4 ± 0.2b,c</td>
<td>22.0 ± 0.3cd</td>
<td>&lt;0.0001⁴</td>
</tr>
<tr>
<td>PFC Sigma</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Foundation</td>
<td>14.3 ± 0.1b,cd</td>
<td>20.7 ± 0.2d</td>
<td>&lt;0.0001⁴</td>
</tr>
</tbody>
</table>

N/A: not applicable. Level of significance: p < 0.05.

³ Significant difference between neutral rotation and 15° of external rotation.
⁴ Significant difference between LPS Flex and Scorpio NRG/Genesis II/Foundation.

Fig. 5. The peak contact stress (MPa) for the five designs at 0°, 45°, 90°, and 135° of flexion with neutral rotation. *: level of significance (p < 0.05).

with a peak contact stress lower than 20 MPa at all conditions. The Genesis II at 20° of rotation was significantly higher than at 0°, 10°, 15°, and 20° of rotation, and higher than 20 MPa at 135° of flexion with 20° of rotation. The PFC Sigma was lower than 15 MPa at 0°, 45°, and 90° of flexion with 0° and 5° of rotation, but did not flex up to 135° or rotate up to 10°. The Foundation at 20° of rotation was significantly higher than at 5°, 10°, 15°, and 15° of rotation, and higher than 20 MPa at 90° of flexion with 20° of rotation and at 135° of flexion with 10°, 15°, and 20° of rotation.

5. Discussion

The present study analyzed the contact stress and area at the tibiofemoral joint of the NexGen LPS Flex, Scorpio NRG, Genesis II, PFC Sigma, and Foundation components mounted on a 6-DOF knee simulator. To the best of our knowledge, no previous study has assessed the contact conditions on the tested implants. The contact area and the mean and peak contact stresses varied among all five fixed-bearing TKA designs and test conditions. In the LPS Flex,
the femoral component could not rotate up to 20° relative to the tibial component at 135° of flexion due to the constraint of articular surfaces and spine-cam mechanism. The Scorpio NRG had a stable contact condition even at 135° of flexion with 20° of rotation. In the PFC Sigma, the femoral component could not flex up to 135° or rotate up to 10° relative to the tibial component due to the impingement of the sidewall of the intercondylar box on the polyethylene post.

There are some limitations to our study. First, this testing condition did not exactly replicate implant-specific kinematics. Second, it is necessary to evaluate the force distribution of the articular surfaces under dynamic loading conditions with muscle/ligamentous constraint. However, the present study was a direct comparison of contact area and stress among different implants under the same conditions. Finally, this study concentrates on the attention on the implant functionality in terms of contact stresses, and disregards the manufacturing methods and polyethylene properties.

In the LPS Flex, the peak contact stress in the lateral articular surface has been shown to increase at deep flexion with the axial rotation approaching the compressive yield stress for polyethylene ranging from 20 MPa to 30 MPa [10]. It has been reported that the lateral femoral condyle translated to the posterior edge of the tibial surface in the NexGen LPS during kneeling [4] and Japanese-style deep flexion (seiza-sitting) [11]. The LPS Flex had more damage in the posterior regions of the retrieval articular surfaces [12], which is consistent with our knee simulator study. The femoral component could not rotate up to 20° relative to the tibial component at 135° of flexion because of the constraint of articular surfaces and spine-cam mechanism. Rotational mismatch between femoral and tibial components could result in even more limited tibiofemoral rotation and poorer subsequent functional outcomes [13].

The Scorpio NRG showed less than 20 MPa of peak contact stress on articular surfaces at all experimental conditions. No remarkable increase of peak contact stress with rotation could be due to the spherical arc articular surfaces in the transverse plane [14]. The Scorpio NRG demonstrated much better maximum flexion, lateral condyle movement, and tibial internal rotation compared with the conventional ScorpioFlex [15]. Other kinematic study also demonstrated a nearly physiological range of axial rotation during activities [4]. The potential benefit to accommodate higher flexion and greater axial rotation could be especially appealing for young and active patients.

The Genesis II showed a generally stable peak contact stress, except in the medial contact location exceeding 20 MPa at 135° of flexion with 20° of rotation. The Genesis II has the inflection point of the curvature in the posterior regions of the polyethylene surfaces. Therefore, the contact area located on the vertically prominent point could be smaller than the anterior and central regions of the articular surface. Although a retrieval study demonstrated that reaching deep flexion itself did not cause articular surface damage [16], it has been reported that in the posterior region in high-flexion PS TKAs including the Genesis II, increased deformation compared with traditional PS designs could be associated with higher contact stresses [12].

The PFC Sigma has a low contact stress from 0° to 90° of flexion with 0° and 5° of rotation because of the high tibiofemoral conformity. However, knee motion was restricted up to 135° of flexion and 10° of rotation because of the box-post impingement throughout the range of motion [17]. High constraint could improve the AP and mediolateral stability and provide reproducible knee-joint kinematics [18], but might cause patient complaints, debonding of the cement-prosthesis interface, progressive loosening, and osteolysis [17]. Even though the components are placed at proper alignment, a fixed-bearing prosthesis without enough rotational allowance could generate high contact stress at articular surfaces transmitting to the modular interfaces and metal-cement interfaces [17]. The PFC Sigma has rotating-platform mobile-bearing as another option to promote a self-alignment mechanism, which may contribute to lower contact stresses even in rotational malalignment [19,20].

The Foundation provided more than 20 MPa of peak contact stress at 0° of flexion with 20° of rotation and at 135° of flexion with 10°, 15°, and 20° of rotation. A high peak contact stress in various conditions may account for the relatively flat polyethylene articular surfaces and small radii of curvatures in the posterior femoral condyles. Although the flat type could be designed to allow
more AP translation and axial rotation, it has been reported that the curved-on-curved design could prevent the increase in contact stresses and improve durability against polyethylene wear [21]. Further investigations are needed to evaluate the durability of clinical polyethylene wear and damage when subjected to over-loading for the long term.

In conclusion, the present study showed that the contact area and stress varied depending on the implant design and tested conditions. Further modification of the tibiofemoral articular surfaces is necessary to provide rotational allowance in the deeply flexed knee. Our findings may help surgeons to be more aware that variable contact conditions on the polyethylene insert can occur in individual TKA designs.

Disclosure of interest

The authors declare that they have no competing interest.

Acknowledgements

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References