Femoral condylar lift-off in vivo in total knee arthroplasty

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We carried out weight-bearing video radiological studies on 40 patients with a total knee arthroplasty (TKA), to determine the presence and magnitude of femoral condylar lift-off. Half (20) had posterior-cruciate-retaining (PCR) and half (20) posterior-cruciate-substituting (PS) prostheses. The selected patients had successful arthroplasties with no pain or instability. Each carried out successive weight-bearing knee bends to maximum flexion, and the radiological video tapes were analysed using an interactive model-fitting technique.

Femoral lift-off was seen at some increment of knee flexion in 75% of patients (PCR TKA 70%; PS TKA 80%). The mean values for lift-off were 1.2 mm with a PCR TKA and 1.4 mm with a PS TKA. Lift-off occurred mostly laterally with the PCR TKA, and both medially and laterally with the PS TKA. Separation between the femoral condyles and the articular surface of the tibia was recorded at 0°, 30°, 60° and 90° of flexion. Femoral condylar lift-off may contribute to eccentric polyethylene wear, particularly in designs of TKA which have flatter condyles. Coronal conformity is an important consideration in the design of a TKA.

Received 5 October 1999; Accepted after revision 24 March 2000

Retrieval studies of tibial inserts after total knee arthroplasty (TKA) have shown many examples of eccentric wear of the polyethylene. The distribution of force across the knee during midstance is approximately 70% to 75% medially and 25% to 30% laterally,1-3 but this may be substantially different if femoral condylar lift-off occurs.4-5 This may lead to: 1) eccentric loading; 2) premature wear of polyethylene; 3) excessive load on subchondral cancellous bone; and 4) premature loosening of the prosthesis. Nilsson and Kärrholm6 carried out a roentgen stereophotogrammetric analysis (RSA) of 45 patients after insertion of either a cemented or an uncemented TKA. They assessed micro-movement of the components and showed that in the presence of condylar lift-off asymmetrical subsidence and tilting of the tibial component could occur, suggesting uneven loading. Our aim was to determine if condylar lift-off occurs during weight-bearing deep knee bends in vivo.

Patients and Methods

Medial and lateral femorotibial condylar separations were determined in the knees of 40 patients with a TKA. A posterior-cruciate-retaining (PCR) TKA with a relatively flat posterior lipped polyethylene insert had been introduced in 20 patients, and a posterior-cruciate-substituting (PS) prosthesis (Press-Fit Condylar design; Johnson & Johnson Professional Incorporated, Raynham, Massachusetts) in a further 20. The coronal conformity of the PCR and PS TKA designs was similar. The patients were chosen randomly from a group with clinically successful arthroplasties (Hospital for Special Surgery Knee Scores,7 PCR = 92.7, PS = 96.9 points), who had no ligamentous laxity or pain. Table I gives the clinical details of the two groups. We performed a statistical analysis comparing these groups using Student's t-test and multivariate regression analysis to correlate clinical parameters with condylar lift-off. All procedures had been carried out by a single surgeon using a standardised technique. Identical techniques for ligamentous balancing were used in both groups. Recession of the posterior cruciate ligament was undertaken when indicated. The femoral component was introduced with its axis of rotation as parallel as possible to the transepicondylar axis. The tests were performed at a minimum of one year after operation.

Under radiological surveillance, the patients carried out three successive deep knee bends from full extension to maximum flexion in the sagittal plane as if picking up an
object from the floor, with no constraints applied to either the hip, knee, ankle or foot. A Siremobil 2000 Digital x-ray image intensifier (Siemens, Iselin, New Jersey) was used and the images were recorded on a workstation computer. They were then stored on videotape for subsequent redigitisation using a frame grabber. The position of contact between the femur and the tibia was determined using a three-dimensional (3D) model-fitting technique.\textsuperscript{8,9} The 3D computer-aided design (CAD) solid models of the femoral and tibial components were overlaid on to the two-dimensional (2D) radiological images using a 3D model-fitting technique as described below (Fig. 1). The 3D image was then rotated to a frontal view and the distances from the medial and lateral femoral condyles to the tibial tray were measured (Fig. 2). The difference between medial and lateral measurements was considered to represent condylar lift-off if it was greater than 0.75 mm. Images were analysed at 0°, 30°, 60° and 90° of flexion.

### Table I. Details of the 20 patients who had PS TKA and the 20 who had PCR TKA

<table>
<thead>
<tr>
<th></th>
<th>PS</th>
<th>PCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>M 14</td>
<td>F 7</td>
</tr>
<tr>
<td></td>
<td>F 6</td>
<td></td>
</tr>
<tr>
<td>Mean age in years</td>
<td>70.3</td>
<td>65.8</td>
</tr>
<tr>
<td>Mean flexion in degrees</td>
<td>Preoperative</td>
<td>112.1</td>
</tr>
<tr>
<td></td>
<td>Postoperative</td>
<td>106</td>
</tr>
<tr>
<td>Mean coronal alignment</td>
<td>Preoperative</td>
<td>2.66 varus (14 varus to 17 valgus)</td>
</tr>
<tr>
<td></td>
<td>Postoperative</td>
<td>5.6 (3 to 8 valgus)</td>
</tr>
</tbody>
</table>

#### 3D model fitting. Using a model developed from a technique of 3D overlay which has been described previously,\textsuperscript{8,9} the relative position of the components was recorded in 3D from a single-perspective image by manipulating a CAD model in 3D space. A 3D unit was then created on a Silicon Graphics Indigo workstation (Mountainview, California) in C++ using the Open Inventor Toolkit library (Mountainview, California). AutoCAD (San Rafael, California) was used to extract measurements.

Individual radiological frames were digitised at specified degrees of flexion. The operator manipulated the models to create a correct fit when the silhouettes of the femoral and tibial components matched the corresponding components in the radiological image perfectly. The position of each component was then recorded and measurements were made using a CAD-modelling program. The process was repeated at each angle of flexion and the kinematics determined.

![Fig. 1](image-url)
An error analysis was undertaken by taking radiographs of components mounted on an apparatus with six degrees of freedom. Accurate positioning of the components was achieved using rotational and translational stages with an accuracy of 15 arc sec and 0.01 mm, respectively. The components were set in an initial position and then rotated and translated to known values. Radiological images of the components were then created at each setting. The 3D model-fitting process was used for each setting of the rotational and translational stages to determine the relative position of the components. A second dynamic test was undertaken to determine the effect of movement. Noise, having the same interference frequency as soft tissue and bone, was added to each error-analysis image (Fig. 3). Thus, the quality of the error-analysis images was less good than that of those in vivo. The components were examined radiologically at a variable speed of between 0.5 and 0.3 m per second. The translational error of the 3D model-fitting technique was less than 0.5 mm. In order to account for unknown variables, separation values of ≥0.75 mm (50% safety factor) were chosen to represent the presence of femoral condylar lift-off. A second validation was used by radiographs in the frontal plane (Fig. 4). The predicted measurements of lift-off were within 0.5 mm of the actual values derived by digitising the frontal images.

Results

There was lift-off in 30 of the 40 patients during a deep knee bend. Examples of condylar lift-off, as determined by the image-matching process, are shown in Figures 5 and 6. There was lift-off at some increment of flexion in 14 of the patients (70%) with a PCR TKA and 16 of those (80%)
with a PS TKA. In the PCR TKA group there was lift-off on the lateral side in 13 and on the medial side in two. In the PS TKA group there was lift-off on the lateral side in 12 and on the medial side in nine. In two patients in the PCR-TKA group and five in the PS-TKA group there was lift-off both medially and laterally at differing increments of knee flexion. In these patients there was lift-off from one condyle and then at a different angle of flexion condylar contact would be re-established followed by lift-off of the other femoral condyle. During a deep knee bend, these patients would thus have a rocking movement of their knee in the frontal plane.

For both the PCR and PS TKA designs, lift-off occurred most commonly at 60° of flexion (Table II), and this was present in 35.0% of PCR and 60.0% of PS TKAs. The maximum lift-off was also observed at 60° of flexion in both TKA designs (Table III). Five (25.0%) patients with a PS TKA and five (25.0%) with a PCR TKA had maximum lift-off at 60° of flexion. For those with a PCR TKA the maximum lift-off was 1.8 mm (mean 1.2 mm) and for those with a PS TKA 2.7 mm (mean 1.4 mm). For those with lift-off, the average was 1.1 to 1.2 mm for the PCR TKA group.

**Table II.** Percentage incidence of condylar lift-off for the 20 PCR and the 20 PS patients

<table>
<thead>
<tr>
<th>Flexion angle (degrees)</th>
<th>0</th>
<th>30</th>
<th>60</th>
<th>90</th>
</tr>
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<tbody>
<tr>
<td><strong>PCR subjects</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medial</td>
<td>10</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Lateral</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td><strong>PS subjects</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medial</td>
<td>20</td>
<td>10</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Lateral</td>
<td>25</td>
<td>30</td>
<td>30</td>
<td>25</td>
</tr>
</tbody>
</table>

**Table III.** The percentage of patients having maximum lift-off after PCR and PS TKA

<table>
<thead>
<tr>
<th>Flexion angle (degrees)</th>
<th>0</th>
<th>30</th>
<th>60</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PCR subjects</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medial</td>
<td>10</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Lateral</td>
<td>15</td>
<td>10</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td><strong>PS subjects</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medial</td>
<td>5</td>
<td>0</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>Lateral</td>
<td>10</td>
<td>10</td>
<td>5</td>
<td>20</td>
</tr>
</tbody>
</table>
at each angle of flexion and 1.3 to 1.8 mm for the PS-TKA
group (Table IV).

Clinical correlation. Statistical analysis of both groups
using Student’s t-test revealed no statistically significant
 differences in flexion and coronal alignment before and
after operation. Patients with a PS TKA were significantly
older (70.3 ± 65.8 years) than those with a PCR TKA
(p = 0.05).

Multivariate regression analysis showed no statistically
significant correlation between the presence of lift-off and
the flexion or alignment in the coronal plane before and
after operation.

Discussion

Numerous kinematic analyses of the knee have shown femoral condylar lift-off in RSA, cadaver and ligament
laxity studies. Bourne et al. in an evaluation of the normal and osteoarthritic knee in vitro, showed that the
lateral condyle can be completely unloaded in the osteo-
arthritic knee aligned in 3.1° of varus. Similarly, Kostuik et
al. analysed 15 cadaver knees under various loading con-
ditions and showed that there is unloading of one condyle if
the knee is positioned in 3° of either varus or valgus. The
effect of lift-off is further seen in retrieval analyses of
failed tibial components. Lewis et al. reviewed a series of
TKA failures with polyethylene wear and recorded a pre-
dominance of wear posteromedially. We have shown that
lift-off, after PCR-TKA, primarily occurs laterally resulting
in high polyethylene stresses medially.

There have been numerous descriptions of the abduction
and adduction moments at the knee during normal gait. It
has been shown that an abduction moment occurs at heel
strike, but quickly reverses to an adduction moment
throughout the remaining stance phase. This abduction
moment has been shown to measure between 36 and 50 N,
increasing if there is a coexisting varus deformity.

During the midstance phase of gait, the medial compressive
load increases to 70% to 75% of the load across the knee. There
are many compensatory mechanisms for resisting this
adduction moment including: 1) the redistribution of
condylar loads; 2) co-contraction of antagonist muscle
groups; 3) increased tension in the lateral soft tissue; 4)
increased tension in the cruciate ligaments; 5) increased
swaying of the body in the lateral direction; 6) decreased
stride length; and 7) a decreased inversion moment at the
ankle brought about by out-toeing. Although these com-
pensatory mechanisms aid stability of the knee, they may
lead to increased joint reaction forces, and if the compensa-
tory mechanisms are inadequate, lift-off may occur.

Increased soft-tissue laxity in the frontal plane would
enhance the likelihood of lift-off. Burstein5 carried out a
study to determine the varus and valgus stabilising struc-
tures in the knee and showed that the primary stabilisers are
the collateral ligaments while the cruciate ligaments serve
as secondary stabilisers. Although the cruciate ligaments
contribute only 25% of the varus-valgus stability of the
knee when compared with the collateral ligaments, the
adduction moment increases in the absence of the cruciate
ligaments. Noyes et al. analysed the adduction moment at
the knee in 32 patients with an absent anterior cruciate
ligament (ACL) and coexisting varus deformity, using gait
analysis. They showed a 35% increase in the adduction
moment and a 51% increase in the soft-tissue tension on the
lateral side of the knee in these patients.

Markolf et al. analysed 35 patients with ACL-deficient
knees in non-weight-bearing conditions in vivo. The results
were compared with 49 patients with clinically normal
knees. They showed that the varus-valgus laxity in the ACL-
deficient knees increased by 36% at full extension and by
19% at 20° of flexion. Other studies have concluded that the
varus-valgus laxity is greater in knees with a TKA than in
normal knees, and that the absence of the posterior cruciate
ligament (PCL) leads to an increase in joint laxity.

There is controversy as to whether static radiological
tibiofemoral alignment reflects the adduction moment. We
found no correlation between the frontal (coronal) tibiofemoral alignment and the pres-
ence of lift-off, although no major malalignment was pres-
ent in any of the patients.

Our study has shown that lift-off commonly occurs in
both PCR and PS TKAs, usually at angles of flexion greater
than 60°. Lift-off occurred both medially and laterally in
subjects with a PS TKA, but was observed predominantly
on the lateral side in those with a PCR TKA. This may be
related to the presence or absence of the cruciate ligaments.

In the knee with intact cruciate ligaments, the ACL origi-
nates at the lateral femoral condyle while the femoral
attachment of the PCL is medial. We suggest therefore that
the ACL acts as a check, limiting lift-off laterally, with the
PCL resisting lift-off medially. In the PS TKA with both
cruciate ligaments resected, the incidence of lift-off was
similar both medially and laterally. In PCR TKA, lift-off
predominantly occurred laterally, since the retained PCL
may resist medial lift-off.

The cause of lift-off is multifactorial and factors affect-
ing its incidence include accuracy of ligamentous balanc-
ing at operation, the position of the components, the
rotation of the femur relative to the tibia (abduction/adduc-
tion in early to mid-flexion, internal/external rotation in
mid to full flexion), the direction of the resultant muscle
force across the knee and the dynamic stabilising effect of
the supporting musculature.

<table>
<thead>
<tr>
<th>Flexion angle (degrees)</th>
<th>PCR knee</th>
<th>PS knee</th>
<th>Both knees</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.2</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>30</td>
<td>1.1</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>60</td>
<td>1.2</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>90</td>
<td>1.2</td>
<td>1.8</td>
<td>1.6</td>
</tr>
</tbody>
</table>
These findings emphasise the importance of coronal femorotibial curvature and conformity in the design of a TKA. Miller et al. in a laboratory analysis, evaluated peak tibial polyethylene stresses under eccentric loading in both flat-on-flat and more coronally curved femorotibial implants. They showed substantially higher polyethylene stresses in flat-on-flat designs, often exceeding the yield strength of polyethylene, whereas designs with increased coronal curvature and conformity proved less sensitive to eccentric loading.

The results of our study also add support for the use of metal-backed tibial components with central stems in order to reduce the peak subchondral cancellous bone load should femoral condylar lift-off occur. Bartel et al. performed a finite-element analysis to study the effect of metal backing on peak subchondral cancellous stresses, and reported a reduction of 16% to 39% with metal-backed compared with all-polyethylene tibial components when measured under eccentric loading conditions. This analysis is supported by clinical studies. Ritter et al. evaluated 200 cases of metal-backed PCR TKA, of a single, flat-on-flat condylar design (Anatomical Graduated Components; Biomet Corporation, Warsaw, Indiana). A survival rate of 98% was observed at ten years. Faris et al. reviewed 538 cases of the same prosthetic design with the exception that an all-polyethylene tibial component was used. At a mean follow-up of only 4.2 years, 50 tibial components had been revised because of medial tibial collapse and loosening. In an additional 155 knees there was a radiolucency in the medial tibial plateau measuring 1 mm or more. We suggest that lateral condylar lift-off may have played a role in the premature failure of these all-polyethylene flat-on-flat tibial components. Excessive medial loading is associated with lateral lift-off. In the absence of metal backing of the tibial component, these high loads become transmitted to the underlying medial subchondral bone resulting in collapse and loosening.

Limitations of our investigation include the lack of accurate assessment of polyethylene wear, deformation, and the sagittal anteroposterior curvature of the tibial polyethylene insert, although no gross wear or deformation was noted on plain radiographs.

We have shown that femoral condylar lift-off can occur after both PCR and PS TKA. This results in eccentric loading and may lead to premature wear of the polyethylene and prosthetic loosening. Our findings suggest the importance of both coronally curved and conforming femorotibial geometry and metal backing of the tibial components to improve the longevity of the arthroplasty. Based on similar findings with other current designs of TKA, the presence of lift-off is not unique to the implants used in this study. Further research is required to assess the contribution of surgical technique as well as the design of the implant in affecting the incidence and magnitude of lift-off.

We wish to acknowledge DePuy and Johnson & Johnson Company for their financial support of our research.

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References


