Design changes improve contact patterns and articular surface damage in total knee arthroplasty

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ABSTRACT

Background: The Optetrak® PS (Exactech, Inc., Gainesville, FL) has been a well-functioning posterior stabilized knee replacement since its introduction in 1995. In 2009, the Optetrak Logic® incorporated modifications to the anterior face of the tibial post and the corresponding anterior articulating surface of the femoral component to reduce edge loading on the polyethylene post. In this study, we provide the rationale for the design change and compare the damage on retrieved tibial components of both designs to demonstrate the effectiveness of the design modifications in decreasing post damage.

Methods: We integrated retrieval findings of tibial post damage with finite element analysis to redesign the anterior tibial post-femoral box articulation. We then used subsequent retrieval analysis on a 3:1 matched sample of 60 PS and 20 Logic® inserts to examine the impact of the design change on polyethylene damage.

Results: Polyethylene stresses were markedly reduced when rounded contact geometries were incorporated. The comparison of the new and old designs using retrieval analysis demonstrated that the redesign led to reduction in surface damage and deformation on the tibial post.

Conclusions: This study shows the use of a design cycle by which a problem is identified through retrieval analysis, analytical tools are used to suggest design solutions, and then retrieval analysis is applied again on the new design to confirm improved performance.

Clinical relevance: Anterior post damage has been markedly reduced through the introduction of design changes to the post-box geometry.

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1. Introduction

The Optetrak® PS (Exactech, Inc., Gainesville, FL) was designed in 1995 as an evolution of the Insall-Burstein® Posterior-Stabilized knee system (Zimmer, Warsaw, IN). The conformity between the tibial and femoral components was modified to reduce polyethylene contact stresses [1], and the trochlea of the femoral component was deepened and lengthened to improve patellar tracking and reduce patellar clunk. The survivorship rate of this knee implant has been excellent, ranging from 94 to 98% at 10 years [2,3].

In 2009, the Optetrak Logic® was introduced, incorporating further modifications to the Optetrak® PS. The articular conformity and patellar tracking remained unchanged; however, the intercondylar box geometry on the femoral component was modified to be more bone preserving by changing the angle of the box cut and rounding off its corners [4]. Maximum flexion was also increased from 120° to 145°.

In addition, the articulation between the anterior face of the tibial post and the corresponding articular surface of the femoral component was redesigned to reduce polyethylene post contact stresses and edge loading when the knee was in full extension. The anterior face of the tibial post was changed from a flat surface to a saddle shape. A matched saddle shape articulation was incorporated into the anterior cam of the femoral component.

Tibial post damage has been found in most PS implant designs examined with retrieval analysis [5–7]. For example, we previously examined PS posts of retrieved components from three knee designs: NexGen® (Zimmer, Inc., Warsaw IN), Optetrak®, and Genesis® II (Smith and Nephew, Inc. Memphis, TN) [6]. Post damage varied among the designs with the Optetrak® inserts showing the most damage on the anterior surface of the post, producing a “bowtie” damage sign (Fig. 1), while Genesis® II inserts had the most damage on the posterior surface. Damage to the posterior surface of the post is expected since repeated articulation with the femoral cam during flexion provides the mechanical constraint to femoral anterior translation that is the prime basis of PS designs [8]. Anterior post impingement is an
unintended articulation occurring in hyperextension and at low flexion angles [6,9,10]. In extreme cases, this damage led to fracture of the post and the need for revision surgery [11].

The damage observed in the retrieval analysis of the Optetrak® PS formed the basis for the design modifications that were introduced in the Optetrak Logic® design. Here we describe the analytical basis for the design changes made to the tibial post and femoral anterior cam from the Optetrak® PS to the Optetrak Logic® designs. We then present the results of a subsequent retrieval analysis comparing the location and severity of damage on the articulating surface and tibial post between these two designs. We aimed to establish the effectiveness of the design modification in successfully decreasing the surface damage on the tibial posts of the Optetrak Logic®, while not adversely affecting damage to the tibiofemoral articulating surfaces.

2. Materials and methods

2.1. Design analysis

Computer models of the Optetrak® PS total knee prosthesis were modified to facilitate finite element (FE) meshing of the tibial post and the femoral anterior cam (Figs. 2 and 3). To model the unintended contact between the post and the cam, the components were positioned simulating 10° of hyperextension. The metallic cam was modeled as a rigid indenter. The post was modeled as ultrahigh molecular weight polyethylene using a true stress-strain relationship [1]. The constitutive model was based upon a von Mises yield surface with isotropic hardening. FE meshes were created using Patran (MSC Software, Santa Ana, CA), which was also used for post-processing.

The tibial post FE mesh was constructed using 8-noded hexagonal brick elements; the anterior cam surface was modeled with 4-noded rectangular shell elements. Because the post-cam mechanism is symmetric about the sagittal plane, a symmetric boundary condition was used, so only half the mechanism was modeled. The distal face of the post was fixed in all directions, and the cam was allowed to translate only in the direction of contact (i.e. perpendicular to the post at the contact point) simulating contact that would constrain movement of this surface.

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The applied load of 445 N was based on a 2D free body diagram of loads derived from gait data at maximum hyperextension. This load was applied to the reference node of the cam indenter, and its direction was perpendicular to the post at the point of contact. Frictional contact between the post and cam was defined with a friction coefficient of 0.15. Analyses were performed using Abaqus (Abaqus Inc, Waltham, MA). Analyses were conducted using three sizes of the Optetrak® PS components and one modified design that was comparable in size to the Size 3 Optetrak®. The goal was to reduce the stress in the post to below the ultimate strength of the material. The new design incorporated changes to the curvature of the post and cam surfaces with the goal of reducing contact stress and edge loading; this design was then incorporated into the commercial Optetrak Logic® design.

2.2. Retrieval analysis

Twenty retrieved Optetrak Logic® polyethylene inserts were match paired on a 1 to 3 basis with 60 Optetrak® PS inserts. This matching was chosen based on the high number of retrieved Optetrak® PS inserts in our retrieval system in order to provide as much data as possible. The matching variables were age, BMI, length of implantation (LOI), radiographic AP and flexion–extension alignment of the femoral and tibial components, and indication for revision (Table 1). The inserts were obtained from our ongoing Institutional Review Board-approved implant retrieval system. The Optetrak Logic® retrievals consisted of all the components of this design removed at revision surgeries performed at our institution up to August 2011. The matching Optetrak® PS inserts were selected from all of the inserts that were retrieved at our institution since 1995 when the implant was first commercially introduced. All of the polyethylene tibial inserts were compression molded and had been sterilized by gamma-irradiation in an inert environment prior to implantation.

No significant differences existed between the two groups with respect to the matched variables (Table 1). The average patient age at the time of revision surgery was 65 ± 9.3 yrs in the Optetrak Logic® group, and 64.9 ± 9.8 yrs in the Optetrak® PS group (p = 0.985). Average BMI of the Logic group was 30.1 ± 5.9, while that of the PS group was 31.4 ± 6.1 (p = 0.412). Because the Optetrak Logic® was only available commercially in 2009, the average LOI was short at 0.83 ± 0.64 yrs; the LOI for the matched PS group was 0.87 ± 0.65 years (p = 0.993). The most common reason for revision in the Logic group was infection (10 of the 20 knees), followed by stiffness...
superior aspects of the post (Fig. 4B). The severity of surface damage the post, and one middle zone posterior to the post (Fig. 4A). The tibial
of the tibial post. The articular surface was divided into 10 zones: four
components were well aligned for both designs; no differences were noted
tray and the line of the tibial shaft mechanical axis. On average, the com-
component was measured between a line parallel to the plateau of the tibial
oral joint line angle, reported as varus or valgus, was measured from a
sion diagnoses for the PS group were infection (21 of 60), stiffness (14 of
(5 of 20), instability (3 of 20), and aseptic loosening (2 of 20). The revi-
se were revised for infection, since presumably these implants did not fail for mechanical
(0.87 ± 0.65) and maximum von Mises stress decreased 35% to 23.8 MPa, and maximum defor-
were calculated by summing the 10 articular and five post zones, re-
were the most prevalent damage mode for both designs, followed by
scores of 1, 2, and 3 indicated damage; scores of 1, 2, and 3 indicated damage over <10%, 10 to 50%, and >50%, respectively, of the area of the zone. Total damage scores for the articular surface and tibial post surfaces
(Table 1).
We evaluated all retrieved polyethylene inserts for evidence of sur-
femoral condyles to a line drawn along the
component was flexion/extension angle was measured between a line per-
femoral shaft axis. The tibial angle was measured between a line drawn parallel to the plateau of the tibial post and a line drawn along the tibial shaft mechanical axis. On the lateral radiograph, the femoral
component deformation occurred in the PS group as the Logic group (4.0 ± 1.6 vs. 0.9 ± 0.9) and
Third body debris, scratching, burnishing, delamination, pitting,
scored system[12] that describes seven damage modes: surface defor-
the PS components that
were calculated by summing the 10 articular and five post zones, re-
student’s t-test was used to determine differences in patient demo-
right observer reliability was 0.96 (a $\kappa$ of 1.0 indicates perfect agreement between observers).
Student’s t-test was used to determine differences in patient demo-
were compared using the Pearson $\chi^2$ test. The damage scores on the
different zones of the Logic and PS groups were compared using the
Fisher exact test. All tests were two-sided, and $p < 0.05$ was consid-
were analyzed using the SAS 9.1.3 statistical software program (SAS Institute Inc., Cary, NC).
3. Results
3.1. Design analysis
In all three sizes of the Optetrak® PS design, the maximum von Mises stress in the polyethylene was located at the lateral edge of the anterior face of the tibial post slightly inferior to the line-to-line contact point of the post and cam (Fig. 5). The magnitudes were 34.4, 36.8, and 42 MPa for the Size 2, 3, and 4 components, respectively. Maximum polyethylene deformation occurred at the same location and, as with the stress, increased with implant size: 0.23, 0.28, and 0.35 mm for Sizes 2, 3, and 4, respectively.
By modifying the design of the contacting surfaces of the femoral component and the tibial post, maximum von Mises stress decreased 35% to 23.8 MPa, and maximum defor-
mation decreased 37% to 0.17 mm compared to the matching Size 3 Optetrak® PS (Fig. 6).
3.2. Retrieval analysis
All 20 Optetrak Logic® and all 60 Optetrak® PS retrievals showed evidence of damage to both the articular surface and the surfaces of the tibial post. The total damage scores for the articular surface of the Logic and PS components were not different (29.6 ± 4.3 vs. 30.0 ± 3.9, $p = 0.686$). However, the mean damage score for the surfaces of the tibial post was significantly greater ($p < 0.0001$) for the PS (17.8 ± 3.6) compared with that of the Logic® retrievals (13.7 ± 3.6). Burnishing was the most prevalent damage mode for both designs, followed by scratching and pitting. No delamination had occurred in any of the 80 retrievals. The two damage modes that demonstrated the greatest differences between the two de-
signs were surface deformation and abrasion. Over four times the amount of surface deformation occurred in the PS group as the Logic group (4.0 ± 1.6 vs. 0.9 ± 0.9) and over three times the amount of abrasion. The differences were most significant ($p < 0.001$) between the PS and Logic implants in the anterior surface of the tibial (the anterior, medial, and lateral zones). Surface deformation of this region was typi-
cantly in the form of a "bowtie" on the PS (Fig. 1); no such deformation occurred in the
Logic group (Fig. 3).
Because components retrieved for stiffness, instability, and aseptic loosening might have failed for mechanical reasons that could have contributed directly to the observed damage, we performed a subgroup analysis of the 10 Logic and 21 PS components that were revised for infection, since presumably these implants did not fail for mechanical

![Fig. 3. A computer-generated solid model of the polyethylene insert in the Optetrak® PS and Optetrak Logic® demonstrating the geometrical changes to the tibial post.](image)

Table 1
Summary of demographic and radiographic data for retrieved Optetrak® PS and Optetrak Logic® implants.

<table>
<thead>
<tr>
<th></th>
<th>Optetrak® PS</th>
<th>Optetrak Logic®</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age at revision</td>
<td>64.9 ± 9.8</td>
<td>65 ± 9.3</td>
</tr>
<tr>
<td>BMI</td>
<td>31.4 ± 6.1</td>
<td>30.1 ± 5.9</td>
</tr>
<tr>
<td>Length of implantation</td>
<td>0.87 ± 0.65</td>
<td>0.83 ± 0.64</td>
</tr>
<tr>
<td>Femoral angle (– varus/ + valgus)</td>
<td>6.3 ± 2.77</td>
<td>6.6 ± 2.8</td>
</tr>
<tr>
<td>Femoral + flexion/– extension</td>
<td>10.85 ± 3.85</td>
<td>12.2 ± 3.6</td>
</tr>
<tr>
<td>Tibial angle (–varus/– valgus)</td>
<td>0.46 ± 2.75</td>
<td>0.7 ± 1.3</td>
</tr>
<tr>
<td>Tibial posterior slope</td>
<td>5.01 ± 2.03</td>
<td>3.8 ± 3.0</td>
</tr>
</tbody>
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![Image](image)
reasons. No significant differences were noted between the two subgroups for age, BMI, or LOI (p = 0.369, 0.679, and 0.219, respectively). A significant difference in surface deformation remained on the anterior, medial, and lateral zones of the tibial posts between the Logic and PS retrievals (p < 0.0001). Nine of the 10 Logic retrievals demonstrated no surface deformation at the anterior post, while 17 of the 21 PS retrievals demonstrated surface deformation. Laterally, none of the Logic retrievals demonstrated surface deformation, while all of the PS retrievals demonstrated surface deformation. Medially, eight of the 10 Logic retrievals had no surface deformation, while 19 of the 21 PS retrievals showed surface deformation.

4. Discussion

We integrated retrieval analysis with design analysis to achieve an improvement in the performance of a contemporary PS knee replacement system. Retrieval analysis was initially used to define the problem [5,6]. Because the problem was mechanical, i.e., permanent deformation and wear of polyethylene, it was amenable to FE analysis as a means of understanding the stresses responsible for the problem and in examining the benefit of design improvements. Retrieval analysis was then used again after commercial introduction of the new design to verify that the change had indeed improved performance. While not exposing a new problem, we have successfully demonstrated using a design cycle to characterize a problem, model design changes to improve the product, and then confirm that the problem has been alleviated with the new design.

The strain contours in the FE models qualitatively matched the deformation pattern observed on the retrieved Optetrak® PS implants, providing confidence that the model was depicting the in vivo situation (Fig. 7). Maximum von Mises stress occurred on the lateral edge of the anterior surface of the tibial face post, where initial contact occurred. Because of symmetry, only half the post needed to be modeled, but the prediction would be symmetrical medial and lateral deformation, again consistent with the bowtie pattern seen on retrievals (Fig. 1). Stress was high at the edges, because the surface of the femoral cam indented the edges of the post before line-to-line contact occurred across the width of its anterior face. The distance that the femoral cam had to travel to reach line-to-line contact increased with implant size, so the stresses increased from Size 2 to Size 4. Contact in the newer design (used as the basis for the Optetrak Logic® design) initiated at the center of the post, eliminating edge loading. The changes in the radii of the contact surfaces also broadened the contact area in the proximal-distal direction, which also contributed to a wider stress distribution and the lowering of peak stresses (Fig. 6).

Other investigators examined anterior post impingement and found similar findings to ours. For example, Hamai et al. [13] determined the levels of contact stress generated in three other contemporary PS total knee designs (Zimmer NexGen LPS Flex, Smith Nephew Genesis II, and the Stryker Scorpio NRG) under the same applied load as was used in our analysis. While variations in the stresses and predicted damage patterns were found among the designs, peak contact stresses approaching and in some cases exceeded the compressive yield stress for polyethylene. Similarly, Huang et al. [14] investigated the influence of post-cam design features on the stress distribution in the anterior tibial post when subjected to impingement loading by comparing flat-on-flat with curve-on-curve contact surfaces between anterior tibial post and
femoral cam. The flat-on-flat model had larger stresses, and stress concentrations were found at the anterior corner of the post that were absent in the curve-on-curve model. However, they did not incorporate the suggested benefits into a design and then determine the outcome through retrieval analysis.

In our subsequent retrieval analysis of the Optetrak Logic®, the design modifications that were made to the tibial post in the Optetrak® system corresponded to a lesser degree of anterior post damage. This correlation between design and damage existed even after accounting for confounding patient and surgical variables (age, BMI, length of implantation (LOI), radiographic AP and flexion–extension alignment of the femoral and tibial components, and indication for revision) that might affect implant performance. Rounding the post/housing geometry might be disadvantageous to the articular surfaces by allowing more internal–external rotation. More rotation might be reflected in more articular surface damage (or at least larger contact areas that show surface damage). However, this was not the case in our retrieved implants, for which the damage scores of the articular surfaces of the Optetrak® PS and Optetrak® Logic implants showed no difference.

Previous studies also demonstrated links between post damage and differences in insert design [5,6]. The Optetrak® PS inserts examined by Dolan et al. [6] had similar damage grades and modes of damage (predominantly polyethylene burnishing and surface deformation on the anterior surface of the post). Anterior surface deformation in the form of a “bowtie” sign was similarly found in a study examining two earlier designs of PS inserts, the Insall-Burstein® I and II PS designs [5]; that study also examined design influence on tibial post damage. No difference was found in damage to the tibiofemoral articular surface between the two designs, which was hypothesized since no modifications were made to the radii of the tibial and femoral bearing surfaces. However, the Insall-Burstein® II had more significant anterior damage because of the more anterior placement of the post compared to the Insall-Burstein® I design, a change intended to increase range of motion in flexion.

A limitation to the design analysis is the lack of a direct connection between von Mises stress values and polyethylene failure. Nonetheless, the locations of highest stresses likely reflect the material condition in these regions accurately and thus explained the anterior surface deformation and drove the subsequent improvement made to the Optetrak Logic® design. We did not examine how axial rotation between the femoral and tibial components would affect anterior post impingement. However, Huang and colleagues [14] previously showed that contact stresses with a flat-on-flat design (similar to the Optetrak® PS) were exacerbated by adding rotation to the FE analysis, while contact stresses for a curve-on-curve design (similar to the Optetrak® Logic®) were insensitive to rotation. A limitation of our retrieval analysis, as with any retrieval analysis, was that the components might not represent well functioning knee replacements. However, we attempted to address this issue by showing that the results and, hence, the conclusions did not change when we restricted our retrieval analysis to implants that were explanted for infection that presumably were well functioning prior to the onset of infection. Finally, our retrieval analysis was restricted to short LOIs, because of the recent availability of the Optetrak Logic® knee system with only 20 revisions to date at our institution. We maximized the number of retrievals used for our study by matching the Logic® retrievals on a 1 to 3 basis with Optetrak® PS retrievals. Moreover, the significant improvement in terms of surface damage to the tibial post will likely persist over longer implantation times, given the linear, cyclic nature of wear.

Though anterior post damage was prevalent on the Optetrak® PS retrievals, it should be emphasized that this implant continues to have a successful clinical performance. Nonetheless, we demonstrated that the design could be further improved through a rational approach combining retrieval and design analyses. Whether the decreased damage that resulted from this change will lead to even better clinical performance remains to be demonstrated with longer follow-up.

Fig. 6. A representative image demonstrating the decrease in von Mises stress and change in region of peak stress after the design modification.

Fig. 7. Deformation contour plots (exaggerated by a factor of 10 to make the deformations more visible) showed bulging of the polyethylene as a result of edge loading on the Optetrak® PS. The same deformation pattern (highlighted by the white arrows) was observed on retrieved components that had experienced anterior impingement.
Conflict of interests

Geoffrey Westrich is a paid speaker for Exactech, Stryker and DJO; a paid employee of Exactech, Stryker and DJO; receives research support from Exactech and Stryker; is a committee member for the Knee Society and EOA. Timothy Wright receives royalties from Mathys AB; receives stock options from Exactech; receives royalties or support from Editorial honorarium from the ORS. Joseph Lipman is a paid employee for the Hospital for Special Surgery; a paid consultant for Ivy Sports Medicine; and unpaid consultant for Exactech. Adam Rana and Susannah Gilbert have no disclosures.

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References