Optimizing Knee Femoral Component Strength and Bone Preservation with Finite Element Analysis

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Introduction

We set out to design a patient specific knee femoral component that preserved bone compared to standard total knee components. In doing so we recognized that fatigue strength could be compromised when we attempt to make condylar sections thinner than traditional implant systems. Understanding existing reported failures, and building upon that knowledge should provide insight into improving the design. Scott1 reported on 7 knee femoral fractures in his early PFC experience. Failure analysis of these components revealed that the fracture initiation site was on the inner bone surface at the intersection of the distal flat and posterior medial chamfer corner. This finding indicates that in these cases, femoral fracture was caused by a spreading apart of the femoral component in the anterior to posterior direction concentrating stress at the medial distal and posterior chamfer intersections.

Method

Using the knowledge of how the early PFC knee femoral components failed, we set out to simulate that failure mechanism in a FEA model. CT scans are acquired on a patient’s lower limb. The CT scan is converted into a segmented surface model with proprietary software and then imported into another software system that allows a knee femoral component to be designed that duplicated the patients natural medial ‘J’ curve, lateral ‘J’ curve and their natural trochlear ‘J’ curve. Minimum thicknesses requirements are embedded within the software, thus each implant will have individualized condyle thicknesses. Two individual CT scans were used to design an extra small and an extra large knee femoral component. Knee components were modeled in CAD in a 5-cut traditional design, see Image #2, in two sizes and then imported into ANSYS R11-SP1. The components were coupled to a bone model that was 0.5mm larger at the anterior flange region of the component, thus causing a wedge effect on the implant, theorizing that the wedge effect would concentrate stress in the region of the reported fracture failures of the PFC. 6-cut femoral components were also modeled and tested in the same method. The 6-cut design adds an additional posterior chamfer, see Image #3. The implant (contact) and femur (target) face connections were modeled as a frictional fit with the coefficient of friction set to 0.5. The surface to surface interface was set to 0nm offset so that the software would acknowledge and calculate the interference fit. The implant (contact) and condyle load pads (targets) were set as frictionless with an “adjust to touch” interface to bring them into initial contact. For both implant to femur and implant to condyle load pads, the contact formulation and stiffness were manipulated during the iterative solve process to aid the convergence of the solution without allowing excessive element penetration.

Loading was applied simulating a 15 degree flexion angle with 60% of the load being applied to the medial condyle and the remaining load applied through the lateral condyle. The total load was adjusted for the size of the implant, where the XS got 1025 N and the XL received 4003 N.

Results:

The results for the maximum principal stress are tabulated in Chart #1. In both size femoral components for the 5-cut and 6-cut designs the maximum principal stress occurred at the intersection of the distal medial and posterior chamfer intersection, see Image #1.

Discussion:

We have successfully demonstrated a finite element model and method that accurately reproduces the reported failure mechanism of an implant system with a long clinical history. In our model we were able to show the exact location of failure of the PFC femoral components as reported by Scott. Although the stress predicted in our model is below any reported endurance limit for a cast cobalt chrome implant, differences in actual implant thickness and/or magnitudes of the load applied could certainly raise the maximum principal stress above the endurance limit of the material.

What we have not addressed in this study is what mechanical process causes a wedge affect on the femoral component of a total knee replacement. This is a subject for further research.

Both sized implants showed maximum principal stress in the identical region as the failed PFC femoral components.

We have also shown that the stress can be reduced substantially by adding an additional faceted cut. The advantage to adding the additional cut is that the overall thickness can be reduced by 2 mm typically compared to the traditional 5-cut implant design. Any reduction in implant thickness translates directly to bone preservation in the total knee surgery, leaving more bone available in the event that a revision of the original implant is required.

Significance:

The significance in this study is that we have shown a previously poorly understood failure mechanism in total knee design can be predicted and avoided. Furthermore, we have shown that the addition of an additional faceted cut in total knee design can reduce the overall stress in the implant, allowing a thinner implant to be produced that will preserve bone stock at the time of primary total knee replacement.

References:


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<th>Thickness</th>
<th>5-Cut Design</th>
<th>6-Cut Design</th>
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<tr>
<td>Medial-Lateral Distal Condyle Thickness</td>
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<td>5.9mm/6.3mm</td>
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<td>X-S Femoral Component</td>
<td>201.4 mPa</td>
<td>161.8 mPa</td>
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<td>X-LA Femoral Component</td>
<td>292 mPa</td>
<td>221.1 mPa</td>
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Chart #1, Comparing maximum principal stress for both implant sizes. Condyle thickness is also shown.

![Image #1](https://via.placeholder.com/150)

Image #1. A typical 6-cut FEA result showing maximum principal stress at the medial posterior region

![Image #2](https://via.placeholder.com/150)

Image #2. A patient matched 5-Cut Femoral Component

![Image #3](https://via.placeholder.com/150)

Image #3. A patient matched 6-Cut Femoral Component, note additional posterior chamfer cut

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