Predicting Bone Damage and Implant Subsidence after Total Knee Arthroplasty

1Wong, J; Steklov, N; Patil S; Kester, M; 1Colwell Jr, CW; +1D’Lima DD
+1Shiley Center for Orthopaedic Research and Education at Scripps Clinic, La Jolla, CA
ddlima@scripps.edu

Introduction
Aligning the tibial tray is typically considered a critical step in total knee arthroplasty (TKA). A number of studies have reported on the accuracy of surgical instrumentation (intramedullary and extramedullary) and surgical navigation systems. It is generally believed that the tibial cut should be as close to 90° as possible to the long axis of the tibia in the frontal plane. Malalignment, (especially in varus) has been associated with soft-tissue imbalance, increased polyethylene wear, and tibial tray subsidence, leading to revision surgery. However, not all clinical outcome studies have found a statistical correlation between tibial varus and revision surgery. While the link between varus malalignment and failure has been attributed to increased medial compartmental loading and generation of shear stress, quantitative biomechanical evidence to directly support this mechanism is incomplete. We therefore constructed a finite element model of knee arthroplasty validated with in vitro cadaver testing to test the hypothesis that varus malalignment of the tibial tray would increase the risk of tray subsidence.

Methods
Cadaver Testing: Fresh human knees (N = 4) were CT scanned and the proximal tibia harvested for implantation of a current generation knee arthroplasty cruciate retaining tibial tray (Triathlon CR, Stryker Orthopaedics). The implanted tibial specimens were mounted on a multimaxial testing rig (Force 5, AMTI) and subjected to loading (ISO recommended knee wear simulation conditions scaled to 3 times bodyweight) for up to 100,000 cycles in phosphate buffered saline supplemented with protease inhibitors. Micromotion sensors were mounted on the tray and underlying bone to measure micromotion in the vertical direction at the anterior, medial and lateral aspects of the tray, and anteroposterior micromotion at the medial and lateral aspects of the tray (Fig 1). In two of the specimens the application of vertical load was shifted medially to generate a load distribution ratio of 55:45 (medial: lateral) to represent a tibial tray in neutral varus-valgus alignment. In the remaining two specimens a load distribution ratio of 75:25 was generated to represent a tibial tray in varus alignment.

Finite element analysis: qCT scans of the tested knees were segmented using MIMICS (Materialise, Belgium) and solid meshed using Hypermesh (Altair Engineering). Material properties of bone were spatially assigned using the following conversion of bone density to elastic modulus.1 2 The tibial geometry was resected with a plane placed at the level of the tibial cut. The geometry of the tray and stem was subtracted using boolean operations between the tibial geometry and implant geometry. A finite element model was constructed using Abaqus 6.8 (Simulia, Dassault Systemes). The tray was simulated as a rigid body and the interface between the tray and bone was constrained to prevent any relative motion. Boundary conditions were applied to the outer surface of the tibial mesh to simulate experimental mounting conditions and the tray was subjected to a single load cycle representing that applied during cadaver loading.

Results
The two cadaver specimens tested at 55:45 medial:lateral (M:L) force distribution survived the 100,000 cycle test (Table 1). The finite element model generated distinct differences in compressive strain distribution patterns in the proximal tibia (Fig 2). A threshold of 2000 microstraw was used as the lower limit for induction of fatigue damage in bone under cyclic loading. Both specimens loaded under a 75:25 M:L distribution demonstrated substantially greater cortical bone volumes in the proximal tibial cortex that were at or greater than this fatigue threshold (Fig 3).

Discussion & Conclusion
We validated a finite element model of proximal tibial loading after knee arthroplasty. Local compressive strains computed under conditions of normal walking directly correlated with subsidence and failure in cadaver testing. Quantitatively, a significantly greater volume of proximal tibial cortical bone was compressed to a strain greater than the threshold of 2000 microstraw in the varus alignment group, indicating an increased risk for fatigue damage. Alteration in the mediolateral distribution of vertical load led to an increase in local strains in the proximal tibia which can be directly linked to tibial subsidence and failure.

The major weakness of our study was that we tested subsidence in nonviable bone. Bone remodeling and healing is likely to reduce the cumulative damage that typically occurs in cadaveric testing. We only tested one activity (walking) for up to 100,000 cycles which was the upper limit of the efficacy of the protease inhibitors in preventing post-mortem degradation of biomechanical properties in bone. Nevertheless we noted a distinct difference in the peak strains of the finite element models which correlated with subsidence and damage.

This model is extremely valuable in studying the effect of surgical alignment, loading and activity on damage to proximal bone.

References

Table 1

<table>
<thead>
<tr>
<th>No.</th>
<th>ML Alignment</th>
<th>Cycles survived</th>
<th>Subsidence (μ)</th>
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<tbody>
<tr>
<td>1</td>
<td>55:45</td>
<td>&gt;100,000</td>
<td>33</td>
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<tr>
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<td>55:45</td>
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<tr>
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<tr>
<td>4</td>
<td>75:25</td>
<td>52,000</td>
<td>250</td>
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Figure 1: Custom adapter mounted on a tibial tray to hold the 5 micromotion sensors. Sensors 1, 3 and 3 measured vertical micromotion, while sensors 2 and 4 measured micromotion in the anteroposterior direction.

Figure 2. The area of compressive strains greater than 2000 microstrain in finite element model were substantially increased in the medial aspect of the proximal tibia when the mediolateral distribution of load was 75:25 (Right) compared to 55:45 (Left).

Figure 3. The volume of cortical bone that was compressed greater than 2000 microstrain was significantly higher in the 75:25 distribution group compared to the 55:45 groups.