HIGH FLEXION IN CONTEMPORARY TOTAL KNEE DESIGN: A PRECURSOR OF UHMWPE DAMAGE? A FINITE ELEMENT STUDY

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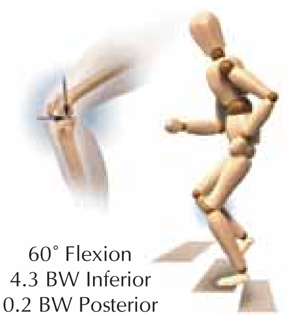
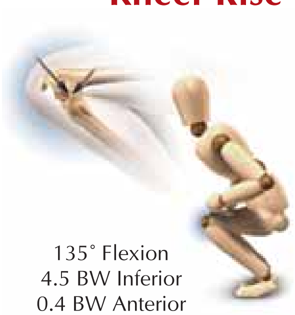
Stair Ascent



Chair Rise

Kneel Rise



INTRODUCTION

The success of total knee arthroplasty has contributed to its widening application to a younger, more active patient population whose daily regimen includes more demanding high flexion activities. Worldwide expansion to Middle Eastern and Asian patient populations, where the attainment of high knee joint flexion is often a cultural requirement, has been steadily increasing in recent years. This in turn has led to design changes in contemporary polyethylene tibial inserts which accommodate these increased flexion ranges. This study reveals the contact areas and stresses that are associated with polymer insert abrasion and subsurface delamination for four contemporary total knee designs during the most highly loaded portions of three different high flexion activities, and suggests their efficacy in clinical use.

Two cruciate retaining designs were evaluated, the 3DKnee (DJO Surgical) and Vanguard CR (Biomet). In addition, two posterior stabilized designs, Legacy LPS-Flex Fixed Bearing (Zimmer, Inc.) and the P.F.C. Sigma RPF (DePuy, a Johnson & Johnson Company), were also included. All four designs are currently available for clinical use in the United States.

METHODS

A three-dimensional, finite element model was created for each total knee design by measuring the articular surfaces of implantable quality parts using a laser profilometer. Maximum joint loads and the angle of knee flexion that they occur at were determined through a meta-analysis of the literature for three high flexion activities; stair ascent[1,2,3,6] (60°), rising from a chair[4] (90°) and rising from a double leg kneel[5,6,7] (135°) using a body weight of 71 kg. The loads were applied and the virtual components were allowed to settle into their preferred alignments without friction or consideration of soft tissue constraints. A protocol exception requiring additional femoral constraint was needed to evaluate the Vanguard CR during stair ascent. To aid in comparison, all polymer inserts were characterized by the same gamma irradiated, nonlinear material[8] of 10 mm thickness maintained at 37° Celsius. Contact areas and stresses on and within the polymer inserts were calculated and their magnitudes and locations were then photorealistically imaged.

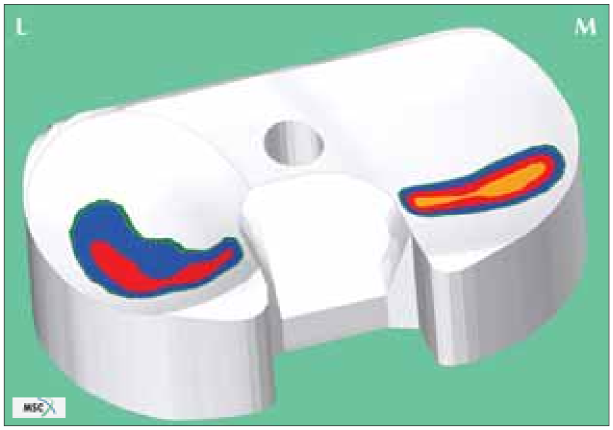
STRESS RESULTS

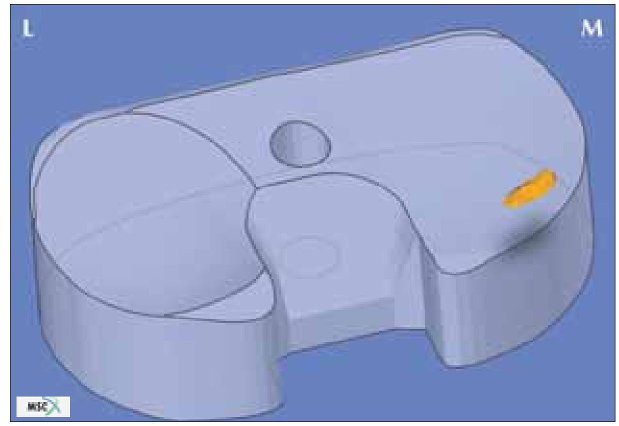
The distribution of surface contact stresses is appreciated from a superior posterior view of the left knee. These stress images (green

3DKnee

Surface Stress

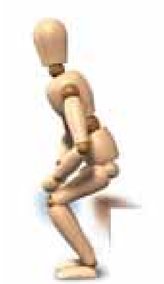
Subsurface Stress

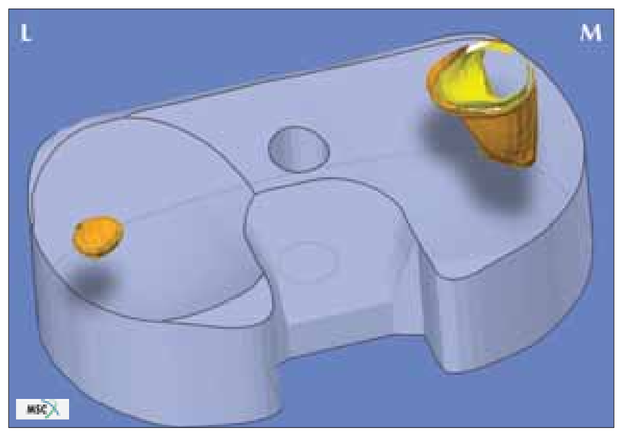




60° Flexion
4.3 BW Inferior
0.2 BW Posterior

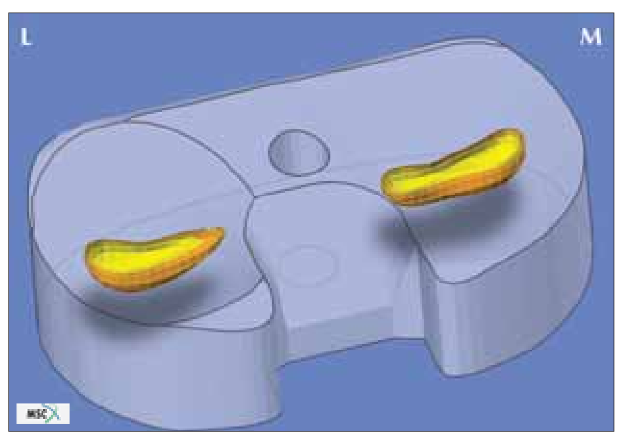
Contact Area: 447 mm²





90° Flexion
3.3 BW Inferior
1.0 BW Anterior

Contact Area: 260 mm²



135° Flexion
4.5 BW Inferior
0.4 BW Anterior

Contact Area: 258 mm²

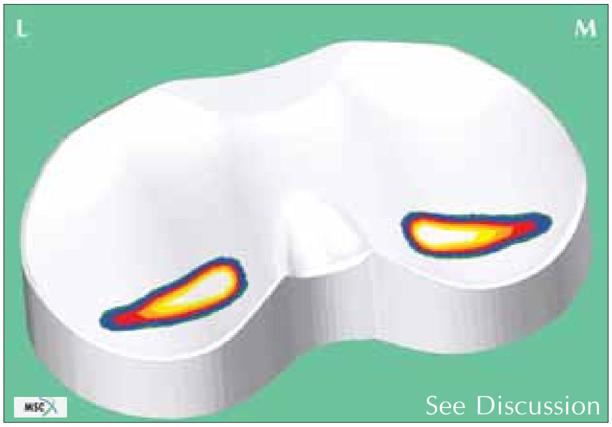
*1 MPa = 1 N/mm² = 145 psi

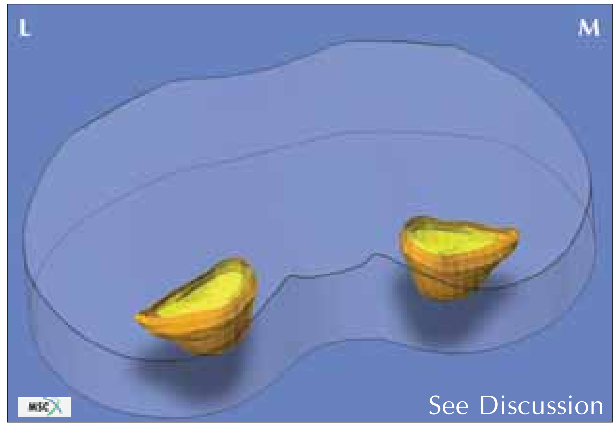
background) give an indication of the areas where surface abrasion caused by contact with the femoral component can occur. The higher the contact stresses, the greater the propensity for abrasive damage. The footprint of the surface stress distributions visualized

Vanguard CR

Surface Stress

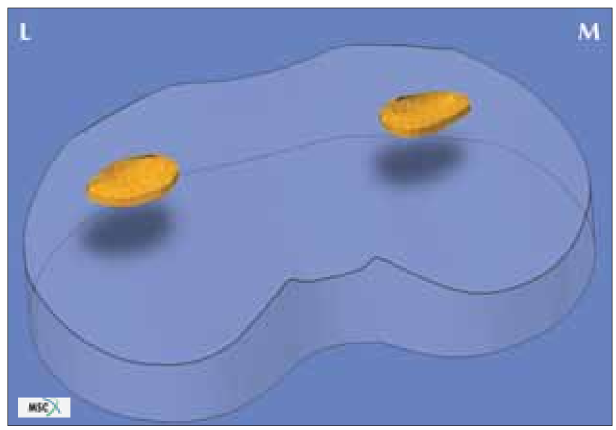
Subsurface Stress





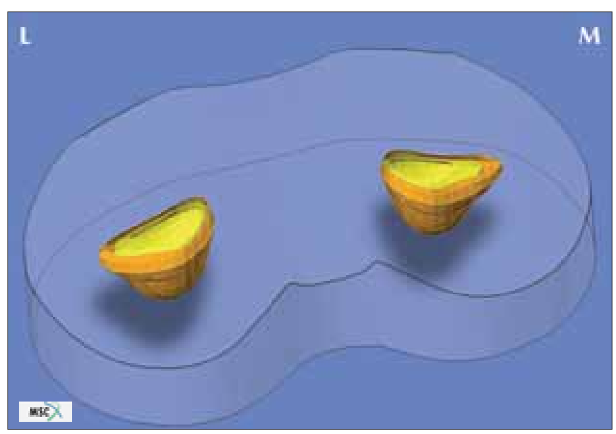
60° Flexion
4.3 BW Inferior
0.2 BW Posterior

Contact Area: 258 mm²



90° Flexion
3.3 BW Inferior
1.0 BW Anterior

Contact Area: 251 mm²



135° Flexion
4.5 BW Inferior
0.4 BW Anterior

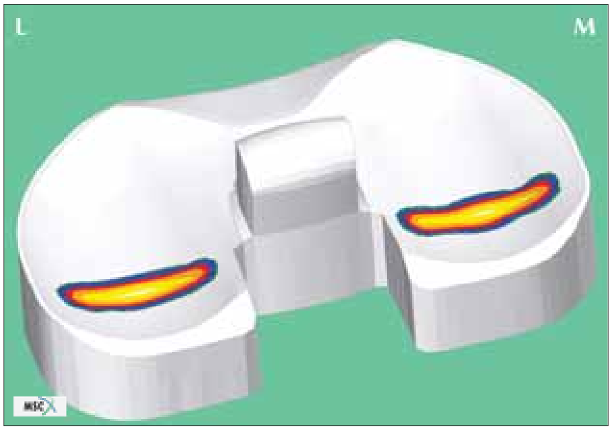
Contact Area: 250 mm²

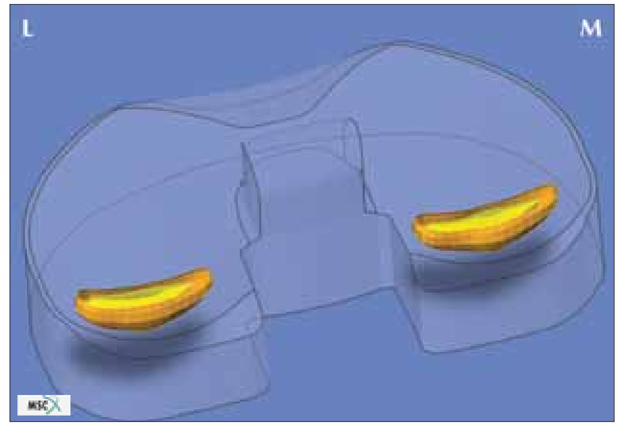
for these designs overlie and influence subsurface Von Mises stress volumes. These isosurface stress images (blue background) illustrate volumes of polymer within the insert stressed above a 9 MPa damage threshold.[9] Isosurfaces are defined by points

Legacy LPS-Flex Fixed

Surface Stress

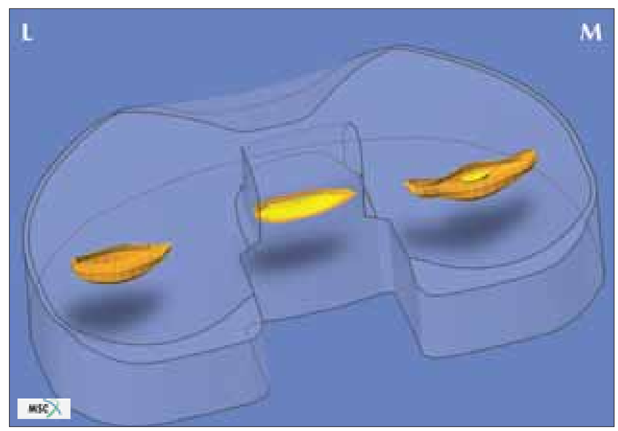
Subsurface Stress





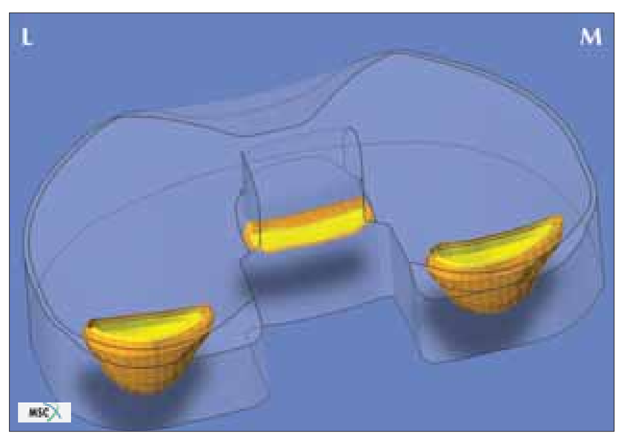
60° Flexion
4.3 BW Inferior
0.2 BW Posterior

Contact Area: 277 mm²



90° Flexion
3.3 BW Inferior
1.0 BW Anterior

Contact Area: 311 mm²



135° Flexion
4.5 BW Inferior
0.4 BW Anterior

Contact Area: 335 mm²

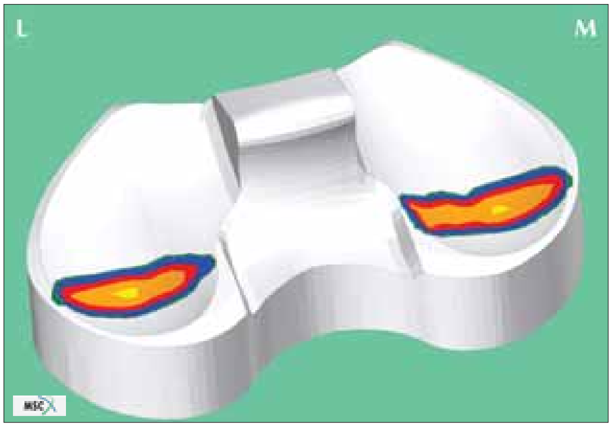
*1 MPa = 1 N/mm² = 145 psi

of identical stress magnitude, and when present, appear as concentric ellipsoids or cylinders. They represent a visual inference of the potential for material delamination, the dominant mechanism of failure in total knee retrievals.

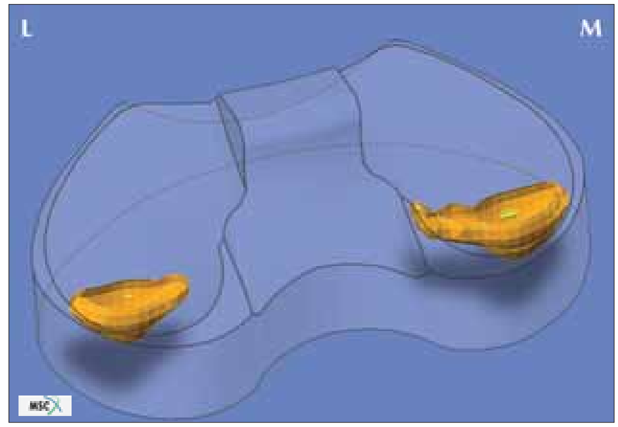
P.F.C. Sigma RPF

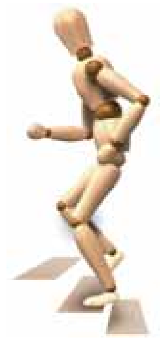
Surface Stress

Subsurface Stress

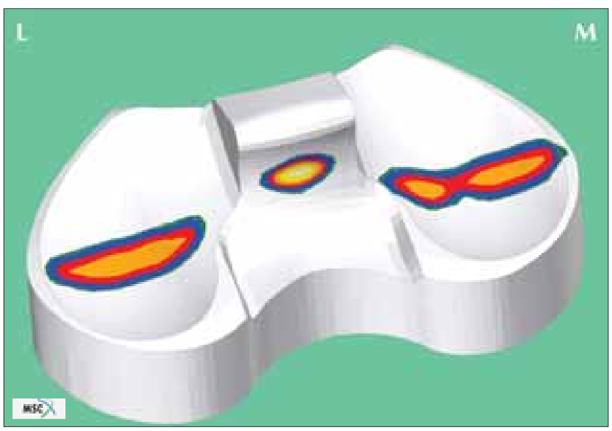


Contact Area: 338 mm²

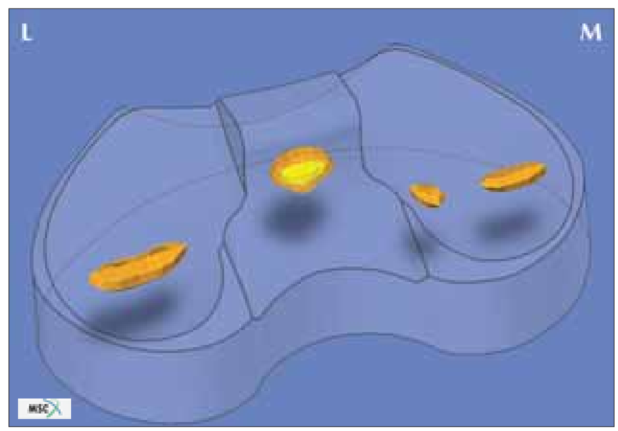


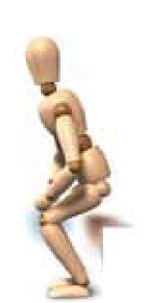


60º Flexion
4.3 BW Inferior
0.2 BW Posterior



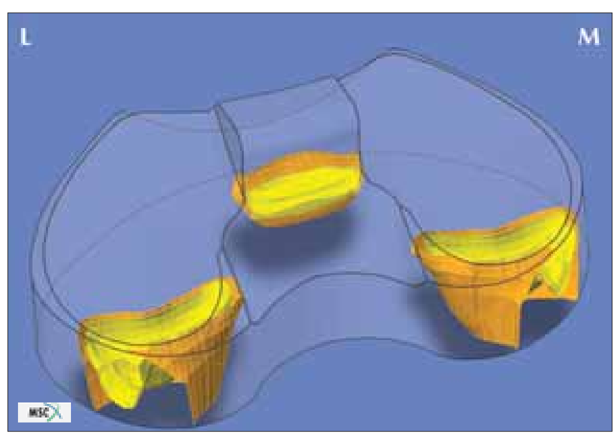
Contact Area: 323 mm²





90º Flexion
3.3 BW Inferior
1.0 BW Anterior

Contact Area: 287 mm²



135º Flexion
4.5 BW Inferior
0.4 BW Anterior

DISCUSSION

The component geometries of each design studied define their respective conformity and intrinsic constraint. The lateral compartment of the 3DKnee has a spherical style conformity and thus offers high constraint and achieves low magnitudes of both surface and subsurface stress. In contrast, the medial compartment has a swept cylindrical shape and allows excursion when presented with a strong anterior femoral thrust during the chair rise activity. The articulation pivots about the lateral compartment, causing medial compartment engagement near the anterior edge.

The Vanguard CR achieves reasonable conformity in the coronal plane, while displaying a relatively flat geometry in the sagittal, with a built in 3° posteriorly directed slope ending in a minimum lip geometry. This design geometry did not provide enough intrinsic posterior constraint during the modeled stair ascent activity and additional anteriorly directed force was required to maintain the femoral component in its pictured position. This low constraint design allows the femoral component to traverse the proximal surface of the tibial insert, distributing stress throughout the entire plateau during high flexion activities, increasing the role of soft tissue load sharing to achieve stability.

In contrast, both the Legacy LPS-Flex Fixed and P.F.C. Sigma RPF designs are less dependent on soft tissue constraints and achieve stability through a polymer spine / femoral cam interaction. This feature constrains contact to the central and posterior portions of each compartment during high flexion activities. The PFC Sigma RPF geometries display lower stress than the Legacy LPS-Flex Fixed with the exception of kneel rise where the geometries promote wedging of the femoral component between the polymer spine and posterior insert lips.

Of the three high flexion activities evaluated, kneel rise is the most demanding. In this position both surface and subsurface stress levels reach large magnitudes and if repetitively encountered are suggestive of material damage. The posterior stabilized designs promote contact near the posterior edge of the insert to increase the opportunity for patients to achieve high flexion, however at the expense of high stresses being located near the posterior edge.

Fluoroscopy studies[10,11] clearly demonstrate that high flexion angles are achievable in different patient populations. The attainment of these orientations as part of normal activity suggest that in the high demand patient the posterior aspects of tibial component inserts may indeed be subject to these high stress environments. Internal rotation of the femoral component relative to the tibia is naturally coincident with high flexion and may further contribute to damage as the lateral compartment of the knee unloads.

CONCLUSION

This study suggests that in high flexion activities polymer stress levels can influence component integrity in total knee replacement. Whether these extremes of flexion are realized is dependent on component design, surgical and patient factors.

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