THE EFFECT OF ARTICULAR GEOMETRY ON ABRASION AND DELAMINATION OF TIBIAL INSERTS: A FINITE ELEMENT STUDY

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INTRODUCTION

The durability of polymer tibial insert components is still considered the primary factor limiting the clinical longevity of total knee arthroplasty. Polyethylene abrasion and delamination in component retrievals are the result of high cycle fatigue loads which act on the tibial insert during daily ambulation. These damage modes, also influenced by component oxidation, contribute to debris generation, the initial step in the sequela of osteolytic response.

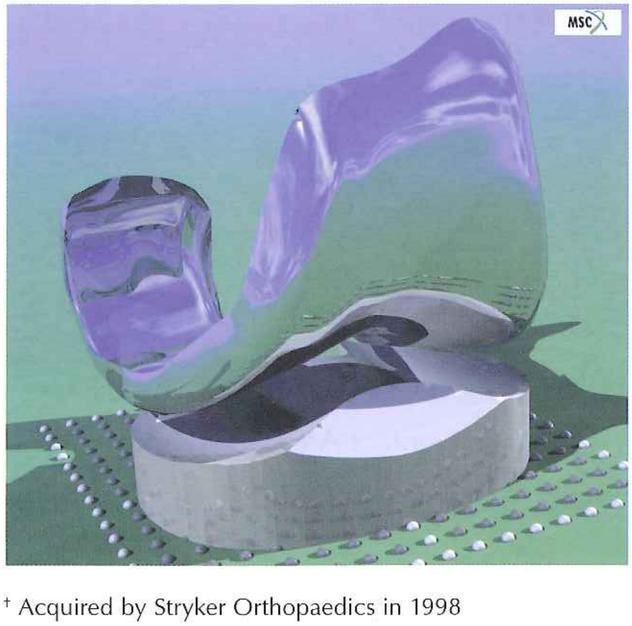
This study isolates the role articular surface geometry plays in the development of damaging stresses acting both on and within the polyethylene tibial insert. The designs presented in this study are the Balanced Knee (Ortho Development, Inc.), Duracon A/P Lipped (Howmedica, Inc.[†]), Genesis II Cruciate Retaining (Smith & Nephew Richards, Inc.) and NK II Congruent (Intermedics Orthopedics, Inc.[‡]).

All four of these contemporary cruciate retaining knee designs have undergone the same testing and thus their results are directly comparable.

METHODS

A three-dimensional, finite element model was created for each fixed bearing total knee design by measuring the articular surfaces of implantable quality parts using both a coordinate measuring machine and a laser profilometer. The average loading conditions for the heelstrike portion of the stance phase of the walking gait cycle were determined through a meta-analysis of the literature to be 1,950 Newtons of compression. This load was applied at 0° of flexion and the virtual components were allowed to settle into their preferred alignments without friction or consideration of soft tissue constraints.

To aid in comparison, all polymer inserts were characterized by the same gamma irradiated, nonlinear material[1] 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.

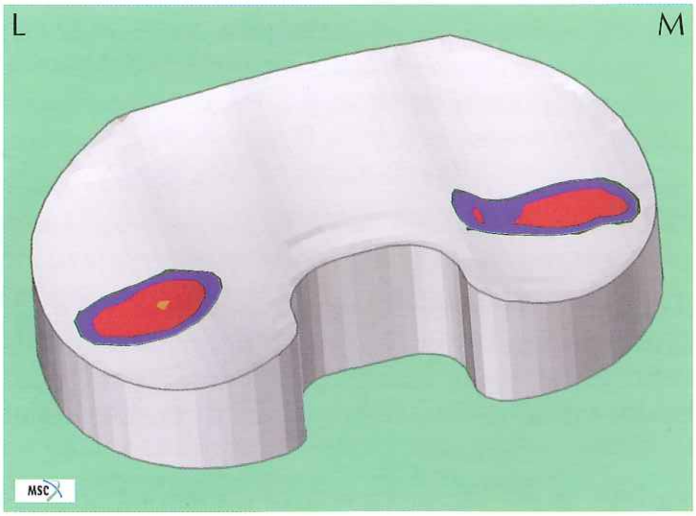


[†] Acquired by Stryker Orthopaedics in 1998
[‡] Acquired by Zimmer, Inc. in 2003

SURFACE CONTACT STRESS

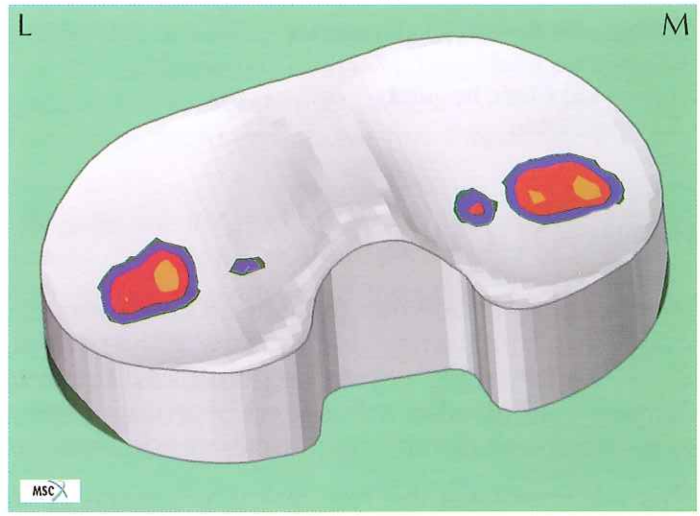
The distribution of surface contact stress is appreciated from a superior posterior view of the left knee. The images below give an indication of the areas where tibial insert surface abrasion caused by contact with the femoral component can occur during walking gait heel strike. Hotter colors indicate higher contact stress. The higher the contact stress, the greater the propensity for abrasive damage.

Genesis II Cruciate Retaining



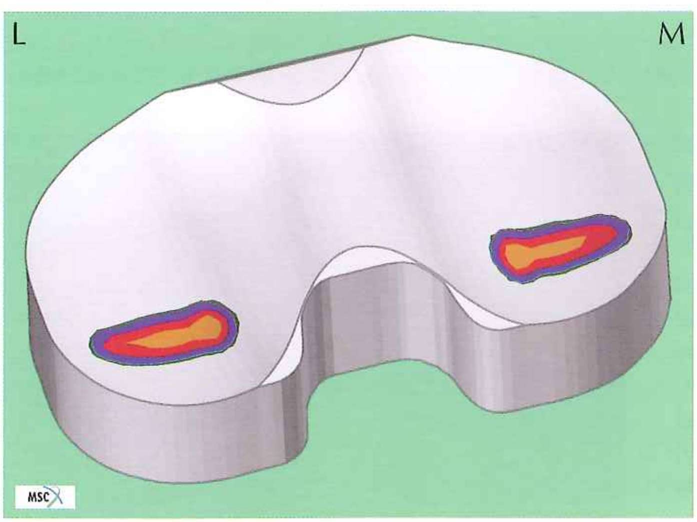
Contact Area: 293 mm^2

NK II Congruent



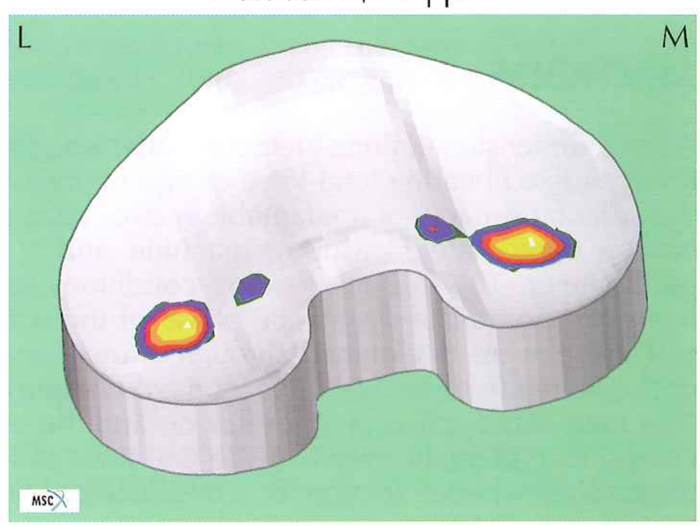
Contact Area: 270 mm^2

Balanced Knee



Contact Area: 241 mm^2

Duracon A/P Lipped



Contact Area: 219 mm^2

*1 MPa = 1 N/mm^2 = 145 psi

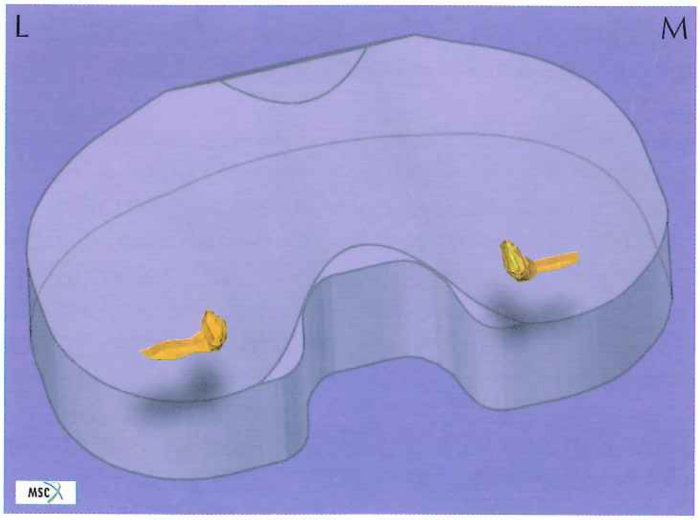
SUBSURFACE DELAMINATION STRESS

The distribution of subsurface delamination (Von Mises) stress illustrates locations where shear cracks may propagate parallel to, but just below, the articulating surface. The isosurface stress images below indicate volumes of polymer within the insert stressed above a 9 MPa damage threshold. Isosurfaces are defined by points of identical stress magnitude and appear as concentric elipsoids or cylinders.

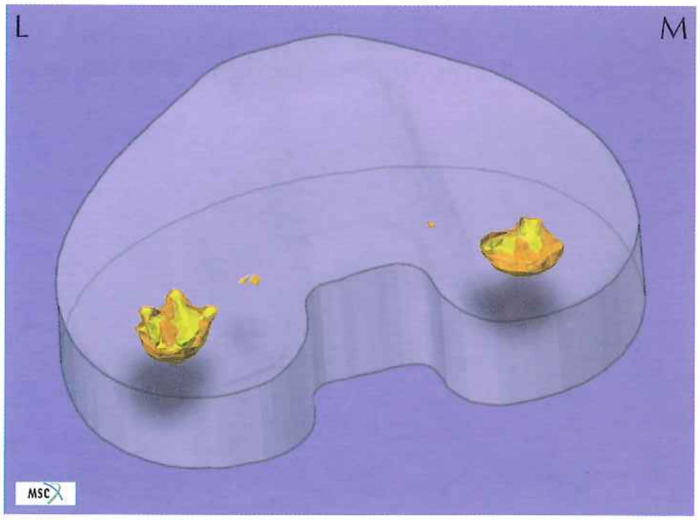
Genesis II Cruciate Retaining

NK II Congruent A/P Lipped

Balanced Knee



Duracon A/P Lipped



DISCUSSION

This study elucidates the role articular surface geometry plays in the development of damaging stresses acting both on and within the polyethylene tibial inserts of four contemporary knee designs. The results are suggestive of locations where surface abrasion and subsurface delamination may occur during long term ambulation.

The footprint of the surface stress distributions visualized for these designs overlie and influence subsurface delamination stress volumes. Large surface contact stress gradients (rapid changes in contact stress magnitude over a small distance along the tibial insert surface) are predictive of increasing subsurface Von Mises stresses that are linked with delamination.

The subsurface delamination stress isosurface images represent a visual inference of the potential for material delamination, the dominant mechanism of failure in total knee retrievals. Material failure theories for polymers[2] suggest that delamination is unlikely to occur in the tibial insert when cycled through a stress range less than 9 MPa. As subsurface delamination stress increases above this threshold, there is a higher potential for crack development.

In less conforming designs, the highest delamination stresses are located at the center of contact and occur approximately 1.5 mm beneath the articulating surface. In general, the stresses in more conforming systems are lower in magnitude and their location shifted into a ring outside of the edge of contact and closer to the surface.

The results presented here are from a single heel strike position in the gait cycle, and represent "best case" stress distributions both on and within the polyethylene. These stresses are expected to increase during the rolling and sliding motions of normal gait and from aberrant kinematics produced by skeletal deformity and component malalignment.

CONCLUSIONS

The visual results of surface and subsurface stress associated with polymer damage serve as a performance "signature" for each design presented. Each design is directly comparable to other designs that have undergone this same testing. Three of the four designs; Duracon A/P Lipped, Genesis II Cruciate Retaining and the NK II Congruent, have enjoyed a long, successful clinical history. The signature of the Balanced Knee places it among these designs, and by extension, suggests similar efficacy in clinical use.

REFERENCES

1. Waldman SD, Bryant JT, "Compressive Stress Relaxation Behaviour of Irradiated Ultra-High Molecular Weight Polyethylene at 37° C", J Appl Biomater 5:333-338, 1994.
2. Williams JG: Stress Analysis of Polymers, Halstead Press, John Wiley & Sons, 1984.

Additional information on knee implant performance for a wide variety of contemporary designs is available at our website http://orl-inc.com

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