POLYMER INSERT STRESS IN TOTAL KNEE DESIGNS DURING HIGH FLEXION ACTIVITIES: A FINITE ELEMENT STUDY

Orthopaedic Research Laboratories
Lutheran Hospital
Cleveland Clinic Health System
Cleveland, Ohio

Edward A. Morra, M.S.M.E.
A. Seth Greenwald, D.Phil.(Oxon)

INTRODUCTION

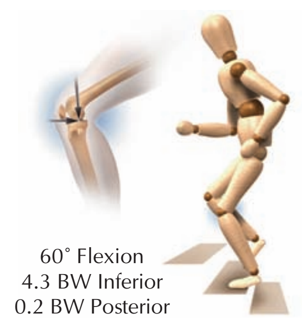
The success of total knee arthroplasty has contributed to its widening application to a younger, more active patient population whose daily regimen includes more demanding high flexion activities. Worldwide expansion to Middle Eastern and Asian patient populations, where the attainment of high knee joint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

Three mobile bearing designs were evaluated, the Dual Bearing Knee (Finsbury Orthopaedics Ltd.), e.motion (Aesculap AG & Co.KG), and P.F.C. Sigma RPF (DePuy, a Johnson & Johnson Company) in addition to the Legacy LPS-Flex Fixed Bearing (Zimmer, Inc.). The latter two designs are currently available for clinical use in the United States.

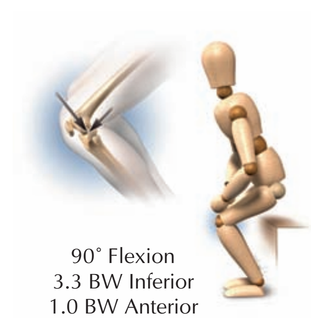
METHODS

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] (60º), rising from a chair[4] (90º) and rising from a double leg kneel[5,6,7] (135º) 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. To aid in comparison, all polymer inserts were characterized by the same gamma irradiated, nonlinear material[8] of 10 mm thickness maintained at 37º Celsius. Contact areas and stresses on the polymer inserts were calculated using a 1 MPa threshold and their magnitudes and locations were then photorealistically imaged.

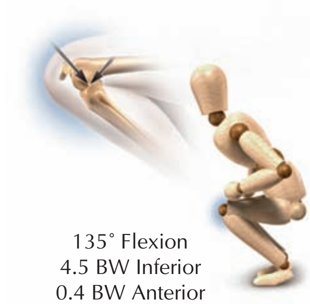
Stair Ascent



Chair Rise



Kneel Rise



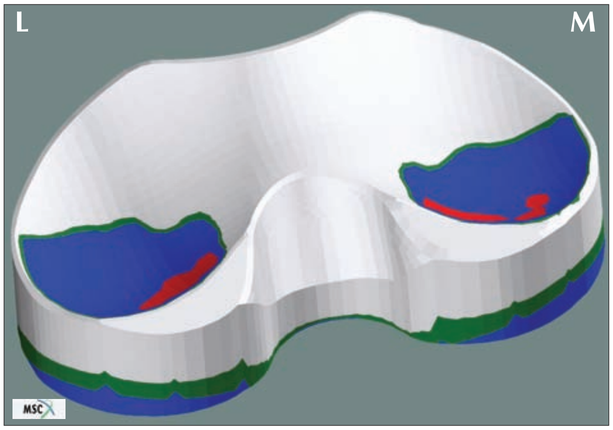
PROXIMAL CONTACT STRESS

*1 MPa = 1 N/mm² = 145 psi

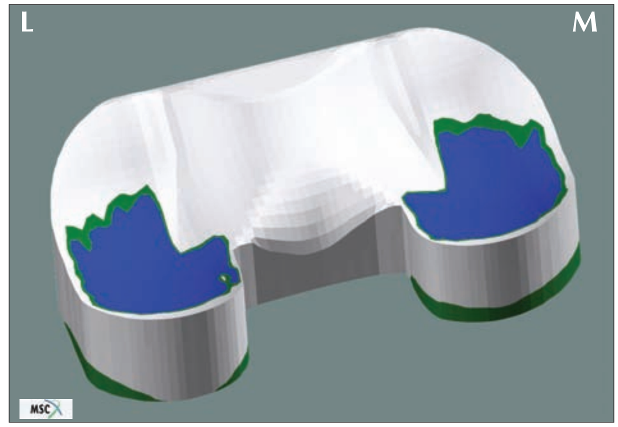
The distribution of compressive normal (contact) stresses is appreciated from a superior posterior view of the left knee for the systems studied during each activity. These images give an indication of areas

Dual Bearing Knee

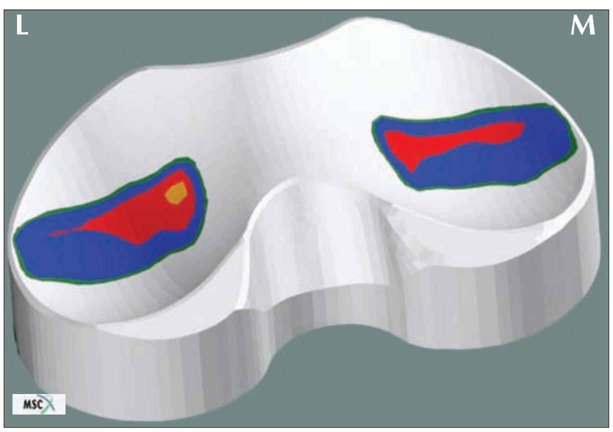
e.motion



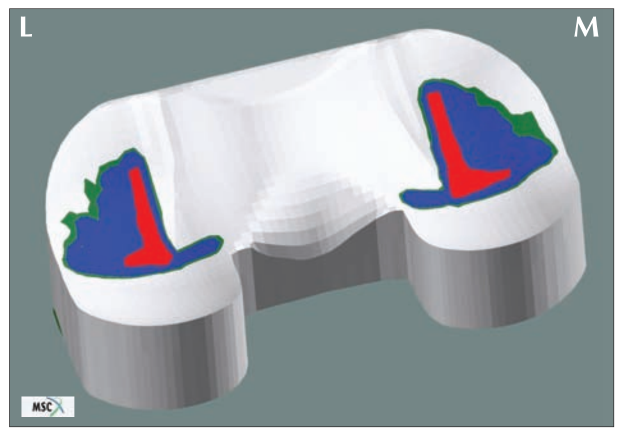
Contact Area: 621 mm²
Stair Ascent: 60° Flexion
Femoral Forces: 4.3 BW Inferior, 0.2 BW Posterior



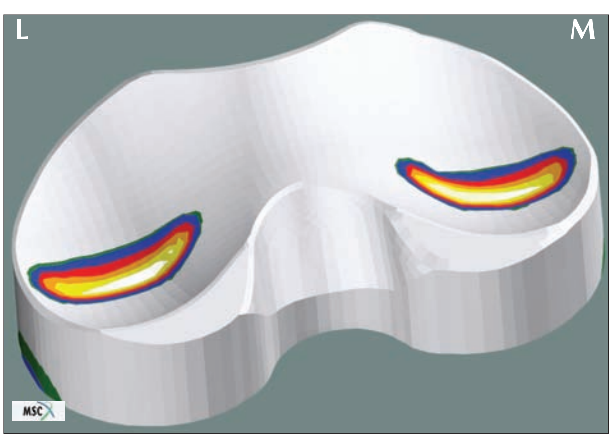
Contact Area: 831 mm²
Stair Ascent: 60° Flexion
Femoral Forces: 4.3 BW Inferior, 0.2 BW Posterior



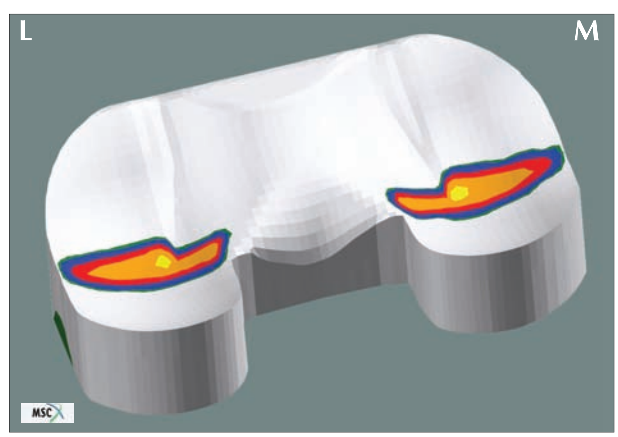
Contact Area: 455 mm²
Chair Rise: 90° Flexion
Femoral Forces: 3.3 BW Inferior, 1.0 BW Anterior



Contact Area: 484 mm²
Chair Rise: 90° Flexion
Femoral Forces: 3.3 BW Inferior, 1.0 BW Anterior



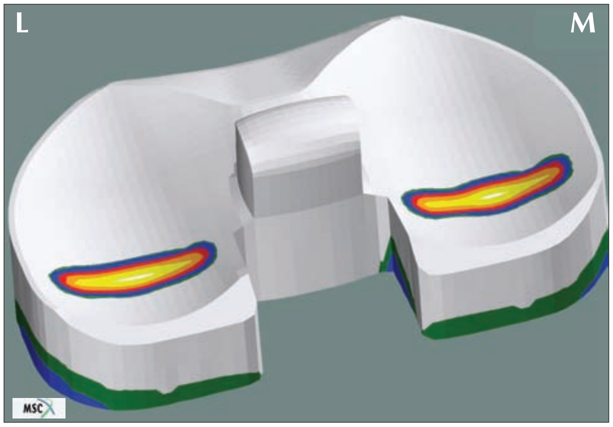
Contact Area: 292 mm²
Kneel Rise: 135° Flexion
Femoral Forces: 4.5 BW Inferior, 0.4 BW Anterior



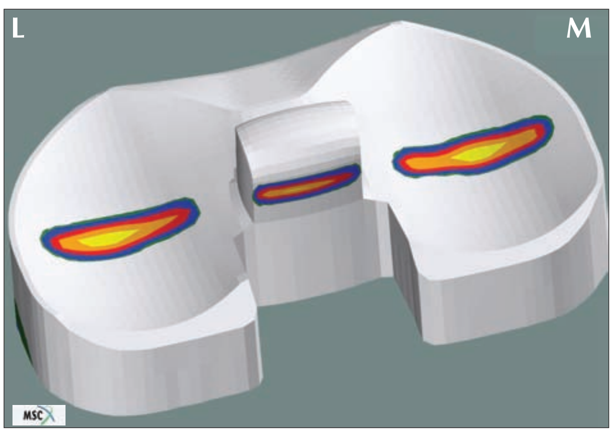
Contact Area: 345 mm²
Kneel Rise: 135° Flexion
Femoral Forces: 4.5 BW Inferior, 0.4 BW Anterior

where surface abrasion caused by contact with the femoral component can occur. The higher the contact stresses, the greater the propensity for abrasive damage. Stresses visualized on the sides of the insert are indicative of contact occurring on the distal surface near the perimeter. Designs are presented in alphabetical order.

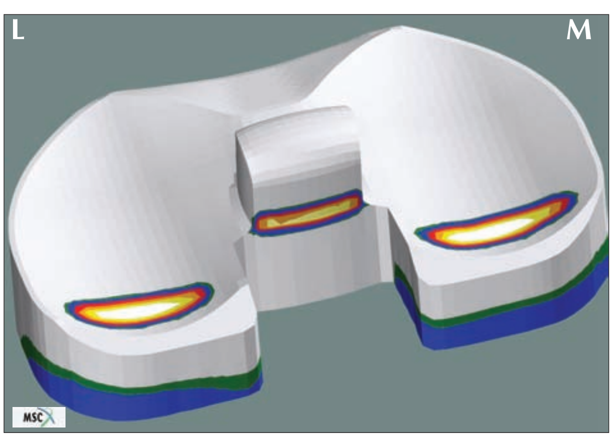
Legacy LPS-Flex Fixed



Contact Area: 277 mm^2
Stair Ascent: 60º Flexion
Femoral Forces: 4.3 BW Inferior, 0.2 BW Posterior

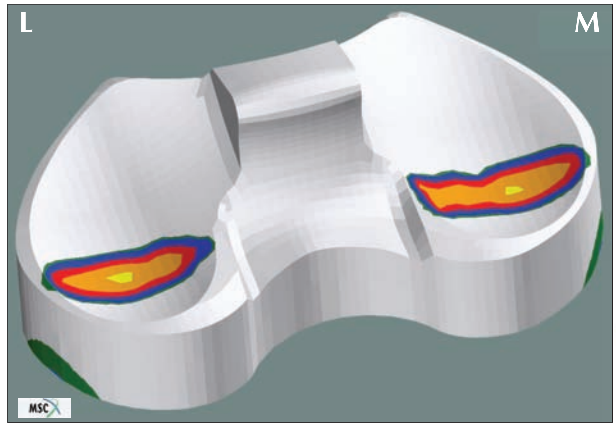


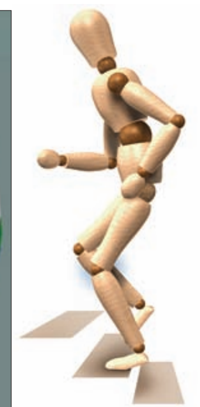
Contact Area: 311 mm^2
Chair Rise: 90º Flexion
Femoral Forces: 3.3 BW Inferior, 1.0 BW Anterior



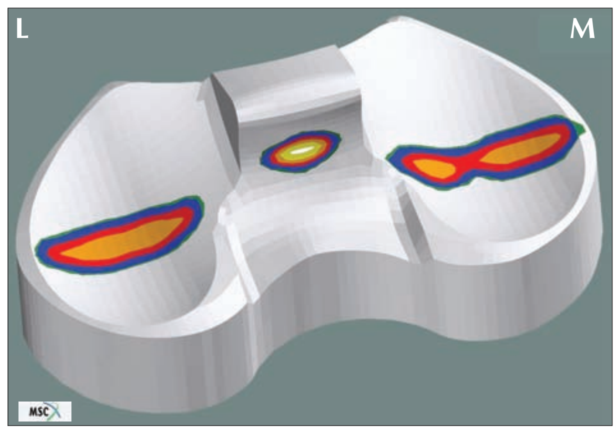
Contact Area: 335 mm^2
Kneel Rise: 135º Flexion
Femoral Forces: 4.5 BW Inferior, 0.4 BW Anterior

P.F.C. Sigma RPF

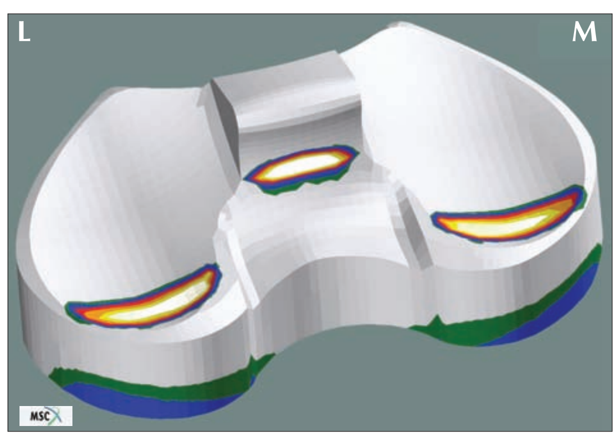




Contact Area: 338 mm^2
Stair Ascent: 60º Flexion
Femoral Forces: 4.3 BW Inferior, 0.2 BW Posterior



Contact Area: 323 mm^2
Chair Rise: 90º Flexion
Femoral Forces: 3.3 BW Inferior, 1.0 BW Anterior



Contact Area: 287 mm^2
Kneel Rise: 135º Flexion
Femoral Forces: 4.5 BW Inferior, 0.4 BW Anterior

DISCUSSION

The Dual Bearing Knee and e.motion cruciate retaining designs display highly conforming geometries during stair ascent with stresses lower than most total knees at full extension[9]. The Legacy LPS-Flex Fixed and P.F.C. Sigma RPF designs feature a polymer spine that interacts with a femoral cam to guide contact posteriorly in high flexion and are, in general, less conforming than the cruciate retaining designs and present with higher stresses.

The large anteriorly directed femoral force in chair rise is handled differently by each type of design in this study. The anterior slopes of the Dual Bearing Knee and e.motion polymer inserts constrain the motion, creating large contact areas with low stresses. The polymer spines in the Legacy LPS-Flex Fixed and P.F.C. Sigma RPF designs offer anterior motion constraint when engaged by their respective femoral cams, resulting in a more central contact location.

Of the three high flexion activities evaluated, kneel rise is the most demanding. Each of the designs studied displays stresses above the yield point reported for the polymer material. It is possible that these high stresses may cause permanent deformation of the polymer insert when patients are engaged in prolonged activities in this position. Fluoroscopy studies[10] of total knees have shown that the more posterior the contact location on the polymer insert, the more flexion the patient can experience. Although the spine cam designs successfully achieve this, they do so at the expense of higher stresses when compared to the e.motion cruciate retaining design.

CONCLUSIONS

In general, the cruciate retaining designs in this study realize lower stress levels than the spine cam designs in high flexion activities. The e.motion design maintains the highest conformity for all three high flexion activities in this study, resulting in the lowest stresses in the polymer insert. However, the maximum amount of flexion that a patient might experience may be less than the spine cam designs that force the location of femoral contact more posterior.

As contemporary total knee designs evolve to address the increased demands of younger and more culturally diverse patient populations, they will need to expand their range of motion envelope. Additionally, forces in the knee joint during high flexion activities vary considerably among patients and will be further influenced by component placement and soft tissue balancing. This information should assist manufacturers in ongoing design optimization required to assure the safety and effectiveness of these systems.

REFERENCES

1. Morrison JB, "Function of the Knee Joint in Various Activities", Biomed Eng., 4(12):573-80, 1969.
2. Taylor WR, Heller MO, Bergmann G, Duda GN, "Tibio-femoral Loading During Human Gait and Stair Climbing", J Orthop Res., 22(3):625-32, 2004.
3. Costigan PA, Deluzio KJ, Wyss UP, "Knee and Hip Kinetics During Normal Stair Climbing", Gait and Posture, 16(1):31-7, 2002.
4. Ellis MI, Seedhom BB, Wright V, "Forces in the Knee Joint Whilst Rising From a Seated Position", J Biomed Eng., 6(2):113-20, 1984.
5. Dahlkvist NJ, Mayo P, Seedhom BB, "Forces During Squatting and Rising From a Deep Squat", Eng Med., 11(2):69-76, 1982.
6. Nagura T, Andriacchi T, Alexander E, Matsumoto H, "Muscle Co-Contraction Increases the Load on the Posterior Cruciate Ligament During Deep Knee Flexion", Transactions of the 49th Annual Meeting of the Orthopaedic Research Society, 28:843, 2003.
7. Spanu CE, Hefzy MS, "Biomechanics of the Knee Joint in Deep Flexion: A Prelude to a Total Knee Replacement that Allows for Maximum Flexion", Technol Health Care., 11(3):161-81, 2003.
8. Waldman SD, Bryant JT, "Nonlinear Viscoelastic Behaviour of Irradiated Ultra-High Molecular Weight Polyethylene at 37° C", UHMWPE Workshop, ASTM Annual Meeting, 1994.

9*. Morra EA, Postak PD, Greenwald AS, "The Effects of Walking Gait on UHMWPE Damage in Mobile Bearing Knee Systems: A Finite Element Study", Proceedings of the American Academy of Orthopaedic Surgeons Annual Meeting 3:740, 2002.

10. Banks S, Bellemans J, Nozaki H, et al., "Knee Motions During Maximum Flexion in Fixed and Mobile-Bearing Arthroplasties", Clin Orthop., 410:131-8, 2003.

*Papers available via the Orthopaedic Research Laboratories website: http://orl-inc.com