Polymer Insert Stress in Total Knee Designs During High-Flexion Activities: A Finite Element Study

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Introduction

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

Three mobile-bearing designs (including the Dual Bearing Knee [Finsbury Orthopaedics, Surrey, United Kingdom], e.motion [Aesculap, Tuttlingen, Germany], and P.F.C. Sigma RPF [DePuy, a Johnson and Johnson Company, Warsaw, Indiana] devices) and one fixed-bearing design (the Legacy LPS-Flex Fixed Bearing device [Zimmer, Warsaw, Indiana]) were evaluated. 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 with use of a laser profilometer. Maximum joint loads and the angles of knee flexion at which they occurred were determined through a meta-analysis of the literature for three high-flexion activities: ascending stairs[1-4] (60°), rising from a chair[5] (90°), and rising from a double-leg kneel[4,6,7] (135°) with use of a body weight of 71 kg (Fig. 1). 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 37°C. Contact areas and stresses on the polymer inserts were calculated with use of a 1-MPa threshold, and their magnitudes and locations were then photorealistically imaged (Table I).

Results

The distribution of compressive normal (contact) stresses in Figure 2 is appreciated from a superior-posterior view of the left knee for the systems studied during each activity. These images provide an indication of 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. Stresses visualized on the sides of the insert are indicative of contact occurring on the distal surface near the perimeter. The designs are presented in alphabetical order (Dual Bearing Knee *[b, f,* and *j],* e.motion *[c, g,* and *k],*

TABLE I Contact Areas

			Contact Area *(mm²)*			
Activity	Flexion Angle	Femoral Forces*	Dual Bearing Knee	e.motion	Legacy LPS-Flex Fixed	P.F.C. Sigma RPF
Stair ascent	60°	4.3 × BW inferior 0.2 × BW posterior	621	831	277	338
Chair rise	90°	3.3 × BW inferior 1.0 × BW anterior	455	484	311	323
Kneel rise	135°	4.5 × BW inferior 0.4 × BW anterior	292	345	335	287

*BW = body weight.

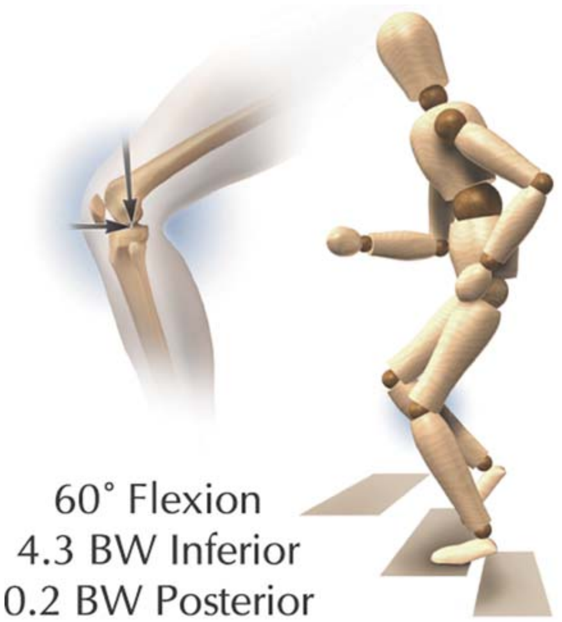

Fig. 1-A

Fig. 1-B

Illustrations depicting high-flexion activities with their knee joint loads and flexion angles at the moment of greatest load during (a) stair ascent, (b) chair rise, and (c) kneel rise.

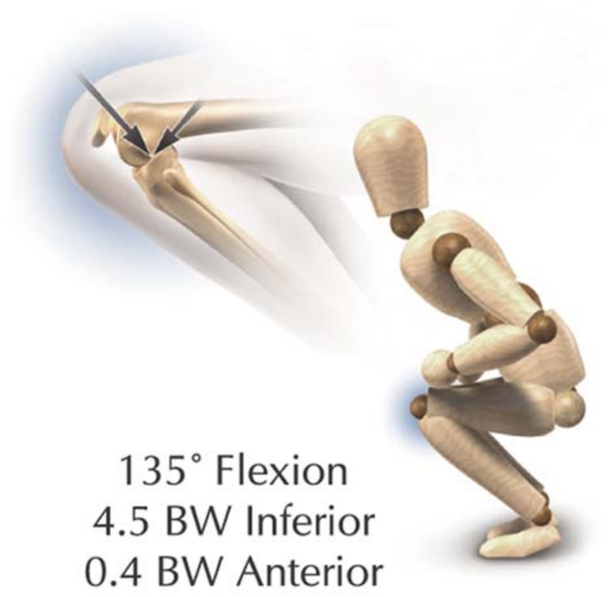

Fig. 1-C

Legacy LPS-Flex Fixed Bearing *[d, h,* and *l],* and P.F.C. Sigma RPF *[e, i,* and *m]).*

Discussion

The Dual Bearing Knee and e.motion cruciate-retaining designs display highly conforming geometries during stair ascent, with stresses lower than those associated with 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 during 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 constrain anterior motion when engaged by their respective femoral cams, resulting in a more central contact location.

Of the three high-flexion activities that were evaluated, kneel rise is the most demanding. Each of the designs that

Fig. 2

a

Fig. 2, *a* through *m* Scale and illustrations depicting the contact stress results during the three high-flexion activities for the four implant designs. *a,* Scale indicating the stress levels corresponding with the different colors shown in the following

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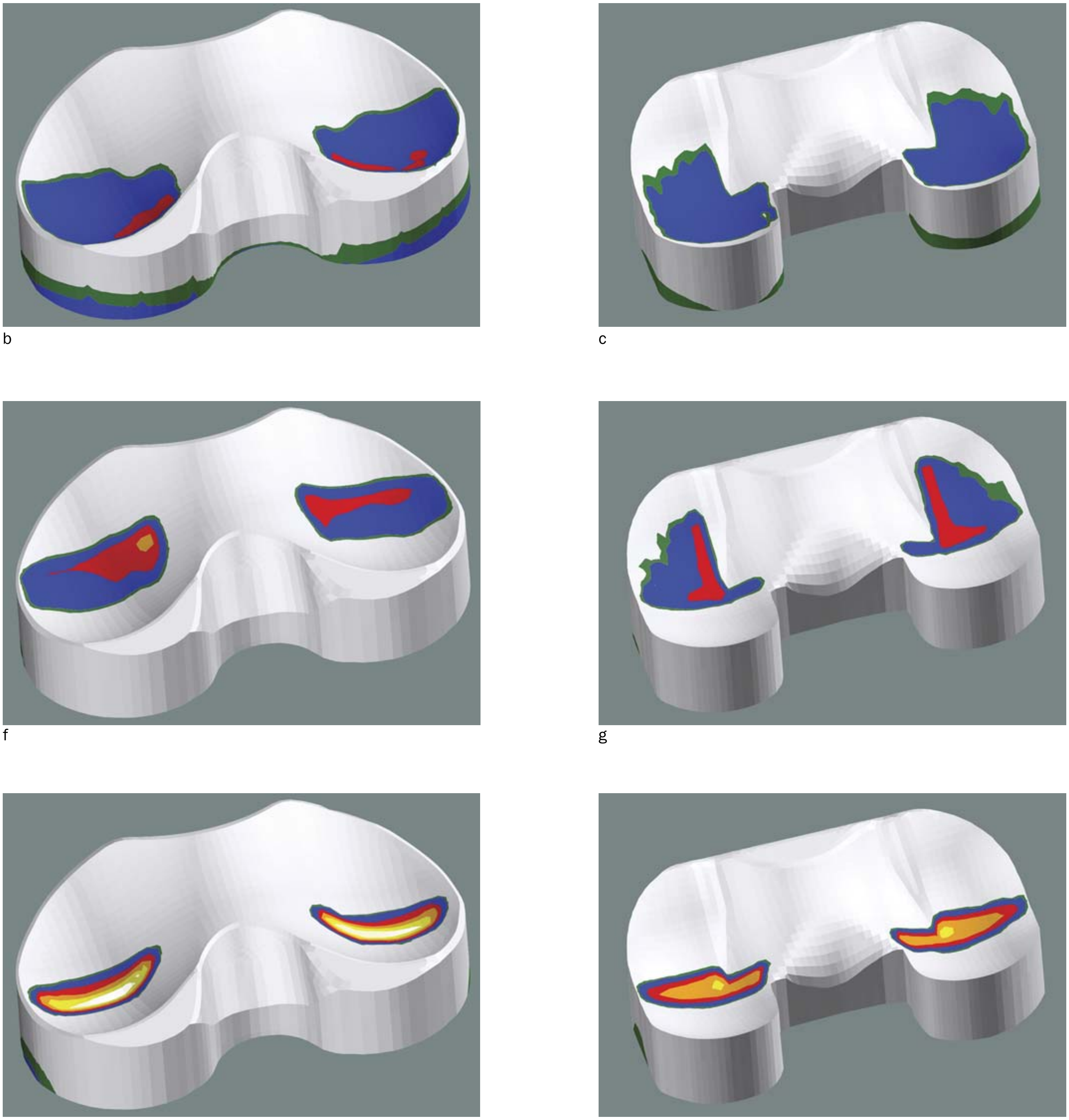


b

c

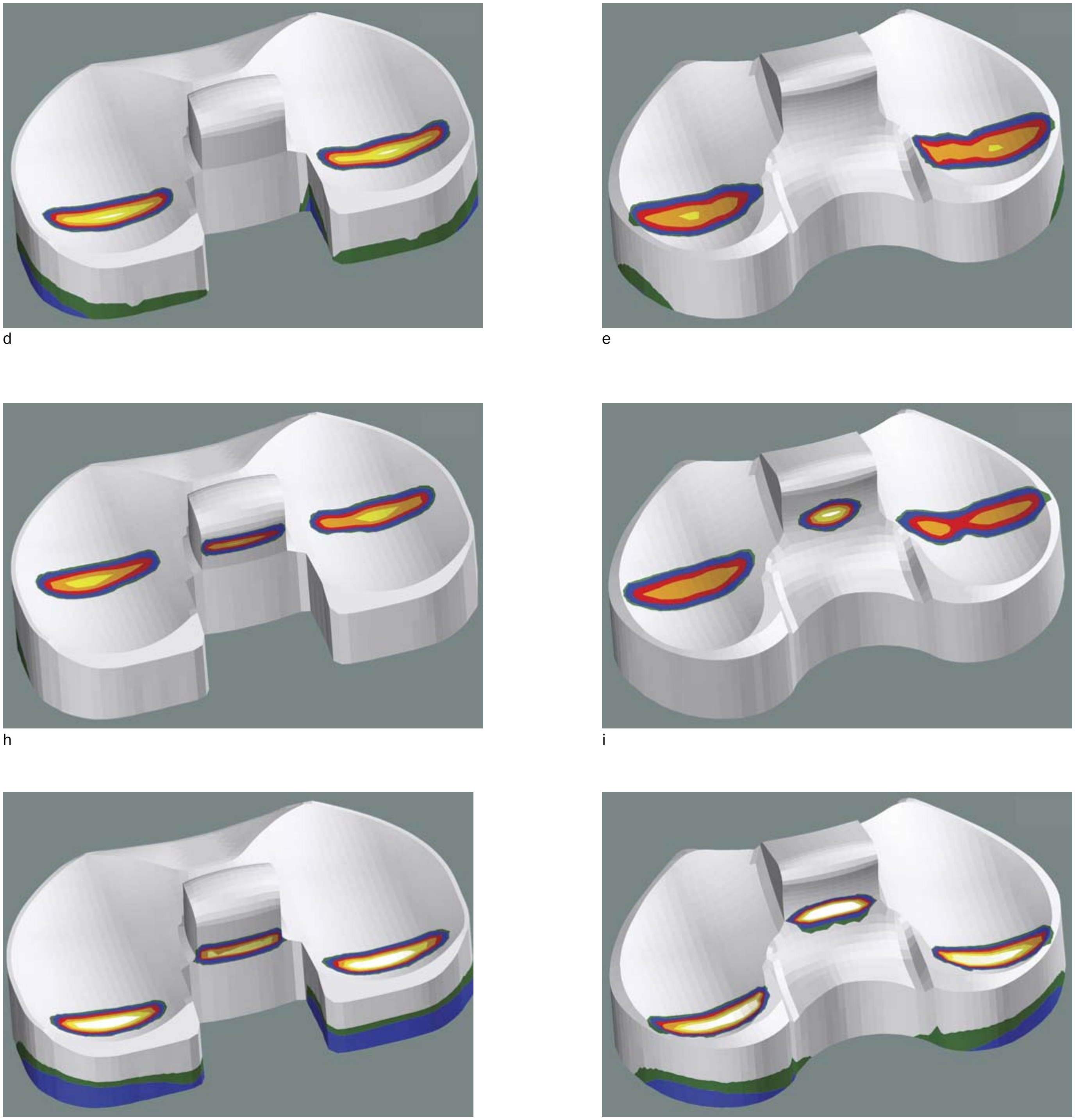
f

g

j

k

illustrations. *b, c, d,* and *e:* Contact stress results during the stair-ascent activity for the Dual Bearing Knee, e.motion, Legacy LPS-Flex Fixed Bearing, and P.F.C. Sigma RPF implants, respectively. *f, g, h,* and *i:* Contact stress results during the chair-rise activity for the Dual Bearing Knee, e.motion, Legacy LPS-Flex Fixed Bearing, and P.F.C. Sigma RPF implants, respectively. *j, k, l,* and *m:* Contact stress results during the kneel-rise activity for the Dual Bearing Knee, e.motion, Legacy LPS-Flex Fixed Bearing, and P.F.C. Sigma RPF implants, respectively.



d

e

h

i

l

m

were studied displayed 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. Fluoroscopic studies[10] of total knee replacements 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 posterior contact, they do so at the expense of higher stresses when compared with the e.motion cruciate-retaining design.

Conclusions

In general, the cruciate-retaining designs in the present study realized lower stress levels than the spine cam designs during high-flexion activities. The e.motion design maintained the highest conformity during 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 with the cruciate retaining designs may be less than the amount of flexion that spine cam designs (which force the location of femoral contact more posteriorly) may provide.

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 the ongoing design optimization that is required to ensure the safety and effectiveness of these systems. ■

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