THE INFLUENCE OF CONTEMPORARY TKA DESIGN ON HIGH FLEXION III: *A KINEMATIC COMPARISON WITH THE HEALTHY INTACT KNEE*

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INTRODUCTION

Although Total Knee Arthroplasty (TKA) surgery enjoys 90% of outcomes with good to excellent results, some patients are uncomfortable adjusting their gait to accomodate the new articulations inherent in many contemporary implant designs. Paradoxical motions, inclusive of anterior sliding and lateral pivot of the femur relative to the tibia are examples of aberrant TKA kinematics that are opposite of those observed in healthy intact knees.

A computational kinematic simulator is employed in this study to quantify the motion of six posterior stabilized TKA designs during high flexion activity, allowing comparison to the motion of healthy intact knees. The VEGA (Aesculap), Vanguard PS (Biomet), Apex PS (OMNI life science, Inc.), Journey II (Smith & Nephew), Legacy LPS-Flex Fixed and Persona PS (both from Zimmer) were evaluated. All six designs are fixed plateau and currently available for clinical use in the United States.

COMPUTATIONAL KINEMATICS

KneeSIM, a dynamic, validated musculoskeletal modeling system was utilized in this study. It provides a musculoskeletal modeling environment of the left leg of a nominal sized patient in which activities such as walking gait, lunge, stair ascent and descent and deep knee bend may be simulated. Activities are propelled by muscle forces and constrained by soft tissues.

Solid models of TKA component geometries are arranged in the joint space to reflect a successful virtual surgery (Figure 1). A specified activity is simulated and animations and plots of component and soft tissue positions, forces and moments are generated.

Factors influencing kinematic function and stability of the knee joint, including surgical technique, component placement, design, and soft tissue competency may be varied within the KneeSIM modeling environment. Patient anthropometrics may also be varied.

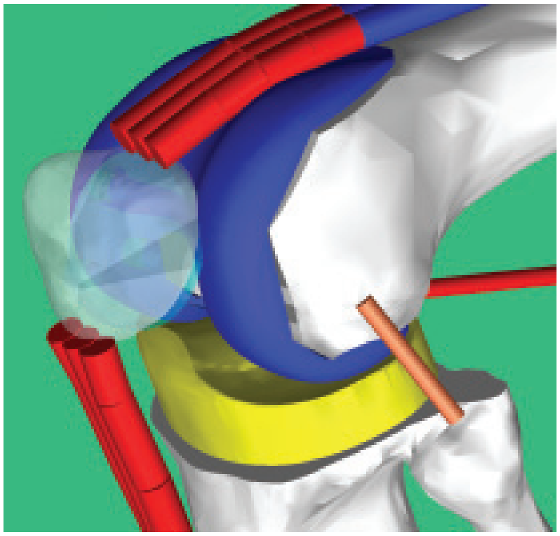


Figure 1: KneeSIM, a dynamic, validated musculoskeletal modeling system.

KNEESIM VALIDATION

Anecdotal validations were performed comparing kinematic performance of a KneeSIM model of the Duracon knee implant to fluoroscopy (Figure 2) and retrieval wear scar data (Figure 3) available in the peer reviewed literature. The KneeSIM model captured distinct signatures of femoral component motion similar to that captured by the fluoroscopy data.[1]

Further, the tibio-femoral contact stress accumulated on the surface of the insert during walking gait and deep flexion activity cycles in the KneeSIM model predicted an unusual wear scar pattern that closely matched clinical retrieval data for 17 Duracon tibial inserts.[5]

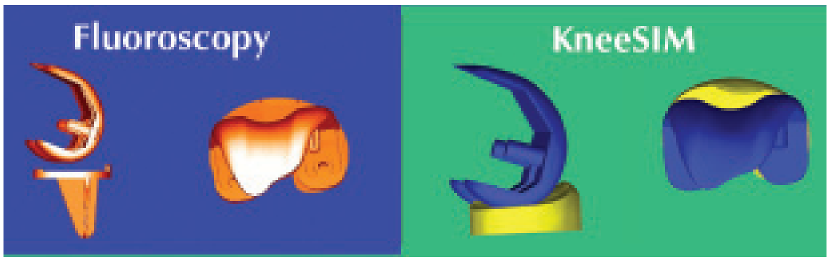


Figure 2: Fluoroscopy and KneeSIM compare favorably.

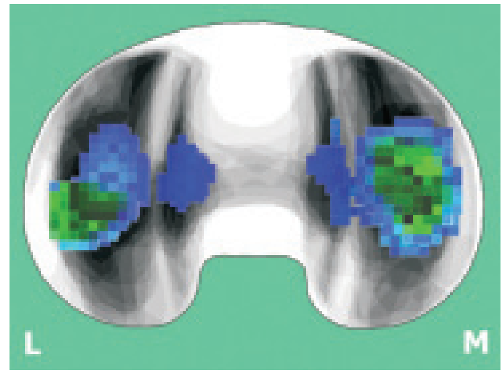


Figure 3: Retrieval wear scar pattern with KneeSIM overlay of accumulated pathways of contact stress.

STUDY METHODS

Three-dimensional solid models of the femoral, patellar and tibial insert components were "implanted" in the KneeSIM joint space per each manufacturer's unique surgical procedure. Both cruciate ligaments were virtually resected in all six cases studied. Weight bearing high flexion activity was simulated, and femoral component motion was quantified as a function of knee flexion angle.

To aid in comparison with published weight bearing, healthy intact knee motion data[4], a common marker describing femoral motion was required. In a manner similar to the clinical study, unique flexion facet centers (FFC) markers were determined for each femoral component using computer aided design tools (Figure 4). A sagittal plane was cut through each femoral condyle and a circle approximating the posterior condyle articulating surface was created. The FFC is depicted as a sphere at the middle of the circle, acting as a center of rotation through most of the flexion arc of motion. Medial and lateral flexion facet centers were joined to create a "barbell" structure, which was rigidly affixed to the femoral component to better visualize its motion.

An initial analysis of a deep flexion activity to 160° of knee flexion was conducted to determine the maximum flexion angle achievable with each design. For the purposes of this study, impingement of the posterior femoral bone cut surface (Figure 5a) with the tibial insert (Figure 5b) was considered the first event that would impede knee flexion, and thus defined the maximum flexion angle.

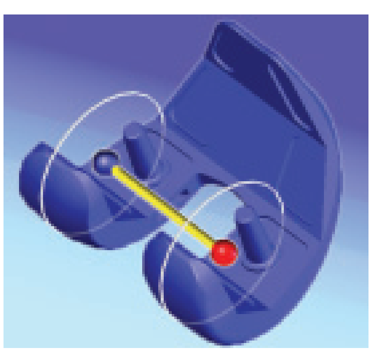


Figure 4: Determining flexion facet centers.

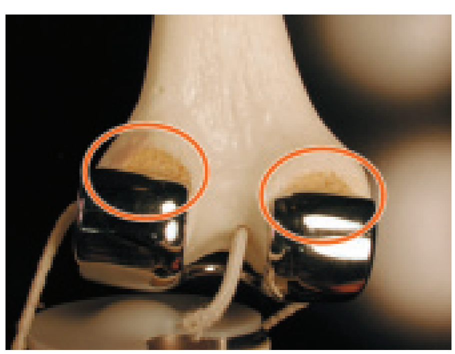
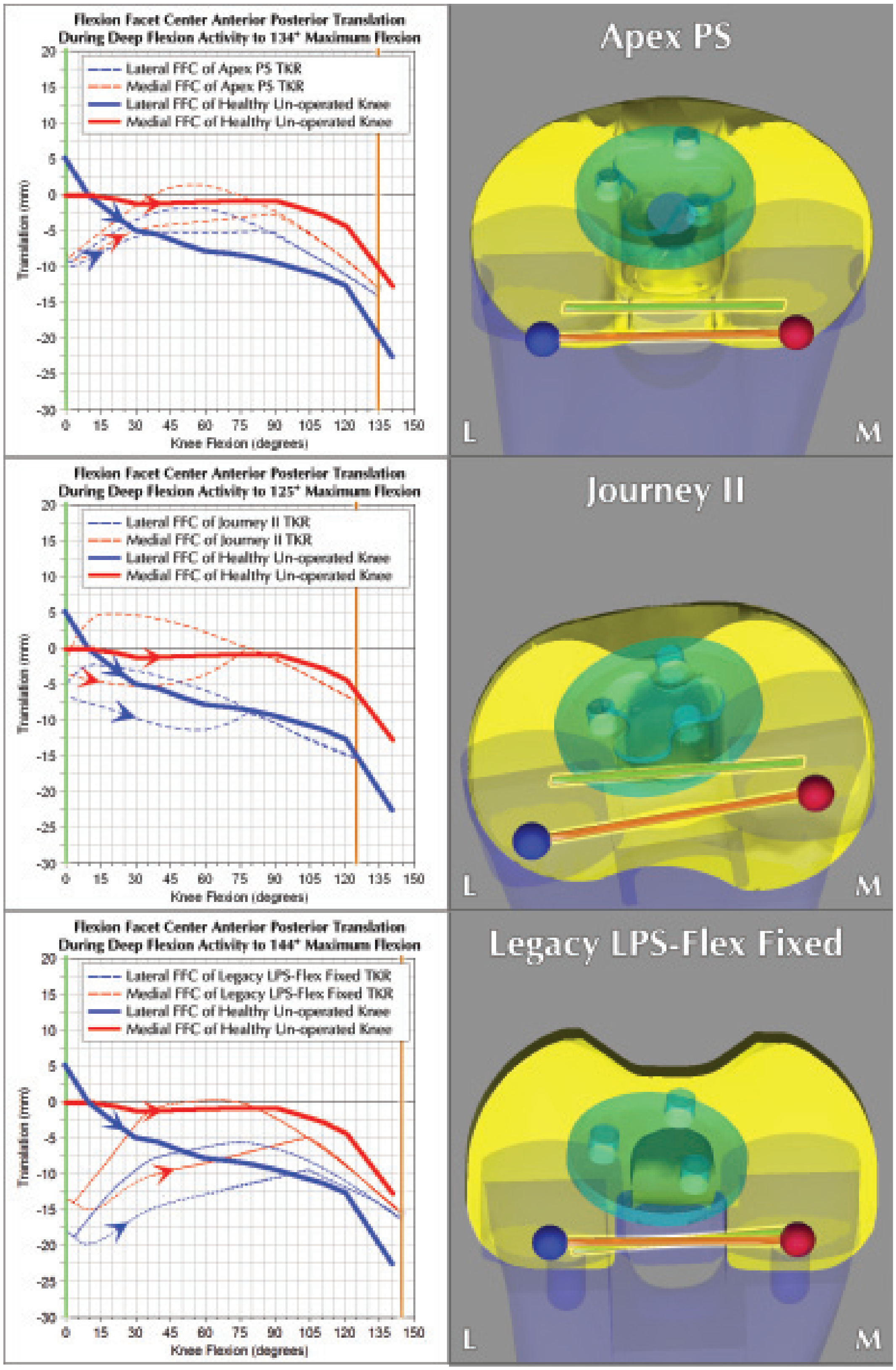


Figure 5a: Posterior femoral bone cut surface.

Figure 5b: Maximum flexion defined by bony impingement.

RESULTS

The resulting animations and plots characterize motion of the femoral component relative to the tibial insert in comparison to that of the healthy intact knee. Each design flexes until the posterior femoral bone cut surface impinges against the tibial insert, then returns to full extension. Figures 6a, 6b, 6c and Figures 7a, 7b, 7c represent the moment when maximum flexion occurred for each design. The plot on the left illustrates anterior (positive values) and posterior (negative values) translation of the flexion facet centers as a function



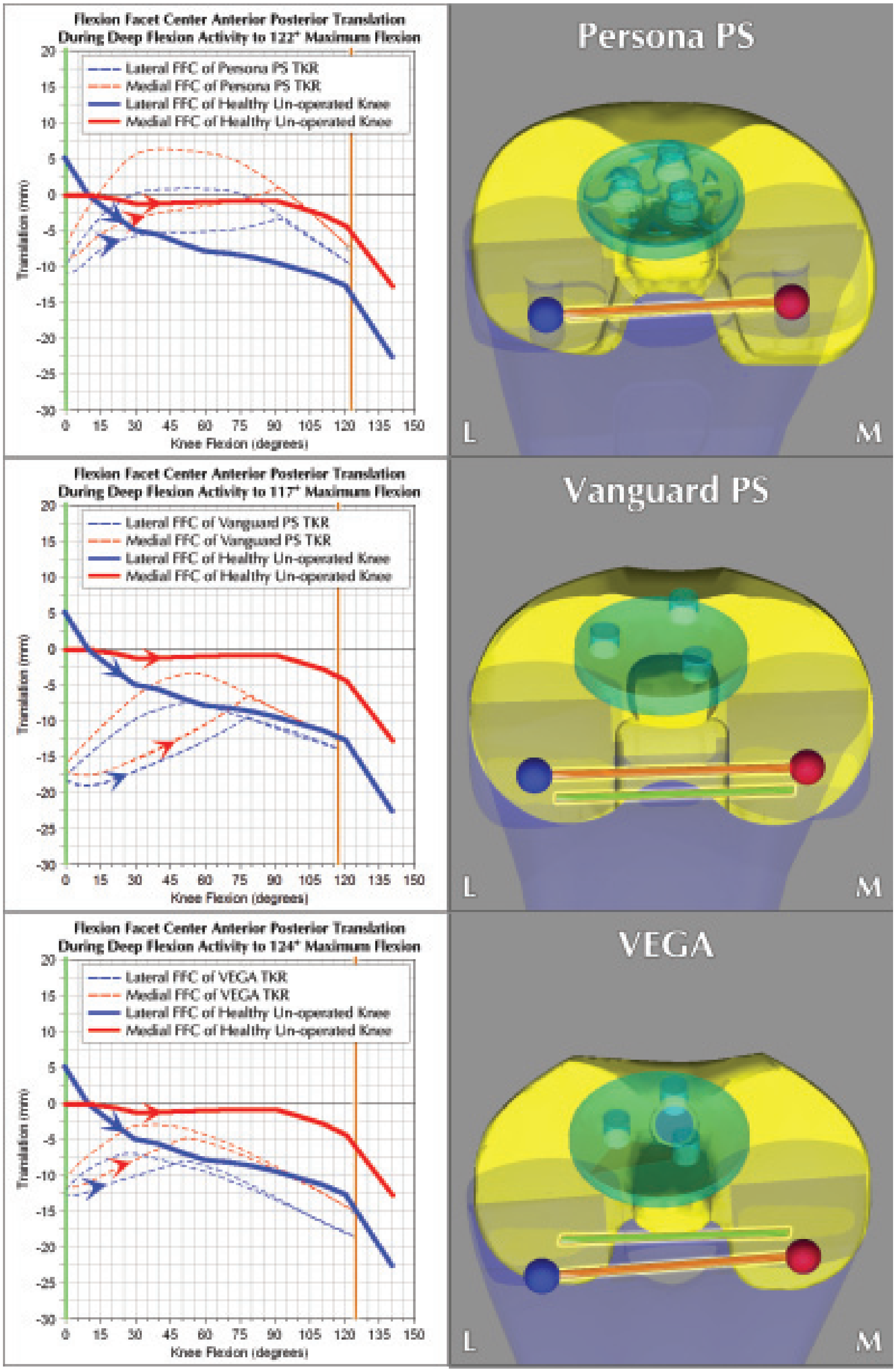
(a)

(b)

(c)

Figure 6

of knee flexion angle, with zero representing the midline of the tibial insert. The image on the right depicts component orientation at maximum flexion appreciated from a superior view. The blue sphere represents the location of the lateral FFC, and the red sphere the location of the medial FFC. Initial location of the FFC barbell at zero degrees of knee flexion is marked as a green bar, the location of the FFC barbell at maximum flexion is marked as an orange bar. These reference points contribute to understanding the relative motion of the femoral component. Designs are presented in alphabetical order.



(a)
(b)
(c)

Figure 7

DISCUSSION

An improved understanding of component motions is appreciated by reviewing animations of the TKA results available at <http://orl-inc.com/animations>. They provide a synchronized understanding of the quantitative plot of FFCs anterior/posterior motion on the left with the qualitative component rotation and translation on the right.

The dotted blue and red lines in the plot on the left indicate the anterior posterior translation of the FFCs for each design. In general the FFCs follow a counter clockwise path on the plot, taking a more posteriorly located path (indicated with arrow heads) as flexion increases and a more anterior path as the high flexion activity returns to full extension. A smaller sized loop indicates that the design component geometries tightly control anterior posterior translation. All designs studied slide anteriorly in various amounts while flexion increases, a motion paradoxical to the healthy intact knee. The direction is reversed when the femoral cam engages the tibial post, forcing movement in the posterior direction while flexion continues to its maximum.

Close inspection of the component motions on the right reveal that contact areas (light yellow patches) are often coincident with the FFC marker from a superior view, but can readily diverge when anterior or posterior forces applied to the femoral component cause the contact area to traverse much farther than the component itself translates. This illustrates why the extent of the burnishing and abrasive wear scars found in tibial insert retrievals are much greater than the motion that the femoral component itself can achieve. FFCs do not indicate centroid locations of contact area, but rather serve as reference points to help visualize motion of the femoral component relative to the tibia.

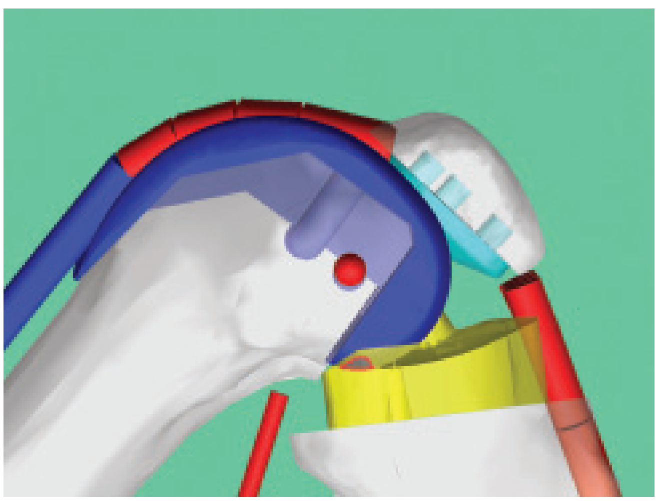


Figure 8: Medial view of Legacy LPS-Flex Fixed at its maximum flexion of 144º.

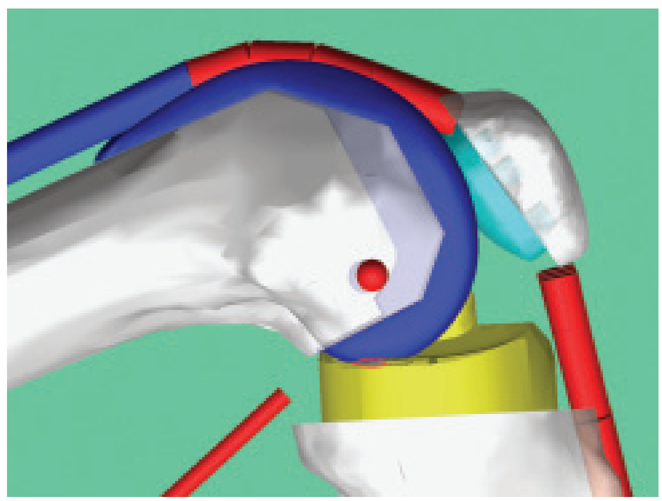


Figure 9: Medial view of Vanguard PS at its maximum flexion of 117º.

The Legacy LPS-Flex Fixed achieved the highest flexion angle of 144º among the designs studied. Design features contributing to this outcome are illustrated from a medial sagittal view (Figure 8). The post/cam mechanism promotes femoral component contact near the posterior edge of the tibial insert (contact area outlined in red), and additional posterior femoral bone resection allow deeper flexion to be achieved before bony impingement occurs. A posterior sloped proximal tibia bone resection of 7º further contributes to high flexion, however at the observed expense of impingement of the anterior aspect of the femoral cam and tibial post at 4º of flexion.

The medial sagittal view of the Vanguard PS (Figure 9) achieved the lowest flexion angle of 117º among the designs studied. This result illustrates a design trade off of very high flexion for bone stock preservation and tibial insert longevity. The Vanguard PS is a more conservative bone preserving design with a less aggressive posterior femoral and 3º proximal tibia bone resection than the Legacy LPS-Flex Fixed. The post/cam mechanism promotes femoral component contact further away from the posterior edge of the tibial insert (contact area outlined in red) allowing more polymer support during demanding high flexion activities.

The method used in this study of posterior femoral bone cut surface impingement with the tibial insert defining maximum flexion is controversial. Although posterior femoral bone cut/tibial insert impingement is a clinical reality evidenced by component retrieval studies[7], many patients achieve higher flexion. When compared to the clinical literature reports of average weight bearing flexion for individual TKA designs, past KneeSIM results below 120° maximum flexion match very closely to published values[6]. However, KneeSIM overpredicted the clinical flexion angle results for designs that achieve flexion above 120°, as the computational model used in this study did not account for posterior femoral shaft impingement[2] or external calf/thigh flesh contact[9], which often limits higher patient flexion.

CONCLUSIONS

None of the posterior stabilized total knee arthroplasty designs investigated in this study were able to closely replicate the motion of the healthy intact knee during a high flexion activity, which remains an elusive goal of contemporary TKA design. Some designs were able to achieve early femoral rollback and external femoral rotation, both hallmarks of healthy intact knee motion. Most designs displayed paradoxical motion of 5 to 10 millimeters of anterior sliding before post/cam engagement and exhibited lateral or no pivoting.

All of the designs investigated in this study achieved high flexion by western patient standards, with maximum flexion angles ranging between 117° and 144°. The results of this study suggest that higher flexion can be achieved at the expense of additional loss of bone stock with aggressive posterior femoral and proximal tibial resection. The consequences of this approach may include premature fixation failures[3] and increased tibial insert damage[8].

The value of this study lies in its ability to hold surgical and patient variables constant, allowing focus on the effect of TKA design on knee motion. Dynamic, validated computational models expand the methodologies available to investigate and better understand factors influencing knee kinematics following total knee arthroplasty. This holds great promise for further total knee design optimization and improvements in surgical procedure leading to better patient outcomes.

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