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Original Research

Increased Intercondylar Femoral Box Cut-to-Femur Size Ratio During Posterior-Stabilized Total Knee Arthroplasty Increases Risk for Intraoperative Fracture

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ABSTRACT

Background: Iatrogenic intraoperative fractures are preventable complications in total knee arthroplasty. As press-fit fixation becomes more popular, further investigation into risk factors is needed. Some authors have suggested that smaller femurs may be at higher risk in posterior-stabilized constructs owing to industry designs trending toward larger, constant box sizes that increase the amount of bone resection relative to bone stock.
Methods: Finite element analysis (FEA) was used to investigate the effect of insertion of posterior-stabilized femoral components on stress distributions in small femurs and whether common bony preparation techniques could further affect risk for intraoperative fracture. The FEA results were validated with mechanical testing by loading to failure with varying resection depths of the distal femur and varying lateralization of the box cut.
Results: With a standard distal resection depth and neutral box position, a decrease in femur size led to an increase in maximal von Mises stresses by 43.6% medially and 44.3% laterally. Box lateralization and increased distal resection depth had minimal changes on the maximal stresses (3.3% medially and −0.4% laterally) on average-sized femurs while having a much larger effect on the stress distribution in small femurs (118.3% medially and 6.7% laterally).
Conclusions: A subset of intraoperative femur fractures is potentially preventable. Small femur sizes, especially ones that would require increased distal resection or change in implant positioning, may benefit from an alternative design without the need for a cam/post mechanism.

Introduction

Total knee arthroplasty (TKA) is a highly successful operation with high patient satisfaction and quality of life improvement [1,2]. Although failure rate is low, complications such as stiffness, infection, loosening, and periprosthetic fracture are major concerns owing to treatment complexity and poorer outcomes [3-5]. With the number of TKAs performed projected to increase to 1.26 million by 2030 [6], minimization of these complications is essential for the continued success of the operation.

Intraoperative fracture is a complication with a reported incidence of 0.4%-2.2% [7-10]. Retrospective studies have shown that these fractures are more likely to occur in the older female population, during bone preparation, impaction of components, and with posterior-stabilized (PS) implants [7-11]. The use of PS implants has been increasing relative to other designs in the United States [4,12], despite no difference in long-term clinical outcomes [13-15]. With continued growth of the number of TKA procedures performed annually, mitigating risks is paramount.

The classic PS design is recognized by the presence of an intercondylar “box” on its femoral component that allows for effective

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kinematics [16,17]. Industry designs vary in the amount of intercondylar bone removed for the box but have trended toward a large, constant box size throughout a range of knee sizes [18-21]. A major concern of this cost-reducing measure is that the increased ratio of bone resection relative to bone stock could predispose the distal femur to fracture [8,9,20,21]. Increased distal resection of the femur, as would occur when balancing in the setting of flexion contracture, could further increase this ratio. [22].

This study aims to use finite element analysis (FEA) to evaluate the impact of using a constant box size in smaller femurs on stresses experienced at the distal femur during component insertion. Additional parameters considered were increased distal resection depth and box lateralization, a change in implant positioning considered in the setting of patellar maltracking [23] that may further alter distribution of forces through the distal femur.

Material and methods

Digital femur meshes were constructed using the Stryker Orthopaedic Modeling and Analytics database, a collection of more than 10,000 computed tomography scans of human bones. Femurs were separated into 8 groups according to medial-lateral width. The dimensions of these femurs were averaged to create representative models for each group that correlated with sizing in the Stryker Triathlon Knee System (Stryker Corp., Kalamazoo, MI). Models generated for the smallest (size 1) and average-sized (size 4) femurs were then imported into SolidWorks Finite Model Analysis software (Dassault Systemes SolidWorks Corp., Waltham, MA) for comparison. Each femur model underwent a total of 4 separate "virtual surgeries" to create a total of 16 models for analysis. The virtual bone preparations included an 8-mm distal resection with a neutral box, a 12-mm distal resection with a neutral box, an 8-mm distal resection with a lateralized box, and a 12-mm distal resection with a lateralized box. The dimensions of the box cut were 20.8 mm in height and medial-lateral width, consistent with the box dimensions in the Triathlon Knee system (Stryker Corp., Kalamazoo, MI). A neutral box position was centered at the midpoint between the most medial and lateral aspects of the femoral epicondyles. A lateralized box was positioned 4 mm from this reference point. Distal resections were performed with 5° of valgus angulation.

Impaction of a femoral component in TKA was simulated in the software by placing a 600-N load on the femur with an aluminum block and evaluating the distribution of stresses on the medial and lateral aspect of the box as shown in Figure 1. The maximum von Mises stresses and their parametric distances from the posterior aspect of the box edge were recorded.

Load-to-failure mechanical testing was then performed on 15 composite femur models (Sawbones, Vashon Island, WA) with the following preparations: 3 control femurs with an 8-mm distal resection and neutral box, 4 femurs with a 12-mm distal resection and neutral box, 4 femurs with an 8-mm distal resection and a 4-mm lateralized box, and 4 femurs with a 12-mm distal resection and a 4-mm lateralized box. Distal resections were performed with 5° valgus angulation. The composite models underwent axial compression with a constant rate of loading until failure in a universal testing machine (Instron, Norwood, MA). As seen in Figure 2, failure was defined as the decrease in integrity after reaching ultimate tensile strength. Significance was determined by Student *t*-test with an alpha level of 0.05 using Statistical Analysis Software v9.4 (SAS Institute, Cary, NC).

Results

The magnitude and position of the maximal von Mises stresses experienced by the various femur preparations are shown in Table 1.

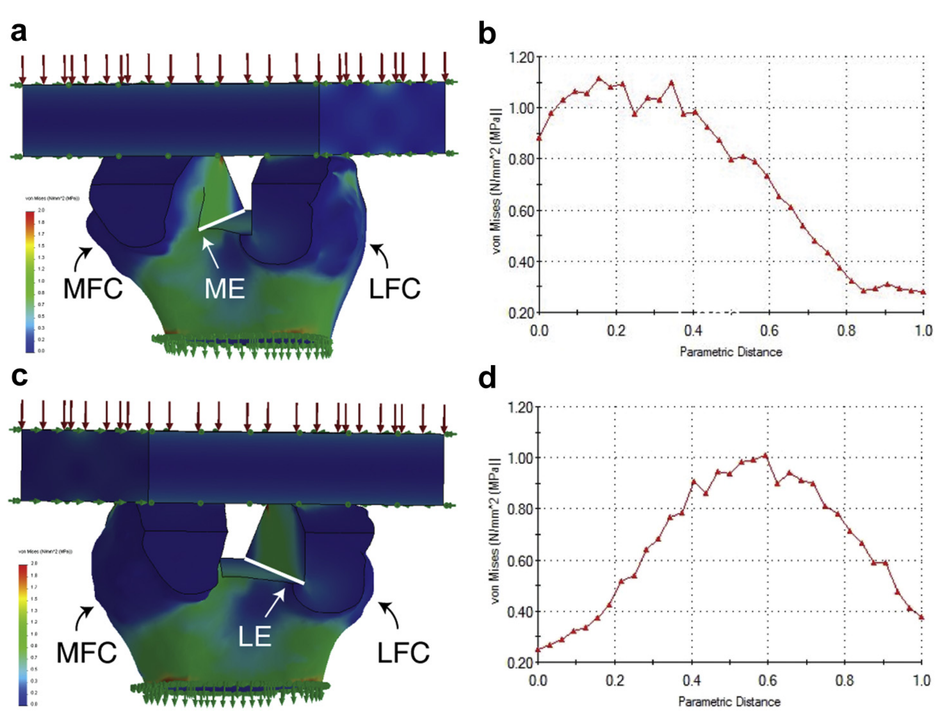

Figure 1. Finite element analysis of a left, size 4 femur with a neutral box cut and 8-mm distal resection under a 600-N load. von Mises stresses were measured on the (a) and (b) medial edge of the box cut and (c) and (d) lateral edge of the box cut. Maximal stresses and the corresponding parametric distance from the posterior aspect of the box edge were recorded. MFC, medial femoral condyle; LFC, lateral femoral condyle; ME, medial edge; LE, lateral edge.

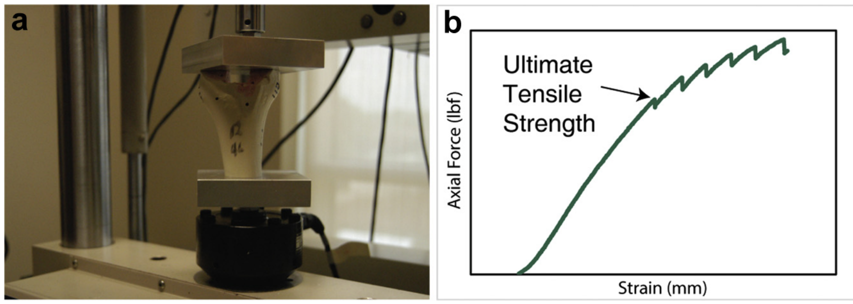

Figure 2. (a) Load-to-failure testing of a composite femur model with a 4-mm lateralized box and 12-mm distal resection in a universal testing machine. (b) Failure was defined as a decrease in integrity after reaching ultimate tensile strength.

Size 4 femurs

In the size 4 femur with a standard 8-mm resection and neutral box, maximal stresses were 1.113 MPa medially and 1.006 MPa laterally. Increasing the distal resection to 12 mm increased the maximal stresses by 1.5% medially and 3.1% laterally to 1.113 MPa and 1.006 MPa, respectively. When lateralizing the box with a standard 8-mm resection, maximal stresses decreased by 3.7% medially to 1.072 MPa and increased by 4.0% laterally to 1.046 MPa. With both box lateralization and increased distal resection, maximal stresses on a size 4 femur increased to 1.150 MPa medially and decreased to 1.002 MPa laterally. This represented a change of 3.3% medially and -0.4% laterally.

Size 1 femurs

With a standard 8-mm resection and neutral box, decreasing the femur size from size 4 to size 1 increased maximal von Mises stress by 43.6% medially and 44.3% laterally to 1.598 MPa and 1.452 MPa, respectively. Increasing the distal resection to 12 mm increased the maximal stresses an additional 31.4% medially to 2.102 MPa and 20.4% laterally to 1.748 MPa. This represented an 86.0% increase medially and a 68.6% increase laterally compared with a size 4 femur with the same preparation. When lateralizing the box with a standard 8-mm resection on a size 1 femur, maximal stresses increased by 20.1% medially to 1.919 MPa and 12.3% laterally to 1.6 MPa. This represents a 79.0% increase medially and 57.2% increase laterally when compared with a size 4 femur with the same preparation. With both box lateralization and increased distal resection, maximal stresses on a size 1 femur increased by 118.3% medially to 3.489 MPa and 6.7% laterally to 1.549 MPa. This corresponded to a 203.3% increase medially and 54.6% increase laterally when compared with a size 4 femur with the same preparation.

Table 1
Magnitude and position of maximal von Mises stress.

Preparation	Maximal von Mises stress		Parametric distance[a]	
	Medial	Lateral	Medial	Lateral
Size 4 femur				
8-mm Resection–neutral box	1.113	1.006	0.156	0.594
12-mm Resection–neutral box	1.130	1.037	0.186	0.654
8-mm Resection–lateral box	1.072	1.046	0.0617	0.654
12-mm Resection–lateral box	1.150	1.002	0.312	0.594
Size 1 femur				
8-mm Resection–neutral box	1.598	1.452	0.251	0.540
12-mm Resection–neutral box	2.102	1.748	0.217	0.530
8-mm Resection–lateral box	1.919	1.630	0.186	0.562
12-mm Resection–lateral box	3.489	1.549	0.000	0.539

[a] Parametric distance is in reference to the posterior end of the box.

Mechanical testing

The average force that led to failure in models prepared with an 8-mm resection and neutral box was 527.6 lbf. An increase in the distal femoral resection significantly decreases the amount of force needed for failure to 455.6 lbf (−13.6%, $P = .03$). When the box was lateralized by 4 mm, increasing the resection also significantly decreased the load to failure from 516.9 lbf to 455.8 lbf (−11.8%, $P = .01$). The act of lateralizing the box by itself did not significantly change the load to failure in preparations with an 8-mm distal resection ($P = .65$) or 12-mm distal resection ($P = .993$).

Discussion

Intraoperative fracture is a rare complication with a reported incidence of 0.4%-2.2% [7-10]. Although rare, a subset of this complication may be iatrogenic and therefore preventable. Previous studies have associated intraoperative fractures with postmenopausal osteopenia because of the higher incidence within the elderly female population [7-9,11]. However, in a series of 1346 patients receiving a PS knee, Pun et al [10] found that none of the patients who suffered from an intraoperative femur fracture had a condition predisposing them to osteoporosis. Instead, all intraoperative fractures were due to technical errors that created stress risers. Previously, Lombardi et al [11] demonstrated that by recognizing and controlling for stress risers, the risk of intraoperative fracture could be significantly reduced. In their case series, better awareness of stress risers and improved implant design led to a decrease in fracture incidence from 4.45% (40 of 898) to 0.19% (1 of 532).

The FEA results from this study suggest that the large, constant box size in current PS designs may create stress risers in small femurs by significantly increasing maximal stresses experienced in the distal femur during impaction of the femoral components. Maximal stresses did not change more than 4% medially or laterally when increasing distal resection depth, lateralizing the box or performing both procedures in average-sized femurs. When the same distal resection and box cut were performed in the smaller femur, as would occur with PS designs with a large, constant box, maximal stresses increased more than 40% medially and laterally (Table 2).

Although a change in implant positioning and distal resection depth had a minor effect on average-sized femurs, maximal stresses were increased substantially when the techniques were performed in smaller femurs (Table 3). Interestingly, the maximal stresses were increased disproportionally on the medial side, where most intraoperative distal femur fractures have been reported to occur [7]. While lateralizing the box led to increased bone resection on the lateral side, the FEA results suggest that the medial side may have experienced greater stresses owing to increased contact area with the aluminum block simulating the axial load from impaction (Fig. 1a).

The inverse relationship of stress and femur size may provide additional insight into why a disproportionate number of women suffer from intraoperative fractures. Gender differences in femur size and aspect ratio have been studied extensively and have shown that women tended to have smaller femurs with a narrower medial-lateral width compared with male counterparts [24-27]. Interestingly, in one case series of intraoperative fractures [8], all intraoperative fractures of the femur occurred in women with narrow distal femurs. The authors noted that the relatively wide box cuts may have predisposed these femurs to fracture. Future research on intraoperative fractures should consider reporting implant sizes to corroborate the findings of this study with patient cases.

Although femur size cannot be controlled, implant design and selection can be. Oversizing the intercondylar resection guide may be beneficial in reducing intraoperative fracture [11], but the findings of this study suggest that manufacturers should exercise caution when designing the size of the resection guides for smaller-sized femurs. In a 20-year retrospective study from 1985-2005, Alden et al [7] reported that a majority of intraoperative fractures occurred in the femur of PS implants. This finding, when considered with the results of this study, suggests that a patient with a small femur, especially one who would need significant changes in bony preparation and implant positioning, may benefit from an alternative design such as a cruciate-retaining or cruciate-stabilizing implant. In a similar 20-year period between 1987 and 2007, Pinaroli et al [9] showed only 25% (10 of 40) fractures occurred in the femur compared with 77% (37 of 48) reported by Alden et al [7]. The authors attributed this discrepancy to their implant choice that used a third median condyle, which allowed for a nonvoluminous box when compared with a classic PS design. Surgeons who regularly use PS implants may therefore reduce potential complications in patients with smaller femurs by considering designs that reduce bony resection such as custom designs with proportionally sized boxes or other modifications such as additional chamfers that decrease stress risers.

Mechanical testing in this study had several limitations. The sample size for mechanical testing was determined after expert consultation with an independent mechanical engineer instead of a formal power analysis. During bone preparation, a control femur was incorrectly cut, and the decision to remove the femur from the study was made rather than purchase an additional femur from another batch, which would introduce additional variability. In addition, the composite femur models were not available in different sizes. Therefore, mechanical testing was restricted to validating box lateralization and increased distal resection depth. Similar to the FEA results, the results of mechanical testing demonstrated no increase in load to failure with a change in implant positioning. However, while FEA results showed only a minor increase in maximal stresses when increasing distal resection in average-sized femurs, the effect on mechanical testing was more pronounced. Closer inspection of all tested femurs demonstrated that failure occurred through imprecise cuts in bone preparation. This finding corroborated with other studies that have highlighted the importance of technical factors contributing to fracture risk [10,11]. More importantly, it appears that the changes in maximal stresses seen in FEA analysis may be amplified when considering other factors such as cortical defects that may predispose the patients to intraoperative fracture. Future research in the benefits and pitfalls in technological assistance may help determine if technology can address these other factors.

A limitation of the FEA analysis was that there was no standard for simulating the force of impaction. The conservative, subphysiologic load of 600 N was recommended after consulting an independent mechanical engineer. Because the study was conducted using bone resections from a single industry design (Stryker Triathlon; Stryker Corp., Kalamazoo, MI), the results may have limited generalizability to other implant designs. However, the results are likely generalizable to other PS designs that have a large, constant box across various implant sizes. In addition, although this study simulated the forces that would occur during impaction of a cementless PS implant, previous retrospective studies of intraoperative fractures in TKAs were performed with cemented implants. Further research is needed to determine if these findings correlate with cemented implants. Finally, it should be noted that

Table 2
Change in maximal stresses on medial and lateral aspect of box cut when varying femur size, distal resection, and box lateralization.

Preparation Femur size Distal resection Box position	Medial condyle		Lateral condyle	
	Maximal von Mises stress (MPa)	%Δ vs control	Maximal von Mises stress on (MPa)	%Δ vs control
Control Average 8 mm Neutral	1.113	0%	1.006	0%
Decrease femur size Small 8 mm Neutral	1.598	+43.6%	1.452	+44.3%
Increase distal resection Average 12 mm Neutral	1.130	+1.5%	1.037	+3.1%
Lateralize box Average 8 mm Lateral	1.072	-3.7%	1.046	+4.0%
Combined[a] Average 12 mm Lateral	1.150	+3.3%	1.002	-0.4%

[a] Combined includes both increased distal resection depth and box lateralization.

Table 3
Impact of additional parameters on smaller femurs.

Preparation (femur size–distal resection–box position)	Medial condyle			Lateral condyle		
	Maximal von Mises stress (MPa)	Percent change from small femur control	Percent increase vs average femur with same preparation	Maximal von Mises stress on lateral condyle (MPa)	Percent change from control	Percent increase vs average femur with same preparation
Small femur control (small–8mm–neutral)	1.598	0%	+43.6%	1.452	0%	+44.3%
Increase distal resection (small–12 mm–neutral)	2.102	+31.4%	+86.0%	1.748	+20.4%	+68.6%
Lateralize box (small–8 mm–lateral)	1.919	+20.1%	+79%	1.630	+12.3%	+57.2%
Combined[a] (small–12 mm–lateral)	3.489	+118.3%	+203.3%	1.549	−6.7%	+54.6%

[a] Combined includes both increased distal resection depth and box lateralization.

the native size of femurs may inherently have a role in the distribution of stresses during femoral impaction. The differences in maximal stresses therefore may not be fully attributable to a large, constant box or operative technique. Future study on the stress distributions during femoral impaction in non-PS designs may aid in addressing this limitation.

Conclusions

A subset of intraoperative femur fractures is a potentially preventable complication of TKA. These results suggest that a patient with a small femur size, especially one who would need significant increases in bony resection or changes in implant positioning, may benefit from a design without the need for a cam/post mechanism, such as cruciate-retaining or cruciate-substituting designs. As press-fit knee arthroplasty becomes more popular, the fracture risk due to large box-to-femoral size ratios could increase the overall failure rate.

Conflict of interest

Dr. William F. Sherman, Dr.Ashton Mansour, and Dr. Victor J. Wu report no funding or commercial associations (eg, consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) that might pose a conflict of interest in connection with the submitted article. Dr. Fernando L. Sanchez lists the following relevant financial activities outside of this work and/or other relationships or activities that readers could perceive to have influenced, or that give the appearance of potentially influencing this manuscript: grants and other from Medacta, grants and other from DJO.

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