Three-Dimensional Analysis of Alignment Error in Using Femoral Intramedullary Guides in Unicompartmental Knee Arthroplasty

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Abstract: We used computerized simulations with 3-dimensional models of 20 cadaver femora, calculated from computed tomographic scans, and a model of a rod measuring 200 × 5 mm to study femoral alignment accuracy for unicompartmental knee arthroplasty via minimally invasive reconstruction. The anatomical axis and insertion site were identified on each femur. A simulation of all feasible flexion-extension and varus-valgus orientations was performed. The average rod orientation was 3.2° flexion and 2.5° valgus. The range of orientation was 3.2° extension to 9.7° flexion and 4.5° varus to 8.9° valgus. The study suggests that a short narrow intramedullary rod inserted according to the manufacturer's specifications does not accurately find the anatomical axis and may lead to poor alignment of the femoral prosthesis. Given our finding of consistent bias toward excessive flexion and valgus alignment, we recommend that the operating surgeon carefully plan the insertion point of the intramedullary rod during surgery to compensate for this bias.
Key words: intramedullary rod, unicompartmental knee arthroplasty, alignment, anatomical axis.

Unicompartmental knee arthroplasty (UKA) is a suitable treatment of anteromedial osteoarthritis of the knee [1] and also for lateral compartment osteoarthritis [2]. Unicompartmental knee arthroplasty has important advantages over alternative treatments when patient selection criteria are carefully followed. Two retrospective studies have shown that midterm and long-term results are superior to high tibial osteotomy [3,4], although 1 randomized prospective study showed no superiority of either technique [5]. Closing wedge osteotomy often results in a cosmetic problem and eventually requires revision to total knee arthroplasty (TKA). In a randomized prospective study [6], UKA was shown to produce better results over 5 years compared with TKA in Bristol Knee Score and range of motion. The procedure preserves the cruciate ligaments and can be performed using a minimally invasive technique that contributes toward less blood loss and lower morbidity, in part, because only a capsule arthrotomy is required in UKA and thus the parapatellar pouch is spared. Contraindications such as patellofemoral erosion, age, weight, and the presence of chondrocalcinosis are considered unnecessary by some [7]. Midterm

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and long-term survival of several different UKA prostheses is comparable to survival of TKA [8], and the procedure can be successfully performed in a community hospital setting [9].

In a retrospective review of patients who had undergone a medial UKA with a follow-up time of at least 5 years, Ridgeway and colleagues [10] found that the mean correction of the tibiofemoral angle was significantly smaller for patients with a Marmor rating of failure than for those who rated excellent; the mean correction was also smaller for those patients who required subsequent revision than those who did not. In a study of 100 consecutive medial UKA procedures, Kennedy and White [11] stated that postoperative alignment of the knee producing a mechanical axis that passed through the center or slightly on the medial side of the knee produced the best Marmor ratings. In a study of 46 lateral UKA cases, Robinson and colleagues [12] found a statistically significant relationship between bearing dislocation and the varus alignment of the tibial component; they did not find a significant relationship with the alignment of the femoral component. In a retrieval study of the Oxford unicompartmental arthroplasty, Psychoyios and colleagues [13] found a strong association between bearing impingement and technical error at implantation. These findings suggest that alignment of UKA components has a strong relationship to outcome.

One significant obstacle to wide acceptance of UKA is that the procedure is technically difficult [14,15], with the components requiring implantation accuracy greater than that required for TKA [16]. This problem is exacerbated when using a minimally invasive technique, and the relatively narrow indications of UKA may prevent many surgeons from performing enough procedures to acquire and maintain their skills [15]. X-ray–based studies [17,18] of femoral intramedullary (IM) guides for TKA show that rod diameter, rod length, and the location of the insertion site strongly influence the potential accuracy of the guide. The typical UKA IM rod is shorter and may be thinner than its TKA counterpart (although this is not universally true); one description [19] of surgical technique does not mention an IM rod at all. Because the patella cannot be everted when using a minimally invasive approach, the rod insertion site may be biased to the medial side of the knee (for a medial knee arthroplasty) or may be inserted just superior to the posterior cruciate ligament (PCL) attachment.

The goal of this study was to quantitatively assess the alignment of the Oxford Phase 3 IM rod (Biomet Merck Ltd, South Wales, UK). To perform this assessment, we computed the distribution of flexion-extension (FE) and varus-valgus (VV) alignment angles that can be expected when using the IM rod. Our calculations were conducted using computer graphics techniques and computed tomographic (CT) scans of cadaver femora.

Materials and Methods

We used 4 frozen and 16 dry cadaver femora, each of which was visually and radiographically inspected by surgeons (WL and JFR) to ensure that they were representative of the population seen in their clinics. Helical mode CT scans of the femora were acquired using a Hi-Speed scanner (General Electric, Milwaukee, Wis). The CT volume was reconstructed with 1.25-mm slice spacing and slice thickness with pixel dimensions of approximately 0.5 mm. Computer models, in the form of triangulated meshes (Fig. 1), of the canal and cortical surface of each femur were constructed using custom-written CT editing software that implements a well-known isosurface algorithm [20,21]. The femora models had between 350 000 and 400 000 triangles, and the canal models had between 80 000 and 100 000 triangles. A mesh of the Oxford IM rod (a cylinder 200 mm in length and 4 mm in diameter) was also created.

On each femur model, we identified the anatomical and mechanical axes as shown in Fig. 2. Our visualization software uses 3 orthographic projection views with viewing directions con-

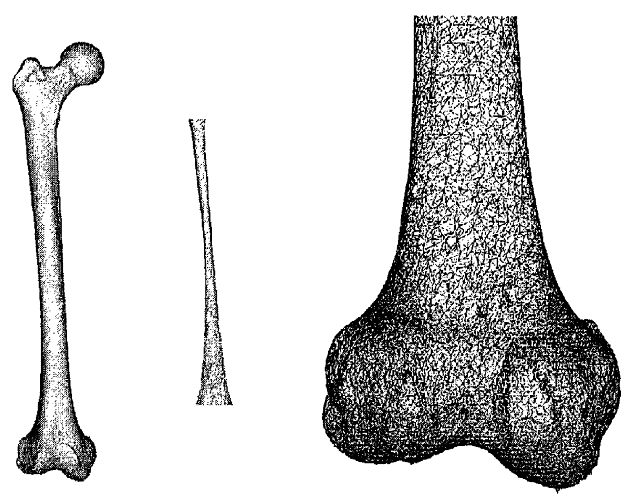

Fig. 1. Computer models of the femur (left) and femoral canal (middle). Detail wire frame (right) of a coarsened or decimated model showing the triangular composition of the model; models used for our experiments were not decimated.

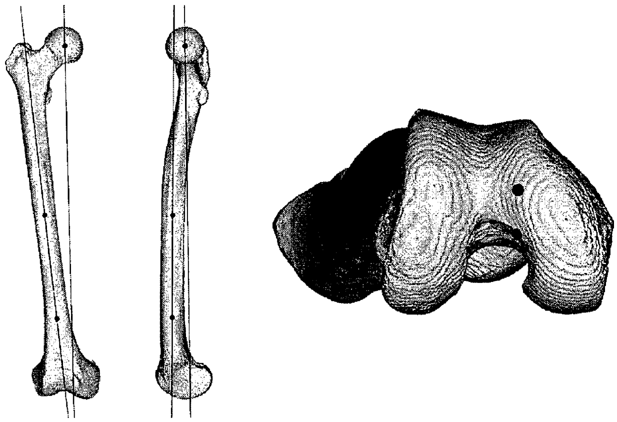

Fig. 2. Points used to define the anatomical and mechanical axes of the femur and the recommended rod insertion site. The 3 viewing directions are constrained to be perpendicular to each other.

strained to be perpendicular to each other. The *3 anatomical directions* are defined by visually orienting the mechanical axis in the vertical direction in the coronal and sagittal views and the posterior condylar line in the horizontal direction in the axial view. This is consistent with the Grood-Suntay convention [22]. The software was written using the Visualization Toolkit [20], which is freely available from Kitware, Inc (Clifton Park, NY; www.kitware.com).

In the coronal plane, the anatomical axis was determined using the definition of Moreland et al [23]. A similar definition of the anatomical axis was also used for the sagittal plane. The 2 points in each view, and the 2 viewing directions define 2 planes whose intersection is the line of anatomical axis in 3 dimensions. The point where the anatomical axis emerged from the distal surface was noted for each femur. The *mechanical axis* was defined as the line joining the center of the femoral head and the PCL insertion [24].

In the axial view, a surgeon (JFR) identified the IM rod insertion point as directed by the manufacturer's manual of surgical technique. To account for possible deviation from the recommended insertion point, we considered the nearby region on the distal surface, defined by intersecting a cylinder with the distal femoral model surface, with the resulting region amply covering surgically accessible insertion points. A cylinder of radius 5 mm centered at the recommended insertion point oriented in a direction parallel to the anatomical axis was used. The region of the model clipped by the cylinder was typically composed of 500 to 600 vertices and approximately 1000 triangles (Fig. 3).

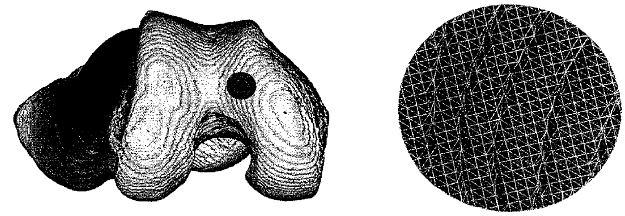

Fig. 3. Selecting a neighborhood (dark gray) surrounding the recommended insertion point (black) by clipping the femur model with a cylinder of radius 5 mm (left). Detail mesh and wire frame of the clipped region (right); approximately 100 to 120 possible insertion sites were sampled from the region.

We used every fifth vertex as a possible IM rod insertion point, which provided approximately millimeter sampling while greatly reducing the computation time of the simulation. For each of the possible insertion sites, we inserted the rod up to the insertion mark (161.5 mm) oriented parallel to the anatomical axis. We then rotated the rod about the insertion site to every possible FE/VV alignment between $\pm 15^\circ$ at 0.1° increments (Fig. 4) for a total of 90 601 unique orientations. If the model rod fit completely within the model femoral canal, we recorded the FE/VV angle pair; we checked for rod-canal interference using a collision detection algorithm [25]. This process resulted in a discrete approximation of the possible rod orientation distribution for each femur.

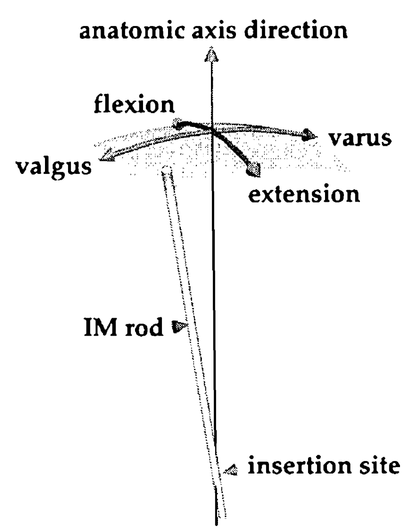

Fig. 4. Sweeping the IM rod through 15° of varus, valgus, flexion, and extension relative to the anatomical axis direction. The rod was inserted to a depth of 161.5 mm and rotated about the insertion site.

Each femur was measured at midshaft to determine the canal diameters. The data for the simulated IM rod in each femur were analyzed by measuring the locations of the emergence of the anatomical axis on the distal femur, the VV deviation from the anatomical axis in the coronal

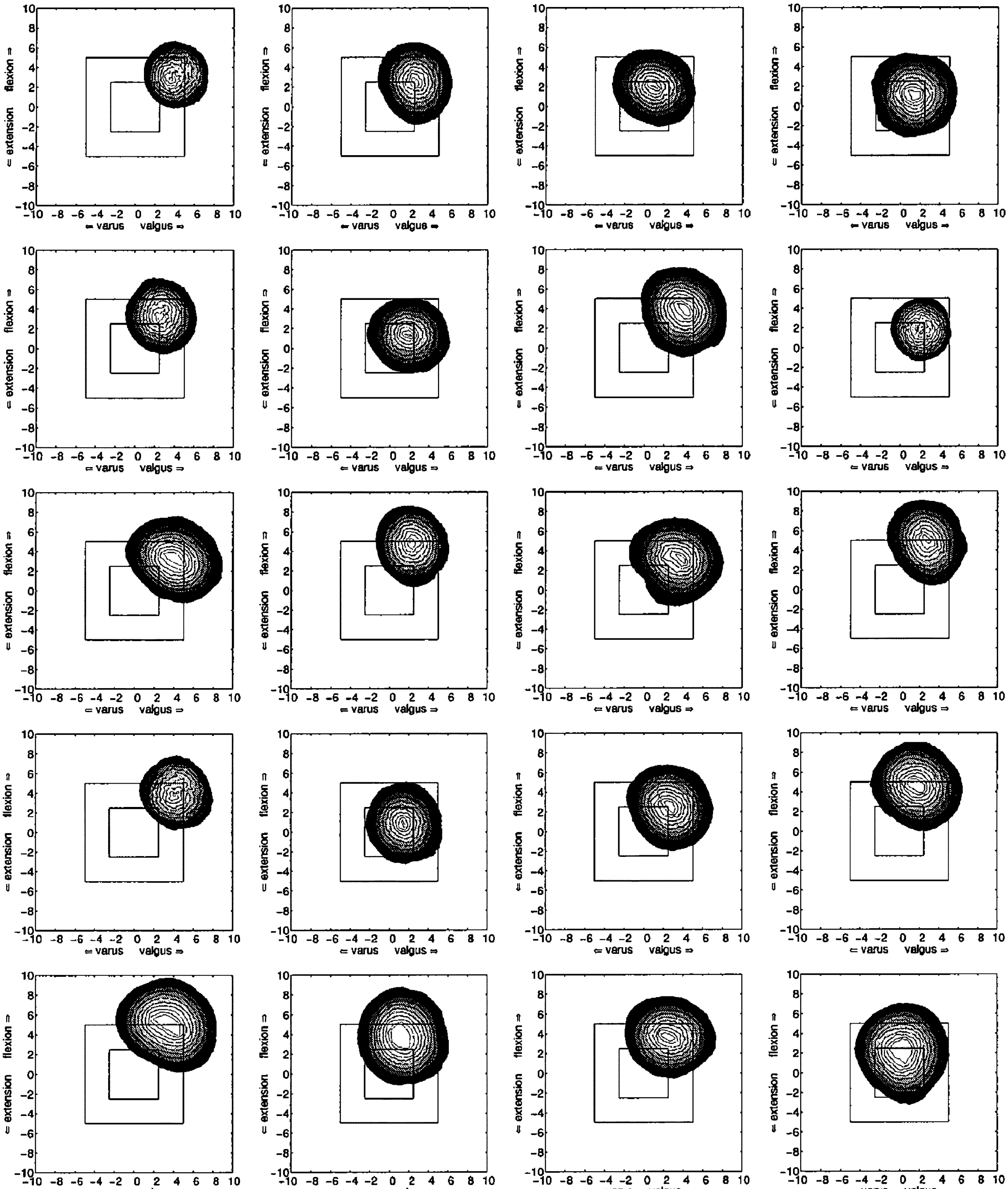

Fig. 5. Contour plots of rod orientation for all 20 femurs. The least likely rod orientations are in dark gray, with likelihood increasing toward the center of each distribution. The 2 square boxes enclose the 2.5° and 5° FE/VV orientation regions.

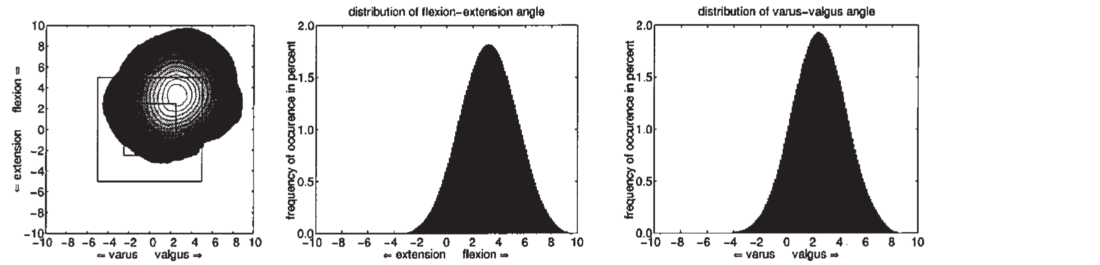

Fig. 6. Contour plot (left), distribution of FE orientation (middle), and VV orientation (right) after pooling the results from all 20 femurs.

plane, and the FE deviation from the anatomical axis in the sagittal plane. The frequency of rod orientations for each femur was visualized using contour plots. Finally, we pooled the angular deviations for all 20 femora and repeated the analysis on the pooled results. The output of our experiment for each femur, f, was a set $A_f = \{(v_1, f_1), (v_2, f_2), ..., (v_{N_f}, f_{N_f})\}$ of N_f pairs of VV, v, and FE, f, rod orientation angles. The pooled results were simply the set of results for all 20 femurs, $\{A_1, A_2, ..., A_{20}\}$, from which we calculated the means and standard deviations (SDs).

To ensure that our study had adequate statistical power, we took the null hypothesis to be that the IM rod produces neutral alignment with respect to the distal anatomical axis with an SD of 3° and that the orientation angle is normally distributed. The alternative hypothesis was that the rod does not produce neutral alignment. If the true mean alignment was 2.5° from neutral, then for these hypothetical values, 19 femora would be required to yield statistical power of 0.95 for a level-0.95 test [26].

Results

When measured in the coronal plane relative to the center of the notch, the mean location of the emergence of the anatomical axis on the distal femur was 3.7 mm medial. The range of values was 0.5 mm lateral to 9.7 mm medial with an SD of 2.8 mm.

Novotny and colleagues [17] measured the location of the anatomical axis on the distal femoral surface as a ratio of the dimensions of the distal femur. We found the mean location to be 0.49 times the mediolateral (ML) dimension of the distal femur measured from the medial cortex and 0.29 times the anteroposterior (AP) dimension measured from the anterior cortex. The range of these ratios was 0.44 to 0.52 for the ML dimension and 0.22 to 0.37 for the AP direction with SDs of 0.03 and 0.02, respectively.

The mean canal diameter measured at the half length of each femur was 11.8 mm. The range of values was 8.6 to 14.9 mm with an SD of 1.8 mm. The mean canal diameter measured at the rod insertion depth of 161.5 mm was 15.5 mm and 15.9 mm in the coronal and sagittal planes, respectively. The range of values was 10.4 to 19.4 mm with an SD of 2.8 mm in the coronal plane and 10.4 to 20.1 mm with an SD of 2.3 mm in the sagittal plane.

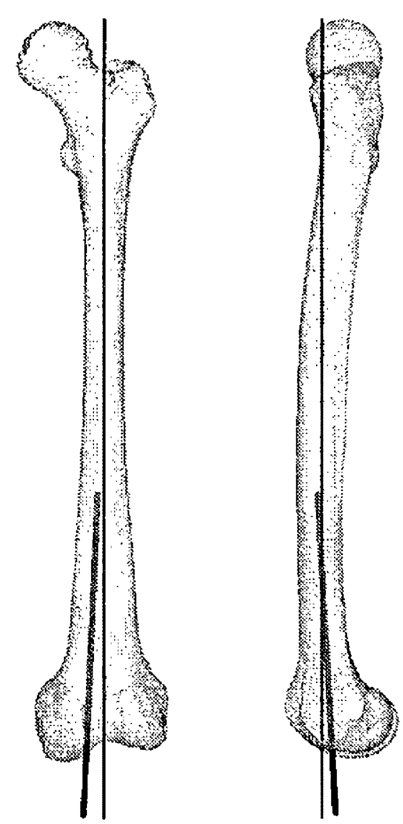

Fig. 7. The IM rod in the pooled average orientation of 3.2° flexion and 2.5° valgus relative to the distal anatomical axis.

Table 1. Intramedullary Rod Orientation Distribution for Each of the 20 Femurs

		Percentage of rod orientation distribution		
Femur	Neutral possible?	<±2.5° VV and FE	<±5° VV and FE	>±5° VV or FE
1	No	4	67	33
2	No	14	83	17
3	No	5	59	41
4	No	1	51	49
5	No	2	36	64
6	Yes	23	90	10
7	Yes	50	98	2
8	No	5	58	42
9	Yes	62	100	0
10	Yes	20	73	27
11	Yes	50	99	1
12	No	4	54	46
13	No	11	69	31
14	Yes	22	86	14
15	No	12	72	28
16	Yes	57	99	1
17	Yes	42	100	0
18	No	3	49	51
19	No	7	57	43
20	Yes	47	93	7

The frequency plots of IM rod locations, shown in Fig. 5, indicated that the expected rod orientation tended to be in excessive flexion and valgus malalignment. Pooling all of the results produced the distribution of rod orientations shown in Fig. 6. For the pooled results, the mean rod orientation was 3.2° flexion and 2.5° valgus with SDs of 2.1° and 2.0°, respectively. The range of orientation angles was from 3.2° extension to 9.7° flexion and 4.5° varus to 8.9° valgus. Fig. 7 shows 1 femur with the rod inserted in the pooled average orientation.

If we assume that reasonable limits on the range of surgical implantation errors for rod placement are ±5° in FE and VV, then 28.1% of the pooled distribution exceeded this range of values (19.9% greater than 5° flexion, 10.3% greater than 5° valgus, 2.1% both). Furthermore, it was possible to exceed this range in almost every femur. If the limits on the range of surgical implantation errors for rod placement are ±2.5° in FE and VV, then only 21.4% of the pooled distribution was inside this range of values. For 11 of the 20 femurs, it was impossible to achieve neutral rod alignment with respect to the distal anatomical axis using the manufacturer's suggested entry point on the distal femur. Table 1 gives the results for all 20 femurs.

Discussion

Other researchers have studied implantation errors of IM rods. Using standardized radiographs of 40 patients, Reed and Gollish [18] reported that the anatomical axis emerged from the distal femoral surface a mean distance of 6.6 mm medial to the center of the notch in the coronal plane with a range of values between 0 and 12 mm. Given the wide range of values, their reported SD of 0.5 mm is impossibly small, which prevents us from performing a statistical comparison without their raw data. However, our mean result of 3.7 mm medial to the notch agrees with their conclusion that the anatomical axis tends to emerge medially to the notch on the distal femoral surface in the coronal plane.

In a study that used radiographs of 45 cadaver femora, Novotny and colleagues [17] reported that the anatomical axis emerged at a point 0.53 times the ML dimension of the distal femur measured from the medial epicondyle and 0.33 times the AP dimension measured from the anterior cortex. Our values of 0.49 and 0.29 are somewhat smaller, but the absolute differences between our results and theirs were only 3.3 mm and 2.4 mm in the ML and AP directions, respectively.

We examined the dimensions of our femora to determine whether our results can be explained by our specimens having unusually wide canals. Novotny and colleagues [17] reported mean femoral canal dimensions of 14.3 mm and 18.7 mm in the coronal and sagittal planes, respectively, at a distance of 228.6 mm from the distal femoral surface and 28.5 mm and 25.8 mm in the coronal and sagittal planes, respectively, at a distance of 101.6 mm. Interpolating linearly to our rod depth of 161.5 mm yields a canal width of 21.8 mm in the coronal plane and 22.5 mm in the sagittal plane. These average dimensions were greater than the largest canal dimensions over all of our femora, and thus, we believe that the femora we used were not abnormally large. The width of the femoral canal at the tip of a relatively short rod is detrimental to the alignment accuracy of an IM jig. In most patients, the canal has not yet narrowed to its smallest width and the IM rod has considerable space to move about.

Our results showed that the alignment of the IM rod was consistently biased. This was not surprising, given that the manufacturer recommends a uniform rod insertion site for all patients; other authors [18,27] have stressed that the ideal rod location for TKA varies among patients. For the Phase 3 Oxford UKA instrumentation, the recommended insertion site is 10 mm anterior to the anteromedial corner of the intercondylar notch [28]. In 11 of 20 femora, we found that this insertion site resulted in interference of the rod with the medial and/or posterior cortex of the canal, thus preventing neutral alignment with respect to the distal anatomical axis. On average, this insertion site resulted in a bias toward flexion and valgus alignment. Because of the morphology of the distal femoral shaft, this bias will worsen if the insertion site is shifted more medially and posteriorly.

Previous studies [14,29] of the Oxford prosthesis have reported 10-year survival rates of 95% and better when careful patient selection criteria were followed. Such high survival rates would seem to suggest that the Oxford prosthesis is relatively insensitive in the range of orientation that results from the IM rod; this is consistent with the spherical design of the femoral component [30]. However, survival results from the Swedish Knee Arthroplasty Register [31] were only 90% at 5 years, and a study of retrieved meniscal bearings [13] found evidence of impingement on 10 of the 16 bearings. Poor outcome and impingement of the meniscal bearing may be related to the accuracy with which the femoral component is implanted, but more research is needed to resolve this issue.

In a retrospective study of medial UKA cases, Jenny and Boeri [32] found that only 10 of 52 patients had satisfactorily implanted prostheses using TKA instruments adapted for UKA. Their definition of a satisfactory implantation was when all of 5 radiographic angles were within $\pm 2^\circ$ of the intended values. Although these results are not directly comparable to ours, they are consistent with our result of 21.4% of the pooled distribution lying within $\pm 2.5^\circ$ in FE and VV. In a retrospective radiographic study of implant accuracy using a minimally invasive approach, Fisher and colleagues [16] found that the range of femoral component alignment in the AP and lateral planes were 22° and 17°, respectively; these results are larger than our values of 13.4° VV and 12.9° FE.

One limitation of this preliminary study is that we used only 20 femora. Although our calculations estimate that this sample size has adequate statistical power, a larger sample size is desirable to reduce the possibility of a type II error and to better represent the patient population. We also knew very little about the provenance of the cadaver specimens; factors such as age, sex, and disease history were not available for the dry specimens. We are confident regarding the accuracy of our computer models because the methods we used have been previously validated [33] and because the highly successful paradigm of image-guided orthopedic surgery is based on such computer models.

Another limitation of this study is that it is not clear that all clinicians follow the recommendations of the manufacturers. Experienced surgeons may palpate the femoral shaft before inserting the IM rod and thus may achieve better accuracy than would be achieved by using the recommended technique. We believe that clinicians need additional guidance on this alignment matter.

We recommend that, to maximize alignment accuracy with current instrumentation, the anatomical axis be preoperatively identified on coronal and sagittal radiographs. Intraoperatively, the surgeon should choose an insertion site that minimizes the worst-case alignment error given the spatial constraints of the minimally invasive technique. Careful preoperative review of radiographs should allow the surgeon to anticipate the possible malalignment errors inherent in using a short and thin IM rod. If accurate orientation of the femoral component is desired, we believe that the short thin IM rod inserted according to the manufacturer's specifications does not provide adequate alignment accuracy. The consequent alignment of the femoral component may be compromised by poor alignment of the IM rod. Given our finding of consistent bias toward excessive flexion and valgus alignment, we recommend that the operating surgeon carefully plan the insertion point of the IM rod during UKA surgery and consider using a more flexed varus orientation of the IM rod to compensate for the bias we found.

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