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Original Article

Evaluation of lower limb axial alignment using digital radiography stitched films in pre-operative planning for total knee replacement

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ABSTRACT

Background: For patients with knee osteoarthritis, even slight anatomical variations in the femur or the tibia could affect total limb alignment during total knee replacement (TKR). Our hypothesis implies that the femoral valgus correction angle (VCA) in patients indicated for TKR, is variable and higher than the reported norm of 6° utilized in most intramedullary instrumentation systems, and that tibial bowing may result to a disparity of the tibial mechanical axis to the anatomical axis.
Methods: Our study is a retrospective review of 216 pre-operative arthritic knees, which investigated the lower limb axial alignment using digitally-stitched films. Patients excluded from the study are those with history of previous tibial or femoral osteotomy, secondary gonarthrosis, rheumatoid arthritis, previous femoral or tibial fracture, patients for bilateral TKR, or history of hip surgery.
Results: The mean age was 68-years old (range 39–86 years). The mean VCA was 7° (4.7–9.3) for men and 6.6° (4.9–9) for women. However, 71 patients (33%) had more than 7° VCA. Subsequently, 46 patients (21%) had tibial bowing producing an angle >1.5° between its mechanical and anatomic axis.
Conclusions: The 6° standard when used as a guide may result in suboptimal prosthesis positioning during conventional TKR surgery. Therefore our findings suggest that the femoral valgus correction angle has a broad range, and using standard femoral intramedullary guides should not be overlooked.

1. Introduction

It has been a long-standing tenet in total knee replacement (TKR), to restore the overall neutral alignment of the knee. The importance of attaining neutral coronal alignment, could not more be emphasized through several finite element analysis,[1] biomechanical,[2] and clinical studies[3–6] supporting it. A total knee replacement with varus alignment has been shown to fail substantially earlier than those with neutral or valgus alignment as reported by Ritter et al.[5] In a series of 3152 TKRs, Berend et al.[7] noted that varus tibial alignment of more than 3° is the most important risk factor for medial bone collapse, leading to tibial component failure. On the contrary, the importance of neutral alignment has been contested with recent publications by Parratte et al.[8] and Matzoilis et al.[9] The conclusions from these reports indicated that clinical outcome and survivorship of the varus-outliers (>3° varus) in TKR had no significant difference with neutral-aligned knees. However, it should be noted that both these authors emphasized that correct component alignment should be intended in every operation. Moreover, surgeons should be reminded that there is no extensive data that any alignment but neutral provides a significant advantage in TKR.

Accurate preoperative planning for TKR is critical to obtain the desired alignment and produce a successful result. Standing radiographs views of the whole lower limb is the benchmark for measuring alignment of the knee, in terms of identifying both load bearing axis and any deformity that might influence the surgery. With the increase frequency of digital imaging, so have the computer-assisted tools clinicians can use when measuring the mechanical axis. Recent publications by Sled et al.[10] and Marx

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et al.[11] demonstrated higher inter- and intra-reader reliability with a range of lower limb measurements including mechanical axis, favoring digital over conventional standing lower limb images.

A valuable radiographic measurement for restoration of correct lower limb alignment is the valgus correction angle (VCA). This is the angle between the anatomical and mechanical axis of the femur. It also correlates with the angulation of the distal femoral cut needed to make it perpendicular to the femoral mechanical axis. Moreland et al.'s[12] landmark series of evaluating the radiographs of 25 Caucasian subjects (mean age: 30 years), established the norm of 6° VCA. This was later on reinforced by Tang et al.,[13] with his series of 25 male and 25 female Chinese subjects (mean age: 24 and 25 years respectively). Subsequently, majority of conventional intramedullary distal femur cutting guides are manufactured with a 6° VCA. However, the subjects involved were young adults without signs and symptoms of knee arthritis. Symptomatic patients with knee OA who have profound femoral and tibial bowing, distortion of the bony canal, mal-united fractures and/or metabolic bone disease further limit the accuracy of an intramedullary alignment system.[14–18] The present study investigated a group of middle aged to elderly patients of multi-racial origin with knee arthritis scheduled for TKR. We hypothesize that femoral VCA is significantly greater compared to the reported 6° valgus, and that tibial bowing may result to a disparity of the tibial mechanical axis to the anatomical axis. These circumstances may have some bearing on instrument sets for total knee replacement that use intramedullary guides.

2. Materials and methods

A retrospective investigation of radiographs was done involving 216 knees in 216 patients diagnosed with primary gonarthrosis scheduled for unilateral TKR, who were seen in our institution from May 2009 to May 2011. Patients excluded from the study are those with history of previous tibial or femoral osteotomy, secondary gonarthrosis, rheumatoid arthritis, previous femoral or tibial fracture, patients for bilateral TKR, or history of hip surgery. Approval from the institution's Human Research Ethics Committee was obtained for this project.

Long radiographic views of the whole limb in stance were ideal for measuring alignment of the knee, in terms of both the load bearing axis and the other joint angles that may contribute to any deformity. Conventional hard copy full-leg plain radiographs (51 in. film) are cumbersome to use in measurements. Over the last decade subsequent research has shown that when comparing measurements of axial alignment between conventional and digital images, digital is as good and in some cases better than conventional.[19–21] Furthermore when conventional images were digitalized and measurements were made from these images, it showed minimal changes in measurement accuracy.[22] When it comes to spatial resolution, conventional imaging reigns supreme producing 2.5–15 lines/mm, compared to digitals' 2.5–5 lines/mm.[23] However, diminished spatial resolution in digital films has been shown to have no effect on diagnostic accuracy.[23,24] Digital imaging makes up for this shortcoming with superior image processing and analysis, reduced radiation per dose, and a wider linear dynamic range.[25,26]

For this study, digital reconstructed composite radiographs of the entire lower limb from the hip to the ankle joint were obtained using a digital X-ray system (Digital Diagnost VS, Philips Medical Systems) applying a standard acquisition protocol. Each subject was placed in a weight bearing platform with the patella at 90° to the coronal plane against a motorized vertical detector stand (Phillips Vertical Stand VS) and 120 cm rule at a standard source-to-image distance of 260 cm from the motorized X-ray tube. A series of three separate overlapping radiographic images were taken and automatically digitally stitched using a software algorithm (Phillips' Digital Diagnost) to generate a composite image of the entire limb. Scrutiny of the appearance of the fibular head and the lesser trochanter profile was done, to ensure that the limb was not internally or externally rotated. The authors obtained measurements through computer-assisted method using IMPAX 6.4.0.3125 software for precise and easy measurement of lower extremity axes based on the load bearing axis of the knee. The Legogram films (17 in. × 14 in.) are then printed out from digital pasted films of the whole leg in standing, which is reduced in size similar to a regular chest radiograph for easier carriage. The limb alignment and angles were measured based on the methods described by Moreland et al.[12] with some modifications. The centers of the femoral head, the knee, and ankle, as well as other essential radiographic measurements documented were described as follows (Figs. 1 and 3):

(a) Femoral head center – determined using Mose circles.
(b) Femoral shaft center I – a point located by bisecting the proximal to distal length of the femur (as defined by a line from the superior aspect of the femoral head to the distal part of the medial condyle) and the mid-shaft medial-to-lateral width of the femur.
(c) Femoral shaft center II – a point midway between the medial and lateral cortex of the femur, at 10 cm above the lowest femoral condyle surface.
(d) Distal femur center – the center of the femoral intercondylar notch.
(e) Proximal tibia center – the midpoint between the tips of the tibial spines.

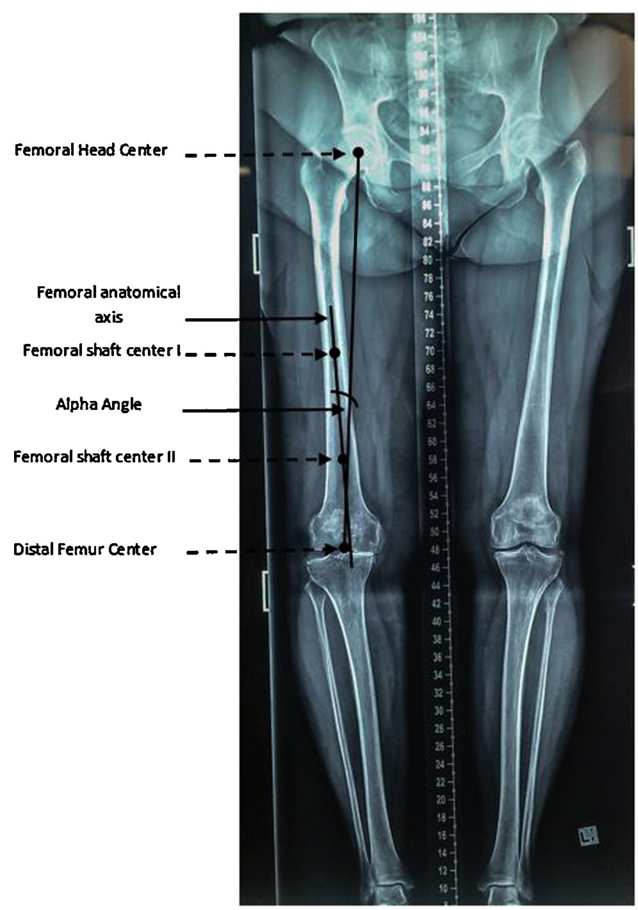

Fig. 1. A representation of the reconstructed composite image for the measurement of axes and angles in the femur. This digital image is developed as a similar dimension print out called Legogram film. The femoral valgus correction angle is depicted as the alpha angle.

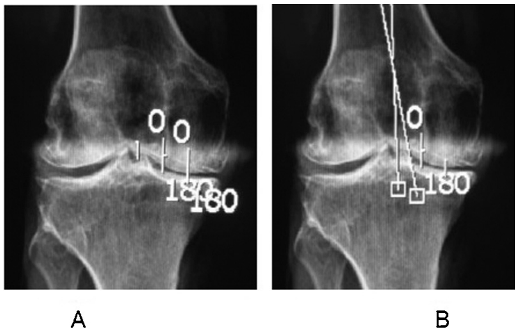

Fig. 2. Exit zones of the femoral anatomical axis. (A) The medial distal femur is divided into three 10 mm zones. Zone 1 is the interval between the distal Femur center (1st line) and the beginning of the medial femoral condyle articular cartilage (2nd line). Zone 2 is the interval between the 2nd line and the 3rd line (midpoint of the medial condyle cartilage). Zone 3 is the area between the 3rd line up to the medialmost edge of the articular cartilage. (B) The femoral anatomical axis passing through zone 1.

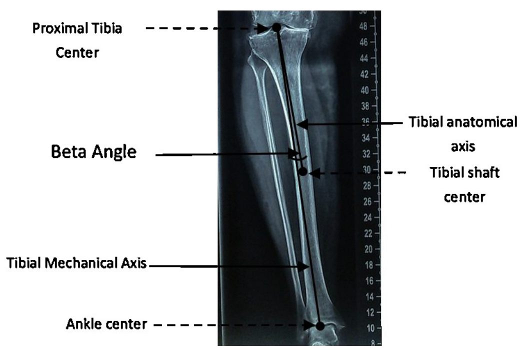

Fig. 3. A representation of the principal tibial axes and angles measured from the digitally stitched radiographic images. The angle between the tibial anatomical and mechanical axis is presented as the beta angle.

(f) Tibial shaft center – point at tibial mid-shaft, at the center of its width.
(g) Ankle center – defined as the midpoint of the talar dome.
(h) Femoral mechanical axis – a line was then drawn from the center of the femoral head to the center of the distal femur.
(i) Tibial mechanical axis – a line drawn from the center of the proximal tibia to the ankle center.
(j) Femoral anatomical axis – a line drawn from the femoral shaft center I and femoral shaft center II.
(k) Tibial anatomical axis – a line drawn from the proximal tibia center to the tibial shaft center.
(l) Valgus correction angle (alpha angle) – angle derived between the mechanical and the anatomical axis of the femur.
(m) Tibia axial alignment angle (beta angle) – angle derived between the mechanical axis and the anatomical axis of the tibia.

Since the anatomical axis of the femur followed the center of the femoral shaft, it does not exit not through the center of the knee but offset and medial. We divided medial half of distal femur into three 10 mm zones from the center of the distal femur (Fig. 2). These zones are according to where the anatomical axis exits, and should represent the entry point of the intramedullary guide intraoperatively. The requirement for entry point medial offset of the femoral intramedullary guide, is confirmed by studies from Novotny et al.[27] and Xiao et al.[28] Geometrical analysis of 45 cadaveric femora revealed that accurate entry point position is 0.53× the width of the distal femur measured from the lateral cortex.[27] Moreover, the mean rod entry point position was 2.94 ± 1.12 mm medial in a computed tomography analysis of 50 normal femurs.[28]

A different method of measuring the femoral anatomical axis, which was not used in this study, is described by drawing a line between points femoral center I and the center of the distal femur. Nevertheless it was recognized that in the femoral metaphyseal region this line was not in the center but instead usually lay slightly to the lateral side of the femur.

3. Results

A consecutive series of 216 knees in 216 patients with primary gonarthrosis, were seen in our institution during May 2009 to May 2011 and were analyzed. The mean age was 67.8 years (range: 39–86 years) with 45% of the population being males and 55% females. Fifty-six percent of the knees analyzed were from the right side (Table 1).

The alpha angle, representing valgus correction angle of the femur (VCA), had a mean value of 6.5° in the 216 knees analyzed (Table 1). Sixty-seven percent had an alpha angle of 4–7°. However, our notable finding was that 71 patients (33%) had an angle of >7° to 9.3°.

The results showed that the alpha angle were not consistent with the usually accepted value of approximately 6° in all patients.[12,13] We compared our alpha angle results with those two similar investigations performed on white subjects in the United States by Moreland et al.[12] and Chinese subjects by Tang et al.[13] In their studies, radiographs of the entire lower extremities were made for each subject. Moreland et al. included only male subjects, and the results of the left and right sides were calculated separately. Tang et al. included both male and female subjects and the laterality were calculated separately as well. We subdivided our population with respect to gender and laterality (Table 2) so as to better compare our results with the previous studies. Continuous variables were compared with use of the independent-samples *t* test. *P* value was set to 0.05.

The alpha angles on male subjects described by Moreland et al. were not significantly different from Tang et al. subjects on either the left or the right side as described by the latter author in his article ($P > 0.1$ for both sides).[23] However alpha angle in our subjects was significantly greater than in the subjects described by both authors for both men and women on the right side. In male individuals, the mean alpha angle was 7° (range 4.7–9.3) while the previous studies had 5.6 (<0.0001) and 5.8 (<0.0001) alpha angles respectively. On the other hand, females had 6.6° (range 4.9–9) compared to 5.7 (<0.0002) from the Tang et al. series. The angles on the left side were relatively elevated but did not show statistical significance.

Our results showed that male patients have slightly higher mean alpha angles compared to females. And for both genders, the right femur alpha angle seems to be increased compared to the left side.

Approximately 77% of the femurs had anatomical axes exiting through zone 1 (Table 1) which is within 10 mm from the determined knee center. The remainder 23% was within zone

Table 1
Descriptive data and patient demographics.

Mean age in years (range)	67.8 years (range 39–86 years)
Gender	119 female, 97 male
Laterality	120 right, 96 left
Mean alpha angle in° (range)	6.5° (range 4–9.3°)
Mean beta angle in° (range)	0.68° (range 0–3.8°)
Distal femoral zones (%)	Zone 1 (n = 166) 77%; zone 2 (n = 50) 23%; zone 3 (n = 0) 0%

Table 2
Comparison of knee alpha angle measurements according to gender and laterality in candidates for knee arthroplasty, with Chinese and Caucasian normal adults.

	Present series (°)		Series of Tang et al. (°)		Series of Moreland et al. (°)	
	Right	Left	Right	Left	Right	Left
Men						
Mean (SD[a]) alpha angle	7.0 (±1.0)	6.1 (±0.9)	5.6 (±0.9)	5.7 (±0.8)	5.8 (±0.7)	6.0 (±1.0)
Number of patients	54	43	25	25	25	25
P value			<0.0001	0.0658	<0.0001	0.6847
Women						
Mean (SD[a]) alpha angle	6.6 (±0.9)	6.0 (±1.1)	5.7 (±1.0)	5.6 (±1.12)		
Number of patients	66	53	25	25		
P value			0.0002	0.1392		

[a] Standard deviation.

2 which is the 10–20 mm gap in the medial condyle. No axis emerged from within zone 3.

The mean tibial axial alignment, which we described as the beta angle, was 0.68 (range: 0–3.8)° (Table 1). There were 46 knees (21%) which had angulation of ≥1.5° while 17 (8%) of these knees were between ≥2 and 3.8°. These 21% had some degree of tibial bowing wherein its mechanical axis line touches the tibial cortices.

4. Discussion

Assessment of the load bearing axis of the lower limbs is very important for pre-operative planning in total knee replacement for patients with osteoarthritis.[12] Long radiographic views of the whole limb in stance are ideal for measuring alignment of the knee, in terms of both the load bearing axis and the other joint angles that may contribute to any deformity. Most facilities use a 36-inch cassette when making radiograph of the lower extremities. The long cassette is loaded with film for three standard radiographs of the chest, and the radiographs were taped together after they were developed, thus it is sometimes called the 3-foot image pasted films.

On the other hand, the films used in our institution for preoperative and postoperative TKA assessment are print outs from digitally-stitched images measuring nearly one third (17 in. × 14 in.) the size of 3-foot image pasted films. The push for digital radiography to become the standard medium has been attributed to several advantages it presents. These attributes are ease of storage, accessibility, long-term cost savings, transportable, and the ability to edit picture properties such as brightness and contrast with the use of specialized software.[25,29] Accuracy and consistency are crucial in the radiographic measurement of the mechanical axis of the lower limb. With improved computer-assisted analysis, inter- and intra-observer reliability now matches that of conventional methods, while the time needed for the analysis is reduced.[21,29] This concept is solidified with recent literature reporting the mean accuracy when measuring small distances using digital radiographs through computer software to be within 0.1 mm and a SD of measurements 0.5 mm.[30] Reliability in digital images in combination with computer-assisted measuring software now has the ability to ensure precise and consistent measurements of femoral and tibial axes and angles.

The use of an intramedullary guide for the distal femoral cut is currently standard practice in total knee replacement and still widely used worldwide, even with the advent of computer navigation. The valgus correction angle of the distal femur determines the choice of the cutting block to make the femoral bone cut perpendicular to the femoral mechanical axis. Most of the instrumentation systems offer a standard 6° cutting block to guide the distal femoral cut in order to match the commonly reported 6° physiological valgus angulation of the femur.[12,13] However, femoral bowing changes the angular relationship between the anatomical axis and the mechanical axis. Therefore, the reliability of using a standard 6° valgus distal femoral cut is questionable.[31–34] In this study, an increased valgus correction angle of the distal femur was seen. The mean was 6.8° (4.7–9.3°) in the right and 6.1° (4–8.8°) in the left were found. While alpha angle in our male (7°) and female (6.6°) subjects were significantly larger than previous series on the right side, there was no significant difference found on the left side.

Our findings noted that 71 patients (33%) had an alpha angle of more than 7° in patients between ages of 53 and 86 years. Femoral components implanted using a standard 6° or even a flexibility option of 5–7° valgus cut during the conventional TKR will result in unacceptable alignment of the mechanical axis of the limb in a significant number of patients. Thus limits the accuracy of the standard cutting blocks set by an intramedullary alignment system. Our results concur with outcomes from Mullaji et al.'s analysis of the influence of pre-operative deformity to femoral valgus correction angle in 503 knees for TKR.[35] They noted that 44.9% of knees had VCA of >7° and 10.9% were less than 5°. However, their description of the femoral anatomical axis as a line best representing the mid-medullary axis of the distal femoral diaphysis was vague and non-specific. Moreover their illustration showed that the femoral anatomical axis exit at the apex of the intercondylar notch, which may be inaccurate since previous studies have shown that correct femoral intramedullary entry point should have a medial offset.[27,28]

The intramedullary guide is best represented by femoral anatomical axis, which did not intersect the mechanical axis of the femur at the center of the knee. In order to get a perpendicular distal femoral cut to the mechanical axis of the femur according to the predetermined valgus correction angle, the entry point of the intramedullary rod should be shifted medially (Fig. 2). Tang et al. addressed this concern and recommended a five-millimeter medial shift of the entry hole from the apex of the intercondylar notch.[13] In this study, we divided medial half of distal femur into three 10 mm zones to specifically determine the point of entries (Fig. 2). Fifty knees (23%) had femoral anatomical axis passing through zone 2 which was 10–20 mm from the apex of the intercondylar notch. On the other hand, 166 anatomical axes exited through zone 1 which was within 10 mm from the defined knee center. Among the group of patients within zone 1, 51 knees (24%) from this group were between 5 and 10 mm from the center. Therefore 115 knees (53%) were in the 5 mm range and conferred to Tang et al. observation. There was no axis that emerged 20 mm beyond the midline (zone 3). This "3-zone method" provided specific point of entries with well defined landmarks useful during preoperative templating as well as an intra-operative technical guide.

Intramedullary guide is not routinely used as a tibial cutting jig for reasons of exceptional low accuracy. Our series showed that 21% of the patients with beta angle ≥1.5° had bowing of the tibia noteworthy enough to render intramedullary guides inaccurate. Our results showed 57% (n = 26) had valgus tibia while 43% (n = 20) were varus. Whether or not the angulation of 1.5–2° is the threshold of significant tibial bowing, additional study is required to confirm this finding.

5. Conclusions

Our attempt to examine the geometry of the femur with respect to its mechanical axes may therefore develop the change in the standard 6° angle reference used in intramedullary femoral guide. The study confirmed the wide variations that were found in the femur angular dimensions among men and women, and the striking feature of our findings was that valgus correction angle was remarkably higher with 7° (4.7–9.3) in the right femur of men and 6.6° (4.9–9) in women. In addition, 33% of the knees have more than 7° of angulation. These data have important surgical implications. Therefore our findings suggest that the femoral valgus correction angle has a broad range, and using standard femoral intramedullary guides should not be overlooked. Furthermore, the femoral component should be placed along a longitudinal axis that is medial to the knee center according to the valgus correction angle measured preoperatively and the 3-zone method described.

Conflicts of interest

The authors have none to declare.

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