The Effects of Femoral Shaft Malrotation on Lower Extremity Anatomy

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Objective: To determine how axial rotation around the anatomic axis of the femur, as would occur with malrotation of a femoral fracture, affects frontal and sagittal plane alignment and knee joint orientation.

Design: Computer-generated models of the lower extremity were constructed using standardized dimensions. To simulate a malrotated fracture, these models were rotated in the shaft around the anatomic axis in 15° increments from 60° internal to 60° external rotation. Rotation was performed at the proximal fourth, mid-shaft, and distal fourth.

Main Outcome Measurements: At each rotational position, the mechanical axis deviation in millimeters and the changes in mechanical lateral distal femoral angle in degrees were measured to quantify frontal plane malalignment and malorientation, respectively. The mechanical axis deviation in millimeters in the sagittal plane was also measured at each rotatory position.

Results: Femoral shaft malrotation greater than 30° internal rotation of a subtrochanteric fracture or more than 45° of a midshaft fracture or external rotation of 30° or greater of a supracondylar fracture resulted in frontal plane malalignment. External rotation of a supracondylar fracture of 45° or more results in knee joint malorientation. Any external rotation at all 3 fracture levels caused posterior displacement of the weight-bearing axis in the sagittal plane.

Conclusions: Malrotation of a femoral shaft fracture is not just a cosmetic problem. Internal and external rotation causes malalignment and malorientation in the frontal plane, depending on the level of the fracture and the magnitude of malrotation. External rotation of any degree at the proximal fourth, mid-shaft, and distal fourth causes a posterior shift of the weight-bearing axis in the sagittal plane.

Key Words: malrotation, femur fracture, intramedullary nailing, malunion

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Malrotation can occur following closed intramedullary nail fixation of femoral shaft fractures. Previous studies of malrotated femoral shaft fractures with short-term follow-up report that malrotation may cause symptoms, but the cause of the symptoms has not been well defined.[1–5] If malrotation causes abnormalities of alignment or joint orientation or both of the knee joint in the frontal plane, eccentric stress on the articular cartilage occurs.[6,7] Eccentric stress may cause degenerative osteoarthritis if the rotatory deformity remains uncorrected.[6,8,9] Also, alteration of the weight-bearing axis in the sagittal plane may cause gait abnormalities.[10] This study investigates how axial rotation around the anatomic axis of the femur affects frontal plane lower extremity alignment, as quantified by the mechanical axis deviation; the frontal plane knee joint orientation, as quantified by the mechanical lateral distal femoral angle (mLDFA); and the sagittal plane weight-bearing line, as quantified by the sagittal plane mechanical axis deviation.

MATERIALS AND METHODS

Three-dimensional representations of femoral-tibial segments were created on a standard personal computer utilizing the software "lightwave" (Newtek, San Antonio, TX; www.newtek.com). This software creates and manipulates 3-dimensional anatomic models. These models may be simultaneously viewed in axial, frontal, and sagittal projections; frontal and sagittal images are shown in Figure 1. Parameters used to create the model included a femoral length of 470 mm,[11] a tibial length of 371 mm,[11] a tibial-femoral angle of 6°,[12,13] femoral neck anteversion of 15°,[14,15] and a neck-shaft angle of 130°.[10] The lengths of the femur were the 50th percentile values for males at skeletal maturity.[11] The femur curve in the sagittal plane was a radius of curvature of 2.2 meters, the radius of curvature of 2 commonly used intramedullary nails (Biomet, Warsaw, IN, and Smith and Nephew, Memphis, TN). Within these models, 3 points were created for subsequent analysis: the center of the femoral head, the point at which the mechanical axis crossed the knee, and the center of the ankle joint.

In each model, an osteotomy of the femoral shaft was created in the proximal fourth (subtrochanteric), midshaft, and distal fourth (supracondylar) to simulate a fracture. The proximal femur was then rotated about the anatomic axis of the femur to simulate malrotation around an intramedullary nail. Ro-

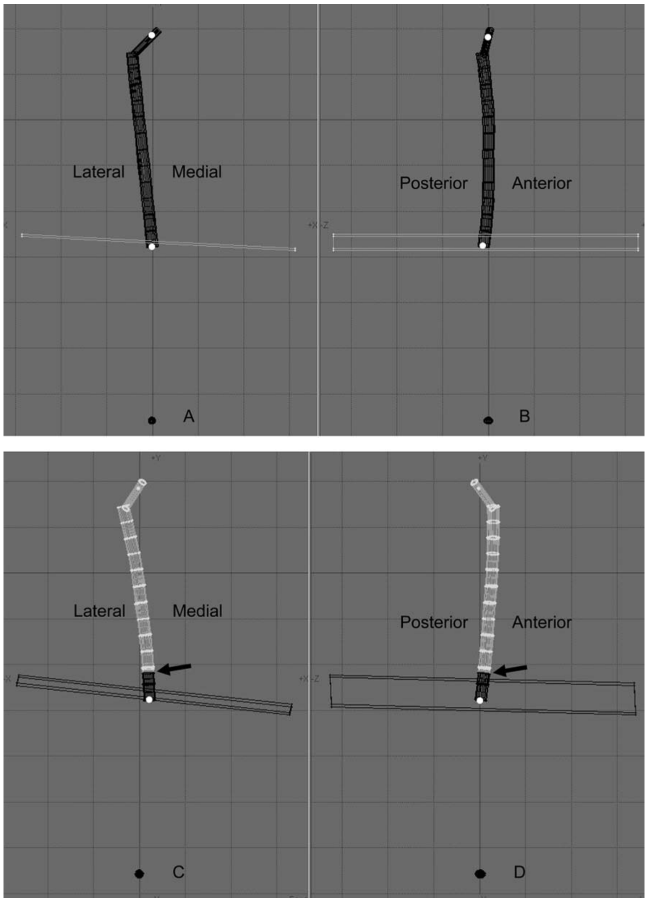

FIGURE 1. The computer-generated image of the right lower extremity. From superior to inferior, the 3 dots represent the center of the femoral head (white dot), the center of the knee joint (white dot), and the center of the ankle (black dot), respectively. The horizontal plane represents the plane of the knee joint. The arrows in 1C and 1D represent the site in the femur at which the axial rotation was performed. A, Frontal plane image, no rotation. B, Sagittal plane image, no rotation. C, Frontal plane image; 45° external rotation of distal segment, distal fourth (supracondylar) fracture. D, Sagittal plane image; 45° external rotation of distal segment, distal fourth (supracondylar) fracture.

tation was carried out from 60° of external to 60° of internal rotation in 15° increments. Deformities were quantified in the frontal and sagittal planes of the knee; therefore, the computer-generated images were analyzed with the distal femoral segment and the adjacent tibia as the stationary fragment with the knee facing forward and with the proximal segment as the moving segment (Figs. 1, 2). For ease of understanding, the data are presented based on the standard convention of the direction of rotation (internal or external) being determined by the direction of the distal fragment with respect to the stationary proximal fragment.

The "lightwave" program was used to measure mechanical axis deviation and mLDFAs in each rotated position (Fig. 3). These parameters were measured by the software to avoid human error in measurement. Frontal plane deformity was quantified by measuring 2 parameters, as described by Paley[16]: malalignment was quantified by the mechanical axis deviation, and knee joint malorientation was quantified by the mLDFA (Fig. 3A, B). Sagittal plane deformity was quantified in a similar manner by measuring the horizontal change in millimeters of the intersection of the mechanical axis at the knee in each rotated position compared with the intersection of the mechanical axis with the knee in the normal model with the knee in extension (Fig. 3C, D).

The normal values for frontal plane mechanical axis deviation and mLDFAs have been described by Paley.[16] The nor-

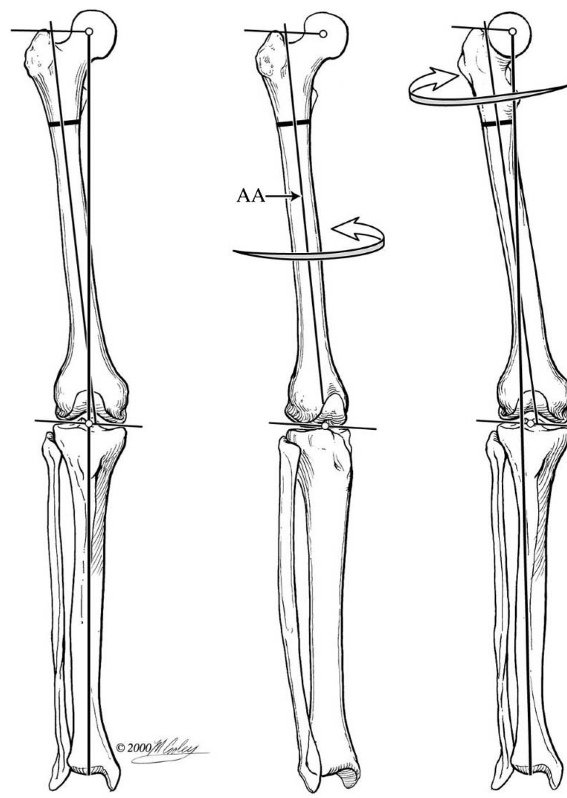

FIGURE 2. The effect of axial rotation at the mid diaphysis of the femur. A, In a normal lower extremity, the mechanical axis (MA) is a straight line from the center of the femoral head to the center of the ankle, passing near the center of the knee joint. The anatomic axis (AA) of the femur is formed by a series of mid diaphyseal points from the piriformis fossa to the medial femoral condyle. B, The distal segment of the femur is rotated internally at the mid axis of the femur and the proximal segment remains stationary, the standard convention for determining direction of rotation. C, The proximal segment of the femur is rotated externally with the distal segment remaining stationary. This rotation results in an identical position as in 2B, but now mechanical axis deviation and the mLDFA can be measured at the knee. The mechanical axis is now shifted lateral to the center of the knee.

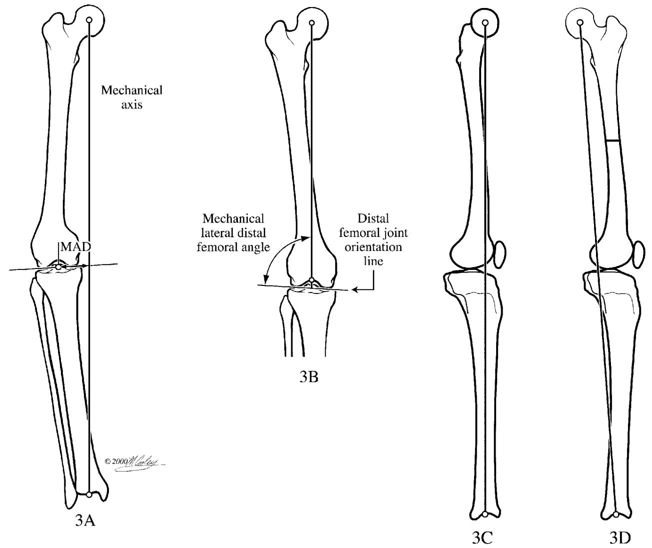

FIGURE 3. Parameters measured were frontal plane mechanical axis deviation, frontal plane mLDFA, and sagittal plane mechanical axis deviation. A, Frontal plane mechanical axis deviation (MAD) quantifies frontal plane malalignment. B, The mLDFA quantifies frontal plane knee joint malorientation. C, Sagittal plane mechanical axis deviation quantifies sagittal plane malalignment. The mechanical axis intersects the anterior fifth of the proximal articular surface of the tibia and is anterior to the center of rotation of the knee when the knee is extended. D, In an externally rotated femur, the mechanical axis intersects more posteriorly. The distance between the intersections in 3C and 3D represents the lateral mechanical axis deviation.

mal value and standard deviation for frontal plane mechanical axis deviation are 10 mm medial to the center of the knee joint ±6.8 mm. The normal value and standard deviation for the frontal plane mLDFA are 88 ± 2°, equivalent to approximately 2° valgus.[16] For this study, values more than 1 standard deviation from normal were considered abnormal. Mechanical axis deviation in the sagittal plane does not have a normal value because it changes constantly during the gait cycle, but passes through the center of rotation in the knee joint when the knee is in approximately 5° of flexion.[10]

RESULTS

All results (Table 1) are based on measurements with the patella forward.

Frontal Plane Mechanical Axis Deviation

Internal rotation of the distal segment of a subtrochanteric fracture greater than 30° or a midshaft fracture greater than 45° resulted in lateral and medial mechanical axis deviation (Fig. 4A), respectively greater than 1 standard deviation (6.8 mm). External rotation of the distal segment of a supracondylar fracture of 30° or more resulted in medial mechanical axis deviation greater than 1 standard deviation.

TABLE 1. The Effect of Femoral Rotation on Lower Extremity Alignment

	Subtrochanteric		
	Frontal	**mLDFA**	**Sagittal**
Internal rotation			
60°	17.0	−2.3	16.3
45°	12.0	−1.5	22.3
30°	6.6	−1	9.4
15°	2.5	−0.8	5.2
Neutral			
0°	0	0	0
External rotation			
15°	1.3	0.4	−4.1
30°	1.9	0	−11.5
45°	−0.1	−0.1	−18.7
60°	−4.7	−0.7	−24.9
	Midshaft		
Internal rotation			
60°	−11.7	−1.4	19.9
45°	−6.7	−1.1	22.5
30°	−2.1	−0.3	10.2
%°	−1.1	−0.1	15.8
Neutral			
0°	0	0	0
External rotation			
15°	−0.1	0	−5.0
30°	−3.9	0	−6.8
45°	−3.2	−0.1	−7.6
60°	−1.1	−1.4	−10.7
	Supracondylar		
Internal rotation			
60°	0.1	0.5	19.9
45°	1.1	−1	22.5
30°	3.0	0.8	10.2
15°	2.8	0.6	15.8
Neutral			
0°	0	0	0
External rotation			
15°	−4.5	−0.4	−5.0
30°	−9.9	−1.5	−6.8
45°	−15.3	−2.5	−7.6
60°	−22.0	−3.1	−10.7

Frontal, mechanical axis deviation (mm) in frontal plane from neutral occurring with rotation. Positive numbers are lateral deviation, and negative numbers are medial deviation; mLDFA, degrees change in mechanical lateral distal femoral angle from neutral occurring with rotation. Positive numbers are less valgus, and negative numbers are more valgus; Sagittal, mechanical axis deviation (mm) in sagittal plane from neutral occurring with rotation. Positive numbers are anterior deviation, and negative numbers are posterior deviation.

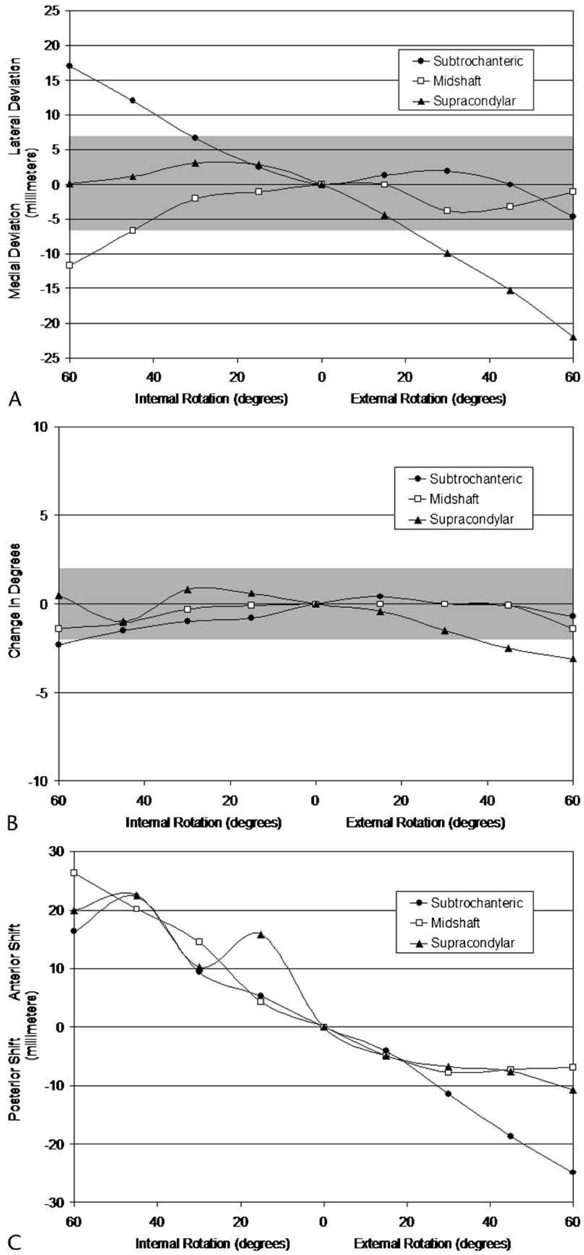

FIGURE 4. Effects of rotation on frontal plane mechanical axis deviation, mechanical axis lateral distal femoral angle, and sagittal plane mechanical axis deviation. Shaded areas represent normal values. A, Frontal plane mechanical axis deviation. B, Mechanical axis lateral distal femoral angle. C, Sagittal plane mechanical axis deviation.

Mechanical Lateral Distal Femoral Angle

External rotation of the distal segment of a supracondylar fracture of 45° or more resulted in a decrease in the value of the mLDFA greater than 1 standard deviation (2°) (Fig. 4B).

Sagittal Plane Mechanical Axis Deviation

Malrotation of the distal segment in either direction altered the sagittal plane mechanical axis (Fig. 4C). External rotation caused a posterior shift of the mechanical axis, and internal rotation caused an anterior shift of the mechanical axis.

Level of the Osteotomy

The level of the shaft at which the osteotomy and rotation were performed affected the results. The frontal mechanical axis deviation was affected most by internal rotation of a subtrochanteric osteotomy and external rotation of a supracondylar fracture. The mLDFA was affected at the supracondylar level of the osteotomy and only at external rotation greater than 45°. The sagittal plane mechanical axis deviation was affected most by external rotation of a subtrochanteric osteotomy.

DISCUSSION

Closed intramedullary nail fixation has become the favored treatment of femoral shaft fractures in adults because of its many advantages[17–19]: it can be performed without exposing the fracture site, it stabilizes the femur and soft tissue using a load-sharing device; and the patient can be mobilized rapidly.

Because of the difficulty assessing bony landmarks of the proximal femur, malrotation may occur after closed nail insertion. Factors associated with malrotation include comminution,[2,5] proximal one-third shaft fractures,[5,17] distal one-fifth shaft fractures,[17] intraoperative lateral positioning,[18] small diameter nails,[3,4] unlocked nails,[20] dynamic locked nails,[21] and retrograde nails.[18,19] Because the surgeon may not recognize the magnitude or effect of malrotation at the time of nail insertion, the femur may be allowed to heal in a malrotated position. The prevalence of femoral malrotation in healed intramedullary nailing has been reported in previous studies[1,5,17,19–22] (Table 2). Winquist and Hansen reported 16 malrotated femurs in their series of 245 femurs, with 3 greater than 30°.[22] Tornetta et al reported 22 malrotated femurs with thirteen being malrotated externally up to 61° and 9 being malrotated internally up to 37°.[17] Bråten et al reported 47 cases of malrotation in a series of 110 femurs, with 11 being symptomatic.[1] Whereas malrotation greater than a certain amount may elicit complaints from the patient, the amount a patient can tolerate before complaining of dissatisfaction with clinical appearance or impaired function has not been clearly delineated.

Some patients with malrotation have symptoms and may require reoperation to correct rotatory deformities.[1–5] The etiology of the symptoms in patients with malrotation is unclear; it may be due to muscle or joint pain.[1,4,5,19] Follow-up on these patients is short, so the long-term effect of malrotation is currently undetermined. If rotatory malalignment causes malalignment and malorientation of the knee joint, osteoarthritis may result.[6,8]

TABLE 2. Review of the Literature Regarding Malrotation Following Intramedullary Nailing of the Femur

Authors (Year of Publication)	No. Malrotated Femurs	Total Femurs Treated	Femurs With External Rotation	Femurs With Internal Rotation	Magnitude of Deformity
Winquist and Hansen (1980)[22]	12		*	*	10–20°
	1		*	*	20–30°
	3		*	*	30–40°
	Total = 16	245	*	*	
Winquist et al (1984)[5]	31		31	0	≥10–20°
	12		12	0	>20°
	Total = 43	520			
Wiss et al (1986)[21]	8	112	8	0	10–30°
Søjbjerg (1990)[20]	3	40	3	0	5–10°
Bråten et al (1993)[1]	26		*	*	10–14°
	21		16	5	≥15°
	Total = 47	110	*		
Tornetta et al (1995)[17]	22	Not consecutive series	13		5–61°
				9	4–37°
Tornetta and Tiburzi (2000)[19]	8	69	*	*	>10°

*, not specified.

The correlations between malrotation and axial malalignment and between malrotation and osteoarthritis have been hypothesized by previous authors. Paley reported that femoral rotational osteotomies around the anatomic axis may lead to malalignment.[23] Eckhoff reported that rotational deformity caused hip and knee arthrosis and hypothesized that rotational malalignment can alter the pressure distribution in an otherwise normal joint.[24] Van Joost and Gastkemper reported a series of symptomatic patients with malrotation after femoral intramedullary nail fixation of fractures and hypothesized the development of arthritic joint changes increased proportionately with the magnitude of malrotation.[4]

Frontal plane angular malalignment of the lower extremity is an etiology of osteoarthritis of the knee. This is due to eccentric joint pressure, with valgus angulation causing increased stress on the lateral compartment and varus angulation causing increased stress on the medial compartment.[6] With the passage of time, this increased stress causes unicompartmental osteoarthritis of the knee.[8]

Frontal plane deformity of the lower extremity due to femoral deformity can be quantified by measuring 2 parameters: malalignment and joint malorientation. Malalignment is quantified by the mechanical axis deviation; malorientation is quantified by mLDFA.[10,25] In the normal lower extremity, the mechanical axis is a straight line from the center of the hip to the center of the ankle, passing just medial to the center of the knee (Fig. 3A). The horizontal distance in millimeters from the center of the knee to the mechanical axis is the mechanical axis deviation. Valgus deformities have lateral mechanical axis deviation; varus deformities have medial mechanical axis deviation. Similarly, the sagittal plane mechanical axis is a straight line from the center of the hip to the center of the ankle (Fig. 3C). The relationship of this line with the center of the knee constantly changes during the gait cycle.

A normal mechanical axis is necessary but not sufficient for normal anatomic configuration. In addition to no mechanical axis deviation, normal anatomic configuration is also characterized by correct knee joint orientation as quantified by the mLDFA. This angle is formed by the intersection of 2 lines: the femoral mechanical axis (a line from the center of the femoral head to the center of the knee joint) and the distal femoral joint orientation line (a straight line tangential to the medial and lateral femoral condyles) (Fig. 3B).

A femoral or tibial intramedullary nail is inserted in the bone's anatomic axis, a series of mid-diaphyseal points that form a straight line in the frontal plane. The mechanical axis of the tibia is a few millimeters lateral to, but parallel to, the anatomic axis of the tibia. The ankle mortise, which defines the distal tibial joint orientation, is perpendicular to both the mechanical and anatomic axes. Therefore, a transverse diaphyseal fracture of the tibia stabilized with an intramedullary nail can be visualized as 2 vertical cylinders placed end-to-end with the same center axis, the anatomic axis (Fig. 5). Rotation around the axis, which may occur in a malrotated tibia fracture stabilized with an intramedullary nail, will not affect the anatomic axis of the tibia or the distal tibial joint orientation, the ankle mortise.[23]

Unlike the tibia, the femur is not a vertical cylinder. Proximally, the anatomic axis intersects the piriformis fossa and is displaced laterally from the mechanical axis by the femoral head and neck. Distally, the anatomic axis intersects the distal femur 1 cm medial to the center of the knee joint at an

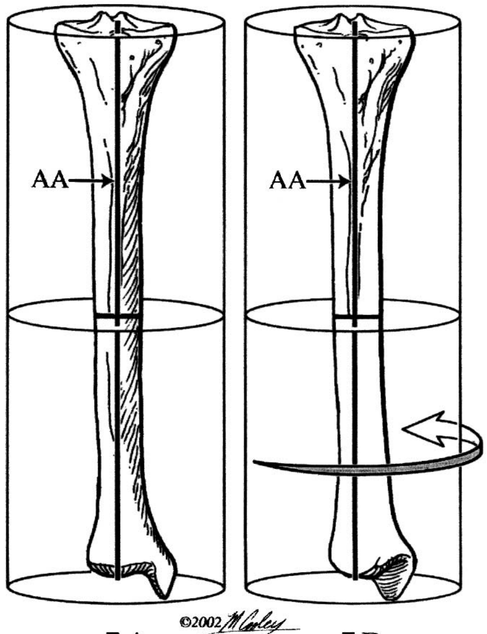

FIGURE 5. Rotation of a tibia fracture around the anatomic axis does not affect mechanical axis or ankle joint orientation. A, The normal tibia. B, Rotation around the axis does not affect the mechanical axis of the tibia or the ankle joint orientation because the anatomic and mechanical axes are parallel and nearly coincide, and the ankle joint is perpendicular to the mechanical axis.

angle of 81° to the knee joint[23] (Fig. 2A). Also, the medullary canal is curved in the sagittal plane concave posteriorly. By definition, the femoral mechanical axis is a straight line from the center of the femoral head to the center of the knee joint, and, in a normal femur and tibia, extends distally to the center of the ankle as the mechanical axis of the lower extremity. Actually, the mechanical axis of the lower extremity intersects the knee slightly medial to the joint center, but this slight medial deviation results in an angle formed by the femoral and tibial mechanical axes of 1° or less.[16] This slight deviation from colinearity does not affect this study. The mechanical and anatomic axes are not parallel but intersect in the distal femoral metaphysis at a 6° angle. Unlike malrotation around the vertical tibial anatomic axis, where the distal joint orientation line is perpendicular to the anatomic axis, rotation around the oblique femoral anatomic axis will affect knee joint orientation because the femoral anatomic axis intersects the knee joint at 81°, not 90° as in the ankle mortise. In addition, the mechanical axis of the lower extremity will be affected because the distal femoral fragment and the tibia are rotating as a unit around the oblique anatomic axis of the femur[23] (Figs. 1, 2).

We defined frontal plane anatomic parameters greater than 1 standard deviation from average values as an alteration of femoral anatomy, based on several studies. A value of 2 standard deviations from the mean is traditionally considered to be abnormal for many medical indices because only 5% of the population would have such values; 95% of the population is considered "normal" by convention. However, a narrower range of values may be defined if health risks are empirically demonstrated to be associated with values that are exhibited by more than 5% of the population. An example is adult body weight in the United States, where 2 in 3 adults exhibit an excessive body weight, which places them at increased risk for hypertension, premature mortality, cardiovascular disease, certain cancers, and type II diabetes.[26,27] Although there are no longitudinal or epidemiological studies that delineate limb deformity parameters that increase the risk of osteoarthritis, several studies indicate that the value for knee deformity parameters relative to risk of progressive degenerative changes is less than 2 standard deviations from the mean.[8,16] In an 18-month longitudinal study by Sharma et al, the radiographic angulation that was tolerated without resulting in progressive degenerative changes was less than 2°.[8] The intervals for mechanical axis deviation and mLDFA in asymptomatic older adults was quite narrow when compared with the population normal values, according to studies by Bhave et al, cited by Paley.[16]

An unexpected finding was the effect of malrotation on the sagittal plane mechanical axis. The sagittal mechanical axis moves during gait as the knee flexes and extends. The normal mechanical axis passes through the center of rotation of the knee joint when the knee is in approximately 5° of flexion.[10] By passing anterior to the center of the knee joint when the knee is extended, quadriceps action is unnecessary for quiet standing. With external malrotation of the femur, the mechanical axis moves posteriorly. As it moves posteriorly, quadriceps action or anterior shifting of the trunk becomes necessary to maintain extension while standing. This need for quadriceps action and/or compensatory anterior shift of the trunk could cause muscle fatigue with prolonged standing. Because the normal sagittal mechanical axis deviation in normal quiet standing has not been determined, our study cannot state how much external rotation can be tolerated.

A weakness of this study is the unproven correlation between computer models and deformity in humans. We used a computer model with standardized anatomic dimensions of the lower extremity. Such standardization would not be possible with cadaver extremities. Rotating plastic bone models would be subject to human error in attaining precise rotation and radiographic measurement. Because all the dimensions we assigned to our model have a range of normal values, the number of combinations of possible normal values for femoral and tibial lengths, femoral anteversion, neck-shaft angle, and mLDFA is extremely large. Measuring the effects of all these combinations in cadavers or patients would be impossible. Theoretically, a patient with a mechanical axis at the medial upper limit of normal or the mLDFA at the upper limit of normal (less valgus) could tolerate more internal rotation of a subtrochanteric fracture but less internal rotation of a midshaft fracture before developing frontal plane malalignment. A patient with more than 15° anteversion would have less effect of external rotation and more effect of internal rotation than our model. Also, more anteversion would result in less posterior shift of the mechanical axis in the sagittal plane. Because osteoarthritis has a multifactorial etiology including age, body weight, and ligamentous pathology, we do not conclude that all malrotated femurs with frontal plane mechanical axis deviation or a mLDFA greater than 1 standard deviation from the mean will develop arthritis; rather, our study indicates that malrotation of certain magnitudes in our model results in femoral deformity greater than 1 standard deviation from the mean, depending on the level of the simulated fracture, and could cause eccentric weight-bearing at the knee.

The model we analyzed was a transverse fractured femur with normal anatomic parameters. The results of this study may not be applicable for an osteotomy of the femur performed for a congenital deformity, where abnormal anatomic parameters, such as antetorsion, exist.

The effect of the posterior shift of the weight-bearing axis with femoral external malrotation is also theoretical. A gait study and oxygen consumption study would confirm our conclusion that this shift of the weight-bearing axis may affect gait, but this type of study cannot be done ethically. Studying patients whose extremity was inadvertently nailed in external rotation would require a preinjury gait study and would need to consider the effect of the concomitant soft-tissue injury on the lower extremity.

In conclusion, this study's 3-dimensional computer modeling demonstrates the complex relationship between femoral rotation and parameters of knee joint orientation and lower extremity alignment. Malrotation of a femoral diaphyseal fracture may not be just a cosmetic deformity, but could possibly cause arthritis or impaired function. In our model, internal rotation of a subtrochanteric fracture greater than 30°, internal rotation of a midshaft fracture more than 45°, or external rotation 30° or greater of a supracondylar fracture resulted in frontal plane malalignment. External rotation of a supracondylar fracture 45° or greater resulted in frontal plane knee joint malorientation. External rotation of any degree resulted in posterior shift of the weight-bearing axis in the sagittal plane, with increasing posterior shift occurring with increasing external rotation. This posterior axis shift may result in increased quadriceps action and trunk shift during gait and quiet stance.

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