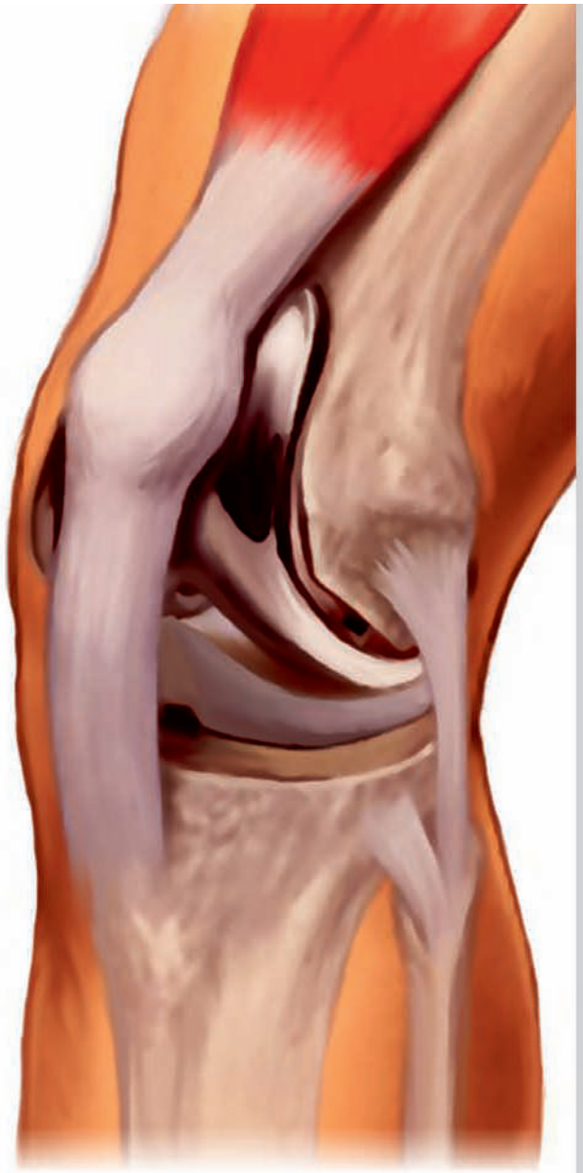


2

Alignment? How Do We Measure It?

Andrea Baldini, Francesco Traverso

Chapter Outline

INTRODUCTION

Achievement of correct limb alignment and the balance of the soft tissue envelope are the main objectives of the surgeon during total knee arthroplasty (TKA). Alignment of TKA should be considered and measured in all the spatial planes. The aim of this chapter is not to define what the correct alignment for each TKA is, since there will be some subtle variants based on surgical technique and implant design. Instead, our objective is to review existing described methods for measuring TKA alignment in each of the three planes.

Definition of Planes

By convention, the anatomical description of the body is in the erect position (Fig. 1). The median plane is an imaginary vertical plane of section that passes longitudinally through the body and divides it into right and left halves. Any vertical, longitudinal plane through the body that is parallel to the median plane is called a sagittal plane. The sagittal planes are named after the sagittal suture of the skull, to which they are parallel. The vertical, longitudinal plane at right angles to the sagittal plane, and dividing the body into anterior and posterior portions is called the coronal (or frontal) plane. The term horizontal plane refers to a plane at a right angle to both the median and coronal planes: it separates the body into superior and inferior parts. This is often called an axial plane. The term transverse means at a right angle to the longitudinal axis of a structure. Thus, a transverse section through an artery is not necessarily horizontal. A transverse section through the hand is horizontal, whereas a transverse section through the foot is coronal.

In this chapter, we will refer to the coronal, sagittal and axial planes as the three planes for the knee joint which is, by convention, in the vertical position with the patella anteriorly directed (Fig. 1).

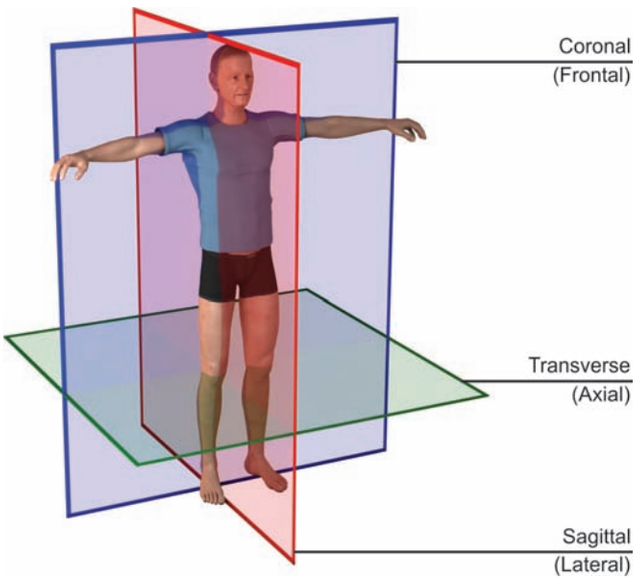


Figure 1 Anatomical description of the human body with definitions of the three spatial planes

Standard Postoperative Assessment and the Need for a Better Insight

Measurements of postoperative TKA alignment is based on the assessment of the components position relative to the bones of the lower limb. A number of axes are described on the three anatomical planes. The "Knee Society Total Knee Arthroplasty Roentgenographic Evaluation and Scoring System" has been developed to uniform radiographic reports of TKAs.[37] In addition to measurement of knee alignment and component position, the system has a numerical score for the prosthetic interface which assesses the quality of fixation (Fig. 2). Prosthetic position is estimated by a system of angle measurements. Alignment of the implant components in the coronal and sagittal planes is described as the resultant angle between the component and the longitudinal mid-medullary lines on a 91.44 cm cassette roentgenogram. This system enabled, for two decades, a uniform data collection in different institutions using various implant types. A recent study evaluated the reproducibility of this system with measurements examined by three independent experienced radiologists.[7] High interobserver correlation was calculated for the prosthetic femoral and tibial component angles. Femorotibial (FT) shaft angle measurements were significantly different between observers. For measurement of radiolucent lines, interobserver correlation was low for all components. High interobserver correlation for the patellar angle and for patellar subluxation and dislocation evaluation was found. On the contrary for the assessment of patellar shift and height, a low interobserver correlation was observed. The authors concluded that single component angles analyzed using the Knee Society (KS) system had sufficient reproducibility to be used in the clinical practice, while the method for assessing patellar shift and height, as for radiolucent lines should be reconsidered.

The improvements in knee implants positioning which has been brought by new technologies such as computer navigation or patient specific instruments, has evidenced the need for a higher level of precision and detail than those obtained by the simple analysis of two short limb X-rays.

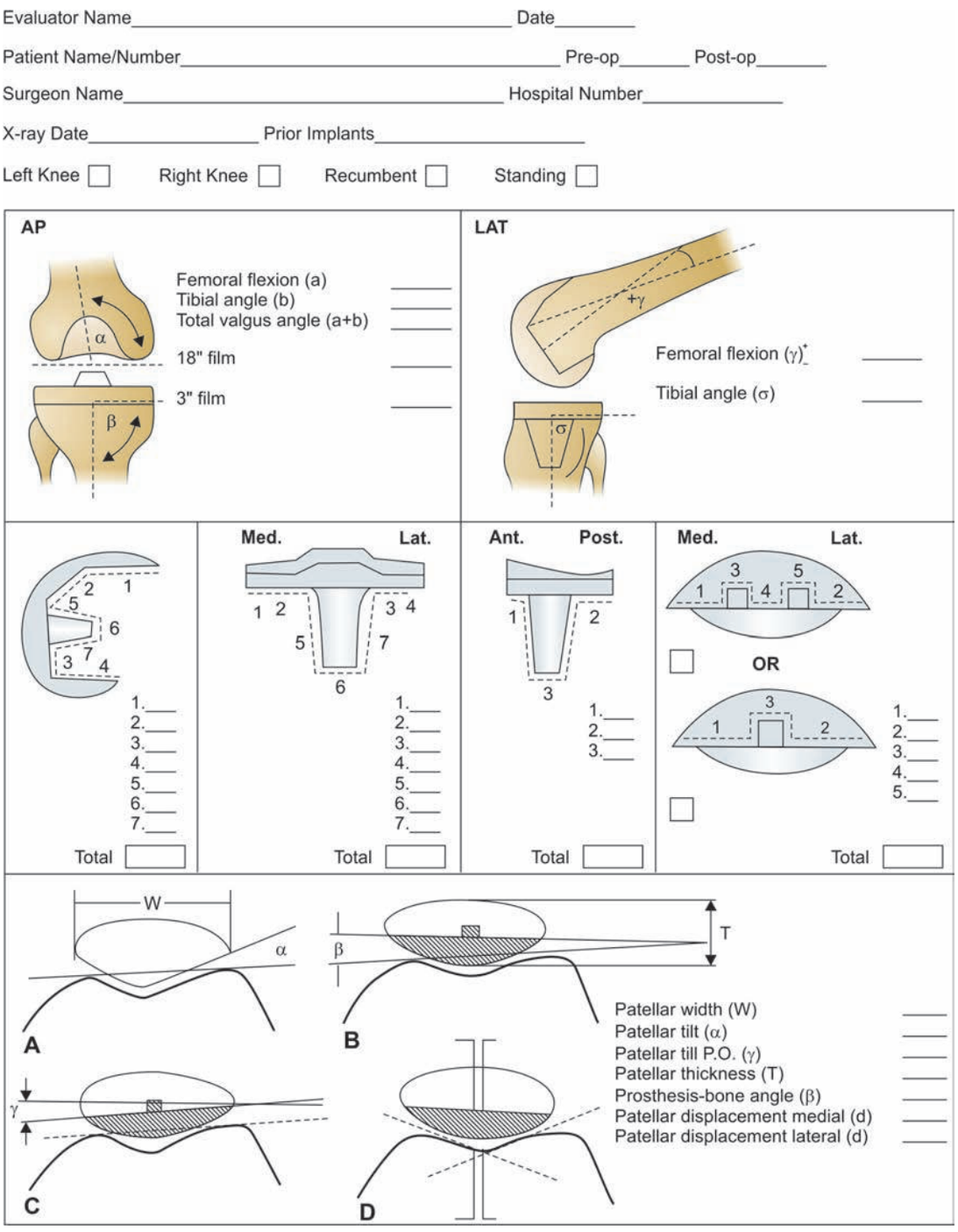


Figure 2 The knee society total knee arthroplasty roentgenographic evaluation and scoring system[37]

Other than for scientific purposes, a careful assessment of TKA components position and fixation enables the surgeon to understand the possible origin of symptoms when analyzing the so-called unexplained painful TKA.

KNEE CORONAL (OR FRONTAL) PLANE ASSESSMENT

Patient Positioning

Precise patient positioning is crucial to achieve good accuracy in radiographic measurements in the coronal plane. A number of studies analyzed the influence of knee joint flexion or limb rotation on angular measurements in the coronal plane.[47,54,73,101] External rotation of the limb will increase the varus angulation of the knee, while internal rotation will decrease this tendency. The magnitude of these variations is amplified if the knee is not in full extension. Jiang and Insall quantified 2.5° angulation changes when malrotation ranges from 20° of external to 20° of internal rotation (Fig. 3).[55] Oswald, in a cadaver model, calculated a 0.2° change in coronal plane angulation for every 5° of limb rotation from the neutral position.[73] This phenomenon is mainly related to the sagittal bowing of the femur, while the tibia is less affected by deformities in that plane.[54,73]

Special frames have been developed to control the ideal patient position, particularly in the frontal plane.[29-31] These systems show good reproducibility and accuracy in patient positioning but their use did not reach a broad clinical use. Wright et al. noted that long-leg radiographs taken without special frames but with a similar degree of care are accurate enough for assessing the mechanical axis.[109]

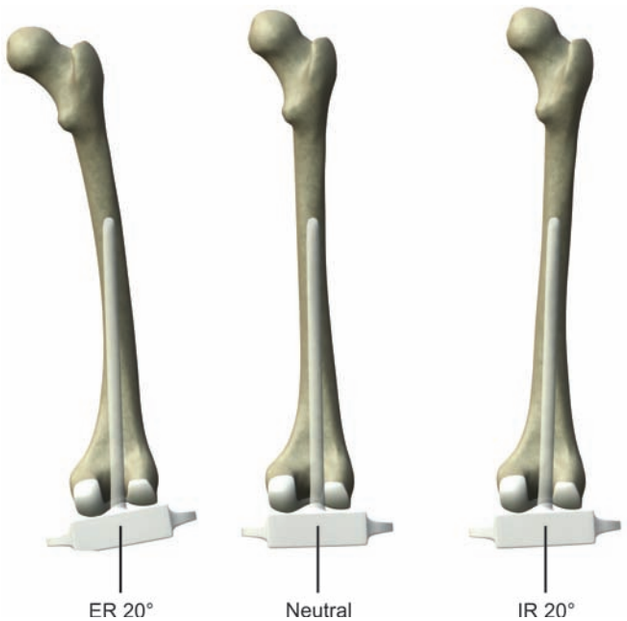


Figure 3 Reproduction according to Jiang et al. of the influence of limb rotation on coronal alignment[54]

Ideally, full-limb anteroposterior (AP) roentgenograms are obtained using a 129 x 36 cm (or 14 x 51 inches) cassette with a graduated grid. With digital radiology, images at three different levels of the lower limb are obtained in three separate 35 x 43 cm (14 x 17 inches) cassettes and then combined through digital processing. A graduated, lead-loaded acrylic filter can be placed in front of the collimated X-ray beam so that the hip and ankle joints can be visualized with minimal distortion. The lower extremities are fully extended and positioned so that the tibial tuberosities and the patellae (if not subluxed) are facing forward. Errors in excessive external rotation of the limb are more common and they should be avoided aligning the second metatarsal ray of the foot perpendicular to the plate (Fig. 4).[47] Both feet can be close to each other, or preferably, 30 cm apart in order to ensure that the tibiae are vertical and facing forward with neutral rotation.[45] The X-ray beam is centered at the knee joint level at a distance of 240 cms (8 feet) to minimize distortion. Centering the X-ray beam at the knee joint is not as important as fitting both the hip joint and ankle joint on the film.[95] A setting of 30 mA per second and a kilovoltage of 75 kV is used dependent on limb size.[45,71] The patient is asked to distribute weight evenly between the limbs and maintain this posture throughout. Radiographic positioning in the frontal plane under weight-bearing conditions is preferable after TKA because it allows for a comprehensive analysis of the magnitude and origin of limb malalignment.[88] Moreover, weight-bearing AP roentgenograms of a limb with a malaligned TKA will give some information about the soft tissue status having the convex part of the deformity under tension.

Short versus Long-Leg Radiograms

Frontal plane X-ray evaluation of the KS roentgenographic evaluation and scoring system is done on a short AP knee film (14 x 17 inches cassette). In the KS form, an anatomic FT angle called *Total Valgus Angle* is obtained with the sum of the femoral anatomic angle α and tibial anatomic angle β (Fig. 2). The form considers angles calculated with short and long films. Angles alpha (α) and beta (β) are not clearly defined in this form (Fig. 2). Angle α, as depicted on the KS form, is an anatomic femoral angle which is formed between a tangent line to the medial and lateral condyles of the femoral component in extension and a distal femoral anatomical line. Angle β, as depicted on the KS form, is an anatomic tibial angle which is formed between a tangent line to the tibial component baseplate in extension and the proximal tibial anatomical line. This angle calculation is not taking into account the influence of ligamentous laxities on

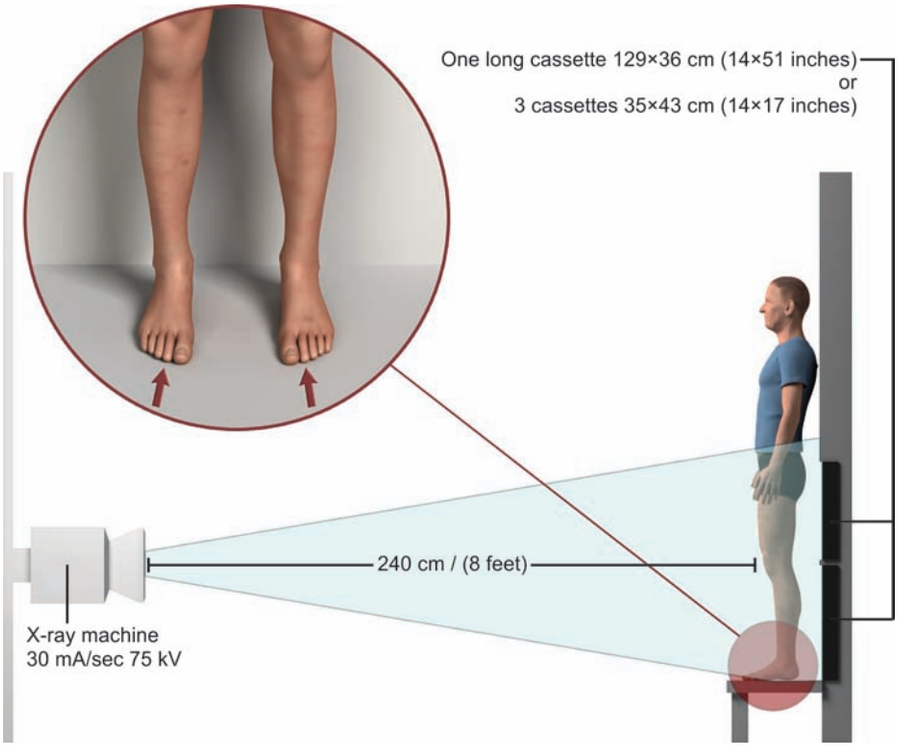


Figure 4 Patient positioning for a coronal full limb radiogram

weight-bearing limb alignment (Fig. 5). The definition of the anatomical axis of the femur and tibia from standard radiographs has several inherent inaccuracies. Standard short knee radiographs offer a limited distance above and below the knee to plot an axis for measuring the tibiofemoral angle. In some instances, the radiographic plate is even not centered precisely at the joint line level. This provides only a short segment on one side of the joint arthroplasty to plot the anatomical axis. In these instances, the anatomical axis of the femur and/or tibia may not be colinear with a point equidistant from the conical margins 10 cms above or below the joint.[81] Bowing of the femur and/or the tibia beyond that portion of bone revealed on short radiographs is the primary source of error of the measurements.[53] Younger et al. developed a mathematical formula using trigonometry in order to determine the position of the knee with respect to the mechanical axis when a short film is used. This calculation is based on data obtained from a preoperative long film where the axis are drawn and calculated. The purpose of their equation was to determine the postoperative position without having to repeat the long-leg radiograph.[113] In a recent study by Skyttä et al., the standard AP knee radiograph appeared to be a valid alternative to the hip-to-ankle radiograph for determining knee coronal plane alignment in routine follow-up after TKA.[94] However,

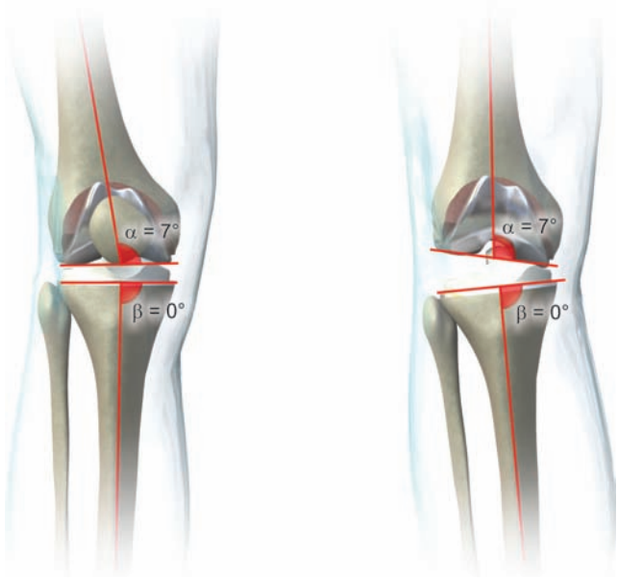


Figure 5 Total valgus angle (α+β) as depicted in the Knee Society Total Knee Arthroplasty Roentgenographic Evaluation and Scoring System does not take into account the influence of ligamentous laxities on weight-bearing limb alignment[37]

the hip-to-ankle radiograph alone provides accurate information on weight-bearing mechanical axis in patients with suspected lower limb malalignment. The authors concluded that they recommend assessing the mechanical axis after TKA with a long-leg radiograph at least once. However, the long-leg radiographs should be replaced in routine follow-up by standard knee films which involve less radiation and costs. In case of conflicting clinical and radiographic findings, they recommended the use of long-leg radiographs.[94]

Computer-assisted TKA literature has recently criticized the reliability of long-leg radiographs in measuring postoperative TKA alignment.[25,84,110] A number of papers demonstrated the reliability of properly performed long-leg radiographs. Recently, the paper by Skyttä et al. criticized previous studies which have inappropriately used correlations to assess the reproducibility of the hip-to-ankle radiographs.[95] They determined the reliability of the hip-to-ankle radiograph using a sophisticated statistical method through a Bland-Altman analysis. Two consecutive hip-to-ankle radiographs were obtained in 52 patients after TKA. There was an excellent agreement between mechanical axis angles, tibiofemoral angles, and femoral and tibial component alignment in the two radiographs. There was also an excellent agreement between all intra- and inter-observer analyses. The hip-to-ankle radiograph appeared to be a reliable and reproducible means for determining the alignment of the knee in the coronal plane after TKA.[95] Oswald and Jakob performed a comparison between long-leg radiographs and computerized calculations of angles on CT scans on a series of 38 bones. This showed a high precision of measurement on standard radiographs in neutral rotation and on bones without osteoarthritic deformations. The authors assumed that preoperative planning, and postoperative TKA measurements on long-leg radiographs, is very precise if neutral rotation of the affected limb is guaranteed.[73]

Evaluation of Axis

Evaluation of axis on the coronal plane after TKA follows the same principles of the normal unreplaced limb. Compared to normal or arthritic joints, measurements on the coronal plane after TKA are facilitated because the geometric center of the knee joint has more recognizable landmarks being the center of the femoral and tibial components. On each bone, a mechanical (axis between the proximal and distal joint centers) and an anatomical (axis through the mid-diaphyseal line) axis is identified,

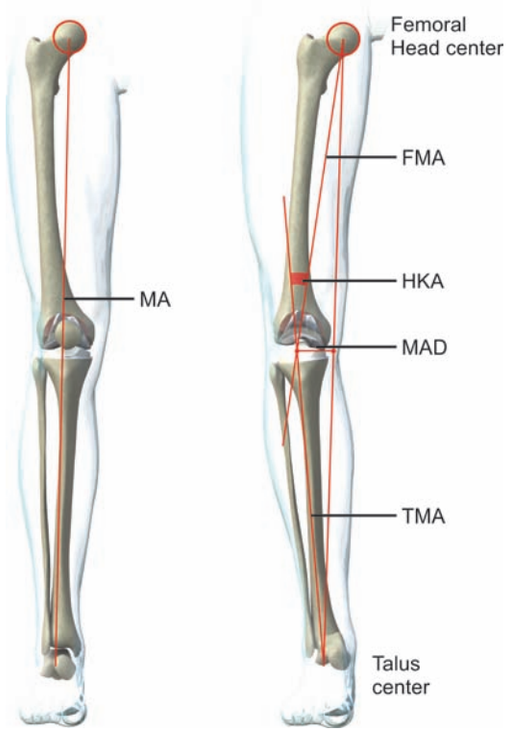


Figure 6 Lower limb mechanical axes and angles
FMA, femoral mechanical axis; TMA, tibial mechanical axis; HKA, hip-knee-ankle angle; MA, mechanical axis of lower limb; MAD, mechanical axis deviation

and an overall limb mechanical (or hip-knee-ankle—HKA) axis and anatomical FT angle can be calculated (Fig. 6).

The following axis and angles are part of the standard coronal plane measurements after TKA:

Femoral mechanical axis (FMA) is the axis between the center of the femoral head identified using Mose circles and the center of the femoral component trochlear notch.[72]

Tibial mechanical axis (TMA) is the axis between the center of the talus and the center of the tibial component.

Hip-Knee-Ankle (HKA) angle is the angle between the femoral and tibial mechanical axis.

Lower limb mechanical axis (MA) is the axis between the femoral head center and the talus center.

Mechanical axis deviation (MAD) is the perpendicular distance between the MA and the center of the replaced joint. The relationship between the MA and the knee center identified by the MAD distance is linear. This relationship can be calculated using trigonometry. For each degree of varus or valgus shift from the accepted norm, the MA shifts approximately 5 mm from the center of the knee.[81]

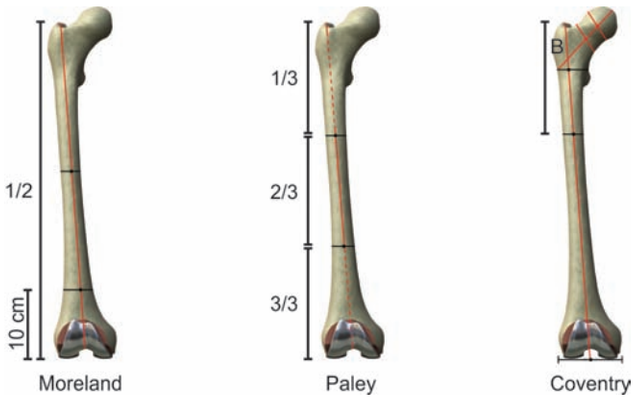


Figure 7 Femoral anatomical axes according to Moreland, Paley, and Coventry[45,71,76]

Femoral Anatomical (Shaft) Axis

Femoral anatomical (shaft) axis (FSA) is the axis between two points of the femoral shaft. There is no agreement in the literature on which points we should refer to. We will describe the most popular ones (Fig. 7).

Moreland's method:[71] The first point (shaft center 1) is 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. The second point (shaft center 2) is located 10 cm above the surface of the knee joint midway between the medial and lateral surfaces. In normal femurs when this axis is extended proximally, it usually passes through the piriformis fossa, and when extended distally, it intersects the knee joint line generally 1 cm medial to the joint center.

Paley's method:[76] The femoral anatomical axis follows the mid-diaphyseal path. Points are located in the geometric center of the proximal and distal endings of the straight mid-diaphyseal femoral canal (no distances are mentioned).

Coventry's method:[45] This method defines the entire femur anatomical axis as a line (BK) between the knee joint center (midpoint of the tibial spine, halfway between the intercondylar notch) K and the intersection B of the femoral neck axis and the proximal femur anatomic axis. The proximal femur anatomical axis is a line (BF) between point B and the proximal one-third bicortical center of the femur F. The distal femur anatomical axis is a line (FaK) between point K and the distal one-third bicortical center of the femur Fa.

Femoral angle α [(corresponding to the anatomic medial distal femoral angle (aMDFA) of Paley)][37,76] is the angle formed between a tangent line to the medial and lateral condyles of the femoral component in extension and a distal femoral anatomical line.

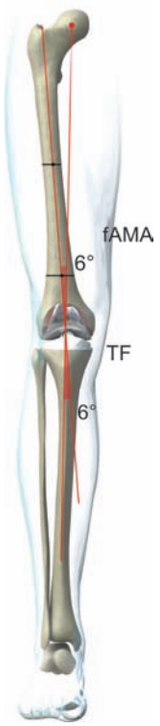


Figure 8 Tibiofemoral angle (TF) and relationship between the femoral anatomical and mechanical axes (fAMA)

Femoral anatomical mechanical angle (fAMA) is the angle between the femoral anatomical and mechanical axis. The two axes intersect at the knee joint level when the rotation of the femur is neutral. In external rotation of 20° and 10°, the intersection lies distal to the femur 4 cm and 1 cm respectively. In internal rotation of 20° and 10°, the intersection lies proximal to the femoral condyles 5.1 cm and 3.3 cm respectively.[54] Based on these data, Jiang and Insall developed a flowchart with the suggested angles of correction for each measured fAMA based on the different rotations of the femur calculated by the intersection level of the two axis (Fig. 8).

Tibial Anatomical (Shaft) Axis

Most of the authors assume that the tibial anatomical axis coincides with its MA.[45,73,81] Other authors found different definitions which are listed here (Fig. 9):

Paley's method:[75,76] The tibial anatomical axis follows the mid-diaphyseal path. Points are located in the geometric center of the proximal and distal endings of the straight mid-diaphyseal tibial canal (no distances are mentioned). According to Paley, the tibial mechanical and anatomical axes are parallel but not the same. The anatomic axis is

Figure 9 Tibial axes: relationship between tibial anatomical and mechanical axes. Tibial shaft (anatomical) axis (TSA) and tibial mechanical axis (TAM). If we consider the TSA as the "mid-diaphyseal" axis, TAM and TSA are not the same axis as you can see in this example. Diaphyseal tibial curves make TSA a highly variable axis

slightly medial (10 ± 5 mm) and intersects the normal knee joint line at the medial tibial spine. Distally, the anatomic axis intersects the talus medially to its center (4 ± 4 mm).

Oswald's method:[73] The tibial anatomical axis is defined as the connecting line between the center of the tibial plateau and the midpoint of the outer shaft diameter at 20 cm distance from the tibial plateau.

Tibial angle β (corresponding to anatomic medial proximal tibial angle (aMPTA) of Paley)[37,75] is the angle formed between a tangent line to the tibial component baseplate in extension and the tibial anatomical axis.

Tibiofemoral (TF) angle is the angle formed between the femoral and tibial anatomical axis (Fig. 8).

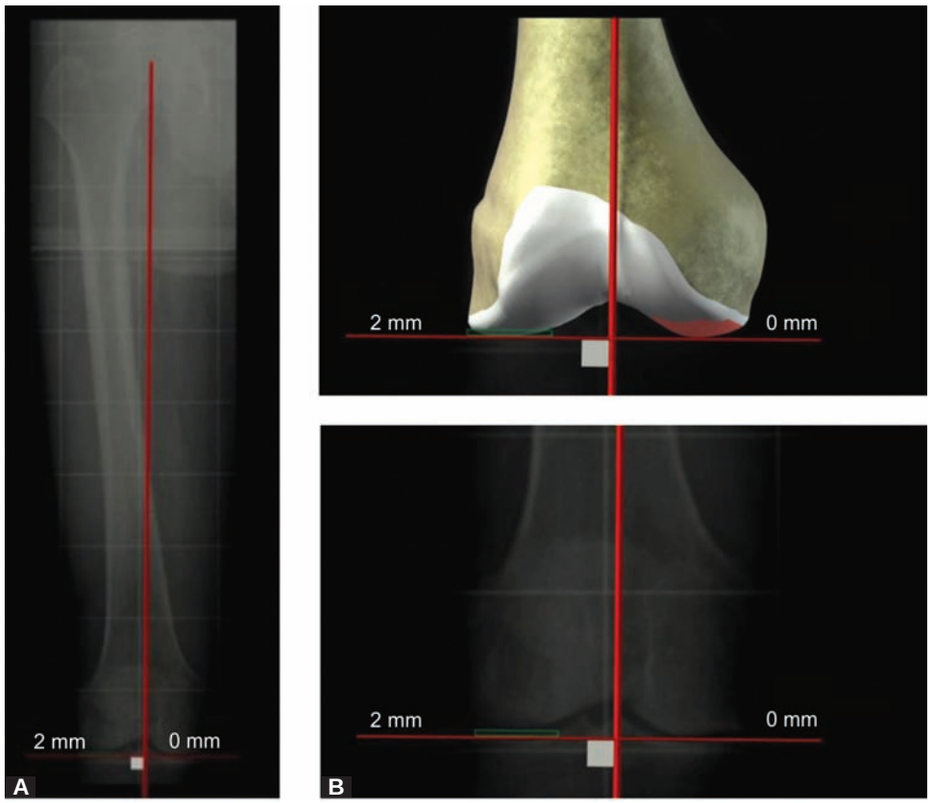
Use of the Femoral Mechanical Axis to Plan the Distal Femoral Cut without IM Instruments

When dealing with extra-articular deformities of the femur or when an intramedullary cutting jig, which are normally utilized in TKA, are impossible to be used (e.g. presence of a long hip stem or retained hardware), it can be useful to employ extramedullary (EM) instruments for the distal femoral resection. The rationale behind the EM instrument the authors developed is based on calculation of the resection plane according to the preoperative radiographic measurements and considering a bone cut perpendicular to the MA of the femur (ExtraBone®, Waldemar link, Hamburg, Germany) (Fig. 9). If cartilage, which is not visible on X-rays, is present on one of the condyles, it has to be removed at the beginning of the surgical procedure. Data obtained from templating the preoperative long limb radiographs were reproduced on the two paddles of the distal femoral cutting jig which is aligned in the sagittal plane with the anterior cortex of the femur using an L-shaped tool (Figs 10 A and B). The level of resection and the varus-valgus orientation of the resection is established by moving the two paddles according to templated data (Figs 11 A and B). In a series of 100 TKA randomized to either use the IM or the ExtraBone® system, the authors showed excellent accuracy of resection on both the coronal and sagittal plane with the latter system.[10] Accuracy of the preoperative measurements for this EM system use is less dependent from limb malrotation because the relationship between the distal femoral condyles and the perpendicular line to the FMA does not significantly change with rotation. Flexion contracture of more than 10° is a contraindication to the use of this system because it does not allow the definition of the distal contour of the femoral condyles for the required calculations.

KNEE SAGITTAL (OR LATERAL) PLANE ASSESSMENT

Patient Positioning

As for the coronal plane, precise patient positioning is crucial for the sagittal imaging of the knee. The sagittal or lateral knee radiogram can be performed either with or without limb weight-bearing. In the unloaded views, the patient lies on the affected knee, contralateral limb with the knee flexed, and anteriorly positioned (Fig. 14). The affected knee is flexed 30°, with the patella perpendicular to the cassette and the limb parallel to the radiologic table. The contralateral hip and limb are placed in a slight posterior rotation, allowing an appropriate lateral bearing on the table for the affected knee.[80] For lateral weight-bearing, the load is placed almost entirely on the leg being examined, the knee in

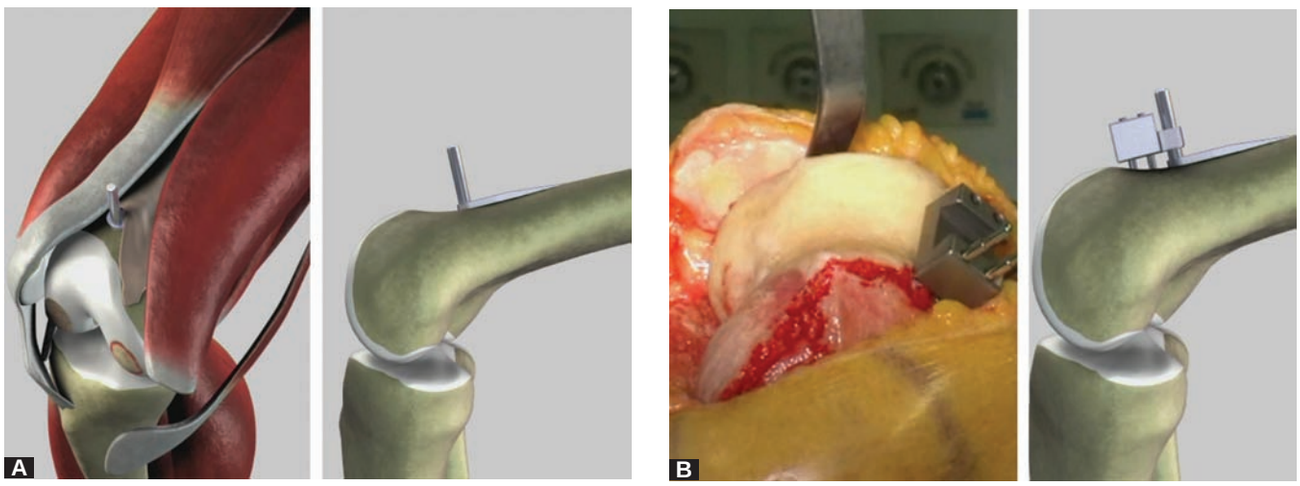


Figures 10 A and B Technique for preoperative measurement of the distal femoral condyles offset[10]

30° of flexion, contralateral limb placed posteriorly with the patient holding the semi-squatted position.

Both views are preferably obtained after fluoroscopic monitoring in order to check the proper joint position.[12,19,55]

Good positioning on the X-rays should achieve an image of the two femoral condyles superimposed. The bowing of the femur and tibia above and beyond the knee joint should be included as much as possible with the use



Figures 11 A and B (A) Positioning of the L-shaped instrument under the synovial layer over the anterior femoral cortex; (B) First block fixed to the femur and controlling the flexion-extension plane of the resection[10]

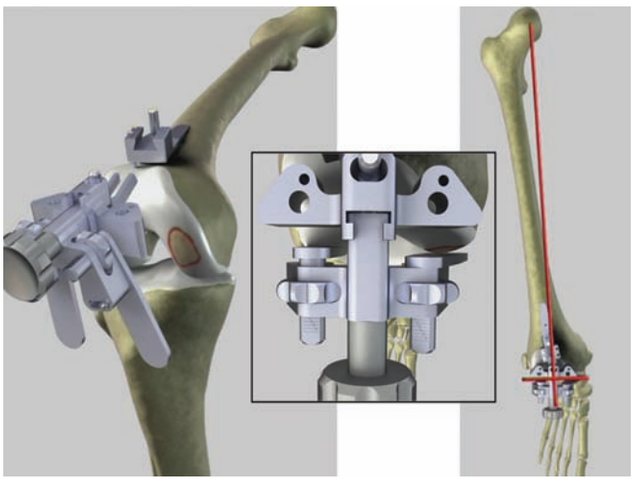


Figure 12 Main Extrabone® (Waldemar-Link, Hamburg, Germany) instrument insertion with regulation of the medial and lateral paddles according to the preoperative planning[10]

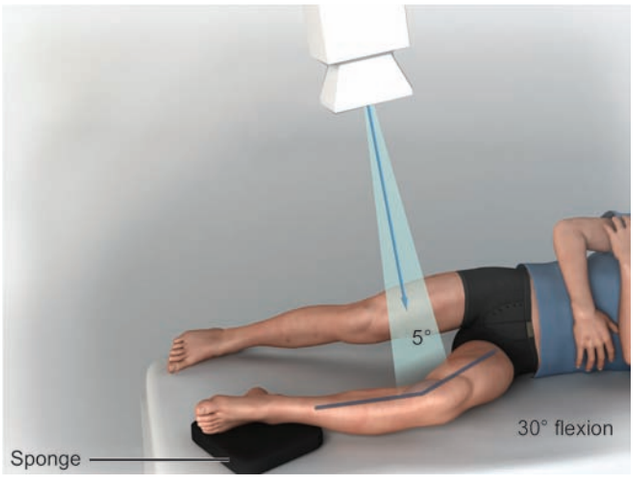


Figure 14 Patient positioning for a sagittal knee joint radiogram

of 24 x 30 cm (10 x 12 inch) cassette. Patella should be tangent to the beam to enable to detect its height relative to the joint line.[19,80] Fluoroscopic monitoring helps achieving condyles overlapping for proper alignment measurements. If fluorocontrol is not available, a 3–5° external rotation of the tibia should be attempted to overlap the contour of the medial and lateral femoral condyles.[76] This view is obtained using 24 x 30 cm (10–12 inch) cassette, and the beam is directed 5° cranially, placed 97 cm (39 inch) from the cassette and centered between the patellar apex and 1 cm distal to the medial condyle.[80,108]

Paley proposed the use of 71 or 91 cm cassettes with the beam centered on the knee joint placed 305 cm (10 feet) from the patient for the lateral full length bearing view. His aim was to assess the mechanical and anatomic axes of the limb in the sagittal view.[75]

Chung et al. developed a new technique for obtaining a true lateral view of the whole femur in which the femoral head is seen clearly and the contours of both femoral condyles are viewed as one line. Patients place their thigh on a 17 inch x 17 inch digital flat detector in a diagonal position, and the X-ray beam tube then was tilted to a 15° cephalad position (Fig. 15).[26]

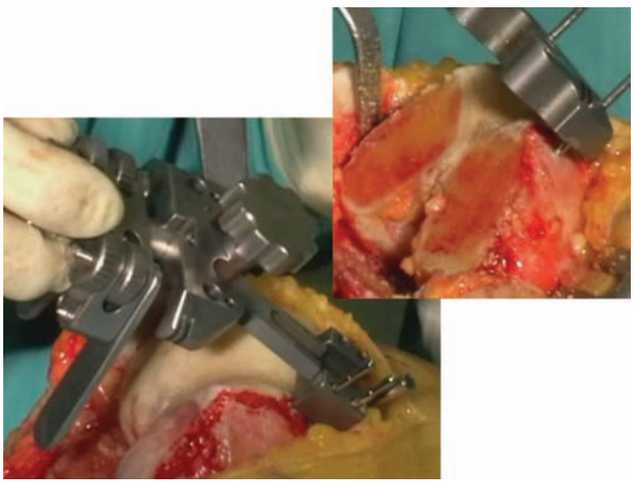


Figure 13 *In vivo* Extrabone® (Waldemar-Link, Hamburg, Germany) instrument *in situ*, and distal femoral resection performed without violating the femoral canal[10]

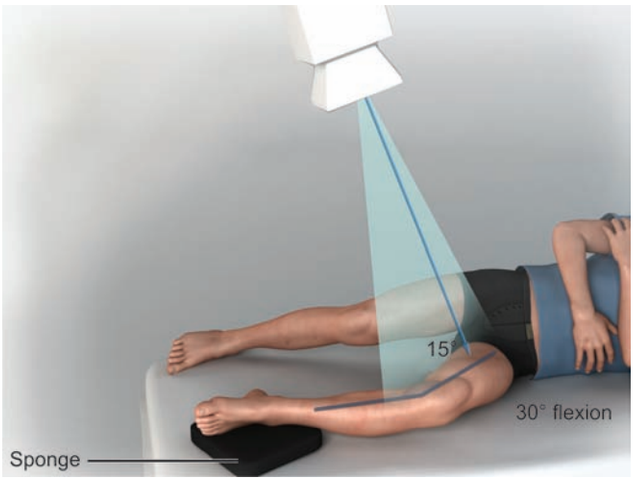


Figure 15 Patient positioning for a sagittal full limb radiogram

Figure 16 Femoral "flexion" (or Y angle) according to the Knee Society Form[37]

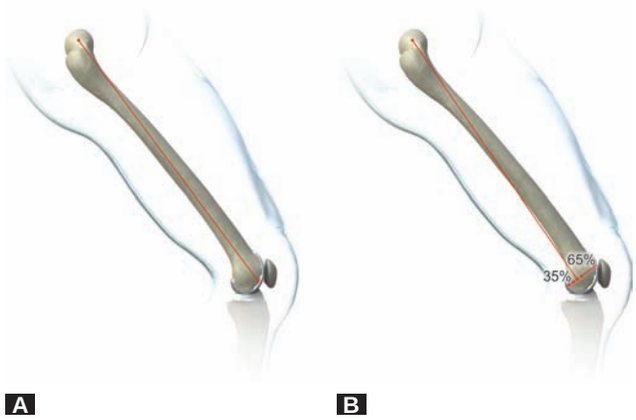


Figure 17 Femoral sagittal mechanical axes A and B

Evaluation of Axes

Femoral Sagittal Anatomical and Mechanical Axis

Sagittal plane X-ray evaluation of the KS roentgenographic evaluation and scoring system is based on data obtained on a short lateral knee film (14 x 17 inches cassette).[37] In the KS form, the anatomical sagittal angle of the femoral component is named as "Femoral flexion" (or angle Y). This value is obtained by the angle of the femoral sagittal anatomic axis and the femoral component sagittal axis (Fig. 16).

Femoral sagittal anatomical axis on a short view is obtained connecting the furthest midpoint on the diaphysis visible on the X-ray and the second is a midpoint 10 cm above the joint line. The femoral component sagittal axis is the perpendicular to the plane of the distal condyle of the implant which can be represented by the resection plane of the distal femoral cut or from the plane of the intercondylar box of the implant if this has a straight linear design.

Femoral mechanical sagittal axis is the axis between the center of the femoral head identified using Mose circles and the center of the femoral component on the sagittal plane.[70,72,75]

Two sagittal mechanical axes are described specifying the exact reference points on the distal femur (Fig. 17):

Mechanical axis 1 is defined as the line connecting the femoral head center to a point 1 cm anterior to the end of Blumensaat's line (a line extending through the intercondylar notch on a lateral view of the knee),[22] which is used as the registration point for the distal femur center in many navigation systems, including VectorVision1 (BrainLAB, Redwood, WA) and the Stryker Navigation System (Stryker Howmedica Osteonics, Allendale, NJ).[14,24]

Mechanical axis 2 is defined as the line connecting the femoral head center and a point identified 65% posteriorly on the line between the anterior cortex and the most prominent point of the posterior medial femoral condyle. The authors assumed mechanical axis 2 was equivalent to the sagittal MA used in the OrthoPilot1 navigation system (B. Braun-Aesculap, Tuttlingen, Germany).[52]

Anatomical sagittal axis of the entire femur (and not just the distal portion) is obtained by connecting the sagittal centers of the proximal, central, and distal femoral diaphysis on the sagittal full limb X-ray (Fig. 18).[76,111] This produces a segmented line which takes into account the femoral sagittal bowing (which ranges from 4°–9°).[26,92]

Anatomical sagittal axis of the distal femur. Two axes are described (Fig. 18):[26,92]

- The "Distal anterior cortex axis" is defined as the line connecting two points on the anterior cortex at 5 cm and 10 cm proximal to the knee line.
- The "Distal medullary axis" connecting midpoints of the outer cortical diameter at 5 cm and 10 cm proximal to the knee line.

A Korean study found an average angular difference of 2° (range 0–4°) between the mechanical and distal anatomical sagittal femoral axis. For each 1° of anterior femoral bowing, the angular deviation between the mechanical and distal femoral axes increases nearly 0.5°.[26] Distal anterior cortex axis has an average angular difference to the mechanical sagittal axis of 4° (range 0–11).[92] Femoral bowing can also be evaluated by

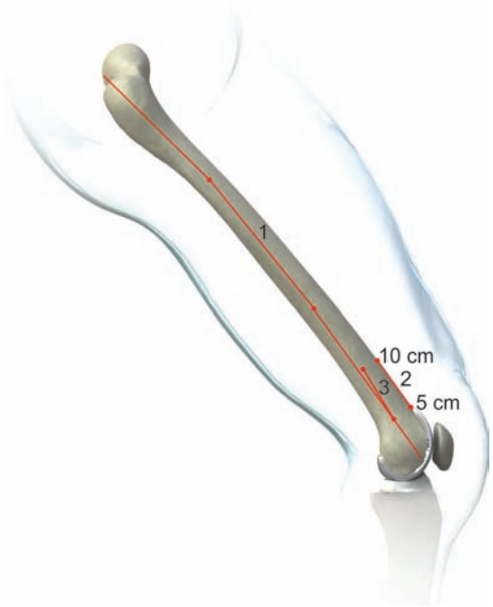


Figure 18 Femoral anatomical sagittal axes. (1) Femoral sagittal axis of the entire femur; (2) Distal anterior sagittal femoral axis; (3) Distal medullary sagittal femoral axis

Figure 19 "Tibial angle" (or angle σ) according to the Knee Society Form

measuring the radius of curvature of the intramedullary canal of the proximal, middle and distal portions of the femur.[103,111]

Sagittal alignment of the femoral component has to take into account the anatomy of the distal third of the femur, and according to the KS evaluation score, the neutral position of the femoral component has the distal condyles perpendicular to the anatomical axis of the distal femur.[19] Computer navigation techniques which calculate the mechanical axis on the sagittal plane may hyperextend 2–4° the femoral component relative to the distal anatomical sagittal axis.[27]

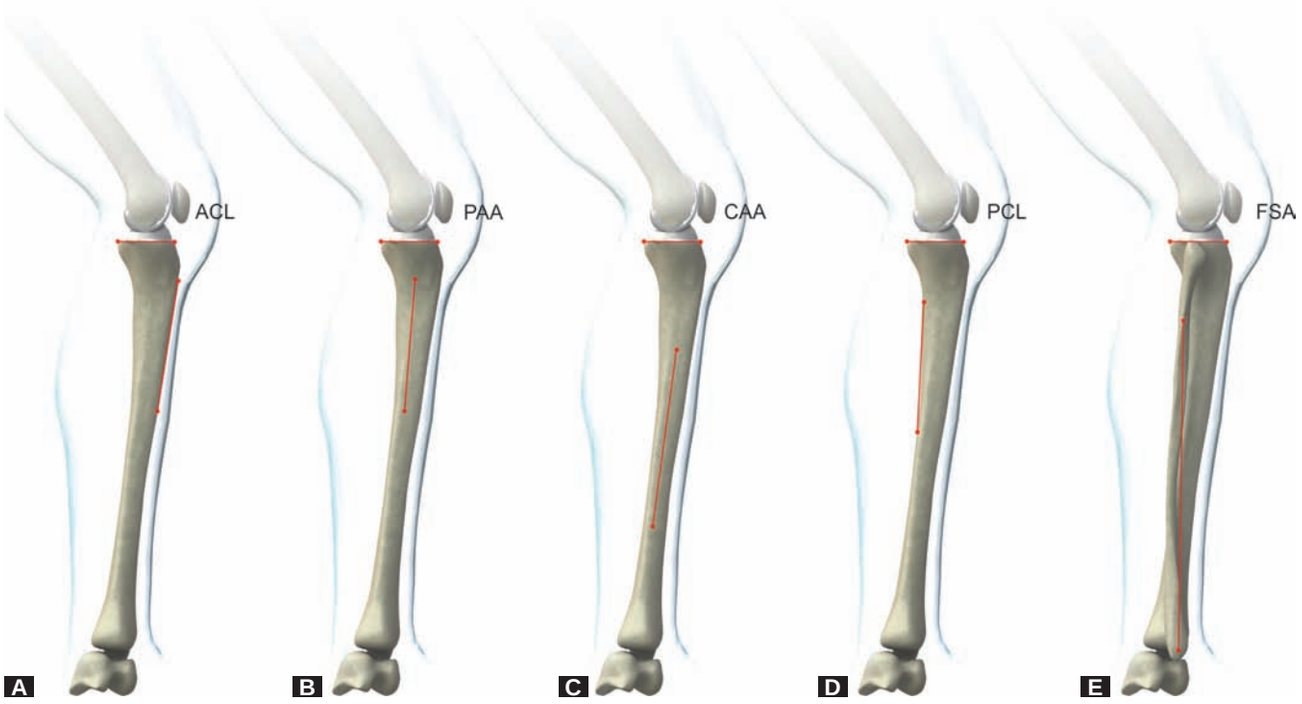
Tibial Sagittal Anatomical and Mechanical Axis

On the tibial side the angle value named "Tibial angle" (or angle σ) is the equivalent of the so-called "tibial slope". This angle, as depicted on the KS form, is an anatomic sagittal tibial angle which is formed between a tangent line to the tibial component baseplate and the sagittal tibial anatomical line which is obtained connecting the furthest midpoint on the diaphysis visible on the X-ray and the second is a midpoint 10 cm below the joint line.[11,37,43,44,59,76,78,81] There is little consensus on the ideal reference for measuring the posterior slope, and many studies did not reveal detailed information of the reference used in the study (Fig. 19).

As the articulating point changes instantly with the degree of flexion, the same definition for the coronal MA might not be applied to the sagittal tibial mechanical axis.[30] However, defining the sagittal MA, as the connecting line between the midpoints of the tibia plateau and the tibia plafond, which is similar to that of the coronal MA, comes with several advantages.[35,73] It is not influenced by the intervening diaphyseal deformity, the bowing of the diaphysis, or individual anatomical variations, and the orientation of the entire bone between the proximal and distal joint can be described efficiently.

Five anatomical landmarks for sagittal tibial anatomical axis are described (Fig. 20):[112]

- The anterior cortical line (ACL) of the tibia is the line connecting the two points on the anterior cortex of the proximal tibia at 5 cm and 15 cm distal to the knee joint line.
- The proximal anatomical axis (PAA) is the line connecting midpoints of the outer cortical diameter at 5 cm and 15 cm distal to the knee joint.
- The central anatomical axis (CAA) is the line connecting midpoints of the outer cortical diameter at 10 cm distal to the knee joint and 10 cm proximal to the ankle joint.
- The posterior cortical line (PCL) of the proximal tibia is the line connecting the two points on the posterior cortex of the tibia at 5 cm and 15 cm distal to the knee joint.



Figures 20 A to E Sagittal tibial anatomical axes. (A) The anterior cortical line (ACL); (B) The proximal anatomical axis (PAA); (C) The central anatomical axis (CAA); (D) The posterior cortical line (PCL); (E) The fibular shaft axis (FSA)

- The fibular shaft axis is the line connecting midpoints of the outer cortical diameter of proximal and distal ends of the fibular diaphysis.

The PAA is equivalent to the reference suggested in the system of the American Knee Society, although it was not clarified explicitly in the evaluation form.[37]

In a large cohort of patients investigated with CT scans, the authors found that posterior tibial slope change markedly (from 7–12° on average) according to the reference axis used, but these axes showed significant correlations with each other and thus, may be used safely if differences with the MA are considered.[42] Utzschneider et al. compared MRI and CT scan to short lateral X-ray films. They found that considering the average values of the axes ACL and PCL as the proximal anatomical axis, they obtained reliable data just using the short film.[106]

Considering different papers, the natural slope angle has been calculated within the range of 5°–11°.[35,62]

Evaluation of Femoral Offset

Posterior Condylar Offset

Posterior condylar offset (PCO) is the maximal thickness of the posterior condyle, projected posteriorly to the tangent of the posterior cortex of the femoral shaft both for the un- and replaced knee (Fig. 21).[15] In a series of posterior cruciate ligament retaining TKA's analyzed under fluoroscopic control they found a significant correlation between operative restoration of PCO and maximal flexion. The more posterior condylar offset was decreased after operation, the more flexion was lost. For every 2 mm decrease in PCO, the maximal obtainable flexion was reduced by a mean of 12.2°. Restoration of PCO therefore has been recommended in PCL-retaining TKA.[15] However, the significance of PCO seems to differ according to the size of joints.[97] By Soda et al. a new parameter, the posterior condylar offset ratio, has been proposed (Fig. 21).[97] In a comparison between PCL substituting or retaining TKA, Arabori et al. found the PCO to be significantly correlated to flexion only in the group of PCL retaining TKA's.[4]

Anterior Condylar Offset

Anterior condylar offset (ACO) is the maximal thickness of the anterior condyle, projected anteriorly to the tangent of the anterior cortex of the femoral shaft both for the un- or replaced knee (Fig. 21).[27,38] Intraoperative measurements found an overall thickness of ACO

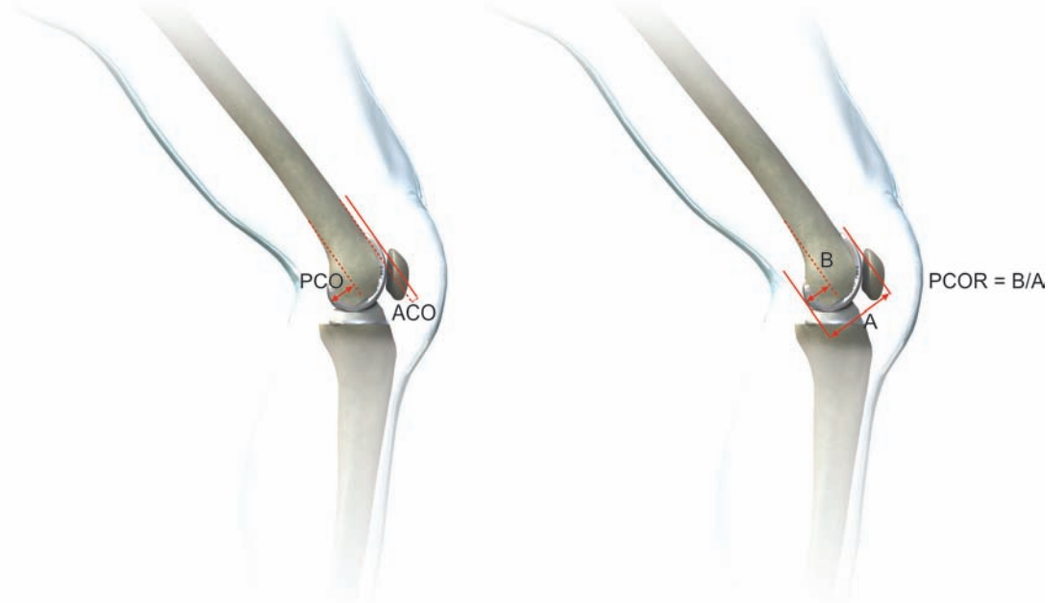


Figure 21 Posterior condylar offset (PCO), posterior condylar ratio (PCOR), and anterior condylar offset (ACO)

obtained from standard TKA anterior resection of 10.9 mm for men and 10.1 mm for women.[82] After TKA, the value of ACO can be different from preoperative with clinical implications. If ACO increases from the preoperative situation, this may result in a patellofemoral joint that feels tight or "overstuffed" after surgery with a limited postoperative range of motion.[29] Variations in the anterior aspects of the femur along with implant size constraints may increase trochlear groove height in the anterior compartment, increase the arc that the extensor mechanism must track, and thereby decrease flexion properties. Mihalko et al., in a cadaver study, found that after TKA the thickness of the replaced lateral and medial anterior flanges increased by 1.1 +/- 2.6 mm and 0.5 +/- 2.2 mm, respectively, whereas the change in trochlear groove thickness was 0 +/- 1.1 mm.[69] They calculated that a 2 mm and 4 mm buildup of the anterior cortex resulted in flexion loss of 1.8° and 4.4°, respectively. The change in the shape of the anterior aspect of the femur may have small effects on passive flexion but its clinical meaning on patients symptoms remains to be clarified.[69]

Measurements for Patellar Height

Of the several indices which can be used to measure normal patellar height, it is only possible after TKA to use those which are referencing of the tibia [Insall-Salvati (IS), Caton-Deschamps (CD), Blackburne-Peel (BP)].[20,23,48] Referencing of the femur is not applicable with the TKA implant in situ (Blumensaat, Bernageau).[18,21]

The most common methods described to evaluate patellar height are:

Insall-Salvati Index

The ratio between the length of the patellar tendon measured on its posterior surface from the lower pole of patella to its insertion on top of the tibial tubercle, and the length of the patella by definition measured over its greatest diagonal length. The normal value is 1.02 (SD 0.13) with less than 20% variation. Ratio higher than 1.2 indicates a patella alta, while under 0.8 suggests a patella baja.[48]

Blackbourne-Peel Index

The ratio between line A represented by the perpendicular distance from the lower articular margin of patella and the joint line level, and line B represented by the length of the articular surface of the patella. The normal value is 0.8 (range 0.65–1.38). Ratio higher than 1.2 indicates a patella alta, while under 0.6 indicates a patella baja.[20]

Caton-Deschamps Index

The ratio between the distance of the lower edge of the patellar joint surface to the upper edge of the tibial plateau (A) and the length of the patellar articular surface (B). Normal value is 1.0 (range 0.8–1.2). Ratio greater than 1.3 is highly suggestive of patella alta. Ratio lower than 0.7 is suggestive for a patella baja.[23]

The IS ratio is the most popular but it has a number of practical disadvantages. The point of attachment of

the tendon to the tibia is indistinct, and the length of the patella is not always an indication of the length of its articular surface, particularly when replaced. Rogers et al. assessed the reproducibility and accuracy of these ratios after TKA.[88] Two independent observers measured the films sequentially, in identical conditions, totaling 720 measurements per observer. Before and after the operation, there was greater interobserver variation using the IS ratio than when using the CD or BP methods. They concluded that the theoretical advantage of using the IS ratio in measuring true patellar height after TKA needs to be balanced against its significant interobserver variability and inferior reliability when compared with other ratios. The BP and CD indexes provide a more useful measure of the relationship of the patella to the trochlea but the articulation of the replaced joint has different features compared to the normal knee. For these reasons, a modified Caton index has been proposed by Aglietti et al. to be eligible for the prosthetic knee.[1] With this method, a line is drawn starting at the FT contact point and perpendicular to the anatomical axis of the tibia. AB, the distance between the reference line and the inferior pole of the patellar implant is the length; CD, proximodistal length of the bony patella. The resultant height is obtained dividing AB on CD. Patella was considered baja for values under 30%.[1]

Joint Line Height

The joint line of a TKA is defined as the line through the distal aspect of the femoral condyles. The level of the condylar aspect depends on the instantaneous degree of flexion of the articulation. The position of the joint line is the distance (on average 2.2 cm) from the proximal aspect of the tibial tuberosity (TT) to the joint line as described by Figgie et al.[32,40] Any post-TKA change in joint line position is measured as the difference between the preoperative and postoperative joint line position, and the value is negative if the joint line position had been lowered and positive if it had been raised.[40] The tibial tubercle may not be always well defined, for this reason Selvarajah et al. propose to use the same methodology but with the tip of the fibula's head instead of the TT.[92] Normal joint line values are 15.4 ± 5.4 mm above the fibular head in the sagittal plane and 13.9 ± 5.8 mm in the coronal plane.[57,91]

Joint line position is a complex three-dimensional concept and it should be assessed for all the joint aspects, anterior, distal and posterior, throughout range of motion, and individually for each compartment. 3D image-matching procedures are under investigation for this purpose.[89]

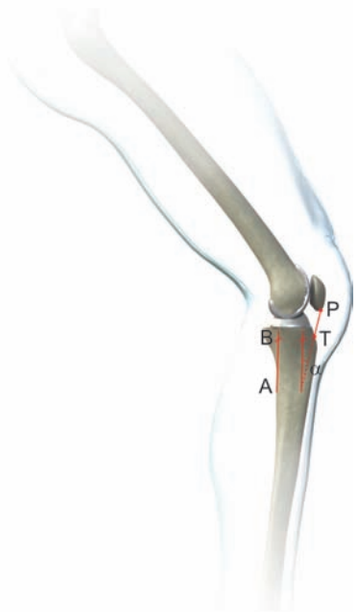


Figure 22 The patellar tendon angle

Patellar Tendon Angle

This value permits to examine the loaded and unloaded knee kinematics in the sagittal plane.[69] The relationship between the patellar tendon angle (PTA, the angle between the patellar tendon and the tibial axis, Fig. 22) and the angle of knee flexion is quantified.[69] The PTA is a good measure of both patellofemoral and tibiofemoral joint kinematics and is related to both the patellofemoral and the tibiofemoral contact forces. It depends primarily on the interactions of surface geometry between the femur and tibia and the shapes of the patellar surface and trochlear groove. Major abnormalities in the PTA are likely to be a result of abnormalities in the relationship of the femur to the tibia. Anterior subluxation of the femur increases the angle whereas posterior subluxation decreases it. In the normal knee, PTA is approximately 20° in the extended position. With flexion, the PTA reduces in a linear fashion, becoming zero at approximately 80° of knee flexion, and the angle decreases to approximately minus 10° at 120°.[69,77,83] The tibiofemoral and patellofemoral joint kinematics affect the size of the PTA and in turn, the magnitude of the PTA influences patellofemoral contact force.[69]

KNEE AXIAL PLANE ASSESSMENT

Patient Positioning for Patellar Views

Patellar axial views are described by many authors with different patient's positions (Laurin, Ficat, Merchant).[39,49,66] We will describe the most popular ones.

Ficat and Hungerford view: The authors described a technique in which the patient's knees are flexed over the end of the X-ray table. The tube is placed at the patient's feet and the cassette is held proximally against the anterior thigh. In this position, it is perpendicular to the beam. Flexion views at 30°, 60°, and 90° can be obtained.

Laurin's view: The patient is seated on the examining table with the feet near the edge. The X-ray beam is parallel to the anterior border of the tibia and the knees are flexed 20°. The cassette is held by the patient against the thighs and at 90° to the beam.

Merchant's view: The patient lies supine on the table with the knees flexed at 45° (using a fixed or adjustable platform) and the cassette is placed on the proximal shins. Both knees are exposed simultaneously, with the X-ray beam directed toward the feet, inclined 30° from the horizontal.

Loaded versus Unloaded Axial Patella-Femoral Views

The views, we have described in the previous paragraph are performed in unloaded nonweight-bearing patient's positions. The effect of the quadriceps muscle contraction on the patella-femoral alignment is not taken into account by these views. For this reason, alternative patellar axial weight-bearing views have been proposed in the past but without obtaining the adequate reproducibility.[36,104] We described and validated a weight-bearing axial view which incorporates all the parameters of the Merchant's view.[9] The weight-bearing axial view is performed with the standing patient's back toward the wall (in front of the sliding radiological support), and approximately 25.4 cm (10 inches) from the wall itself. The X-ray source is brought to the level of the patient's head. The cassette (18 x 43 cm) is positioned on the dorsum of the feet, which are maintained parallel to one another. The long side of the cassette contacts the tibio-talar joint bilaterally, and foam wedges are positioned on the floor (opposite the long side of the cassette) to ensure the cassette remains parallel to the floor. The crosshairs of the beam are projected at the center of the cassette. Patients were then asked to squat to a level that enabled the shadow of the knee to be projected onto the center of the X-ray beam crosshairs. This allowed the angle of the patient's tibia to be maintained at 15° from the beam. By maintaining the tibia in this fixed position, the required 45° knee flexion angle was achieved by simply adjusting the angle of the thigh (Fig. 23). In our experience, the axial weight-bearing view showed the following patellofemoral tracking changes, compared to the standard Merchant axial view: lateral tilt and subluxation of the replaced patella were significantly reduced, the prevalence of exposed, uncovered patella bone impingement on the femoral trochlea was significantly increased, and radiographic evidence of maltracking more closely correlated with clinical symptoms. This view demonstrated that the position of the patella, as seen on the standard unloaded Merchant view, may change during activities of daily living when the quadriceps muscle is involved. Utilization of an axial weight-bearing view to evaluate TKA provides additional information over standard radiographic views.[8,9]

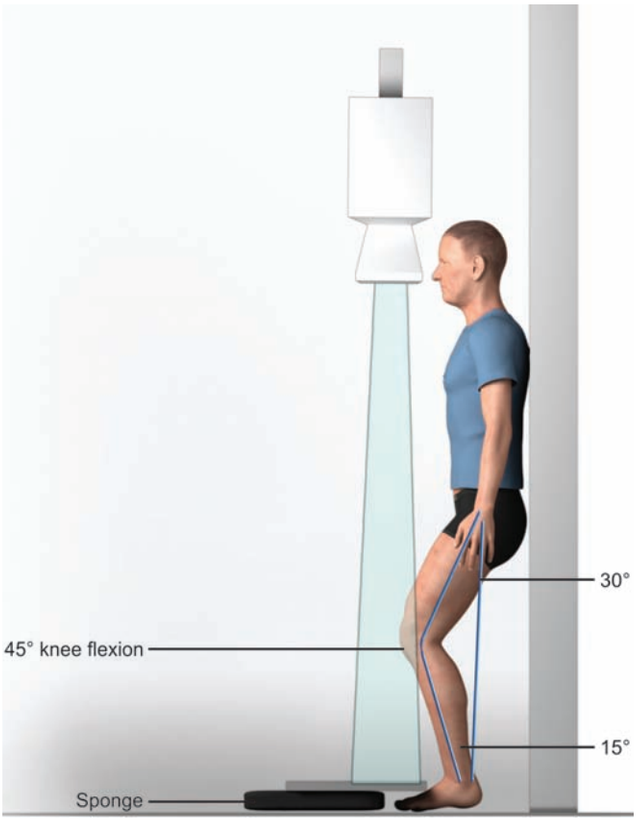
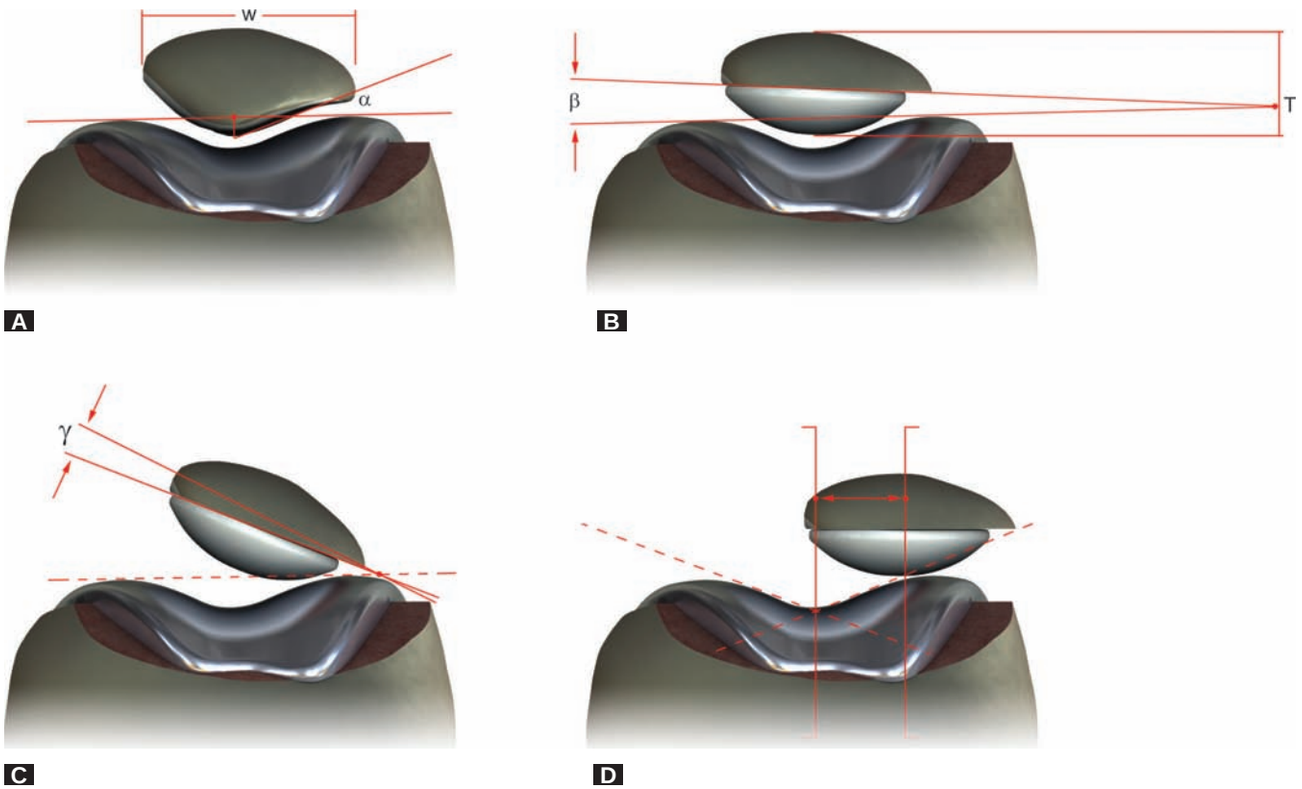


Figure 23 Patient's positioning for the weight-bearing axial patello-femoral view[9]

Evaluation of Patellofemoral Axis

Patellofemoral alignment measured accordingly to the American Knee Society Total Knee Arthroplasty Roentgenographic Evaluation and Scoring System takes into account patellar thickness, width, tilt, medial-lateral displacement, and the angle of the patellar prosthesis in patellar bone. These measurements are calculated referring to the description by Gomes and Gustilo[41] (Fig. 2).



Figures 24 A to D (A) Patellar tilt angle (α) of an unresurfaced patella;(B) Patellar tilt (β) of a replaced patella. Patellar thickness (T);(C) Symmetry (angle γ) of resection for a resurfaced patella;(D) The medial-lateral position of the patella[37]

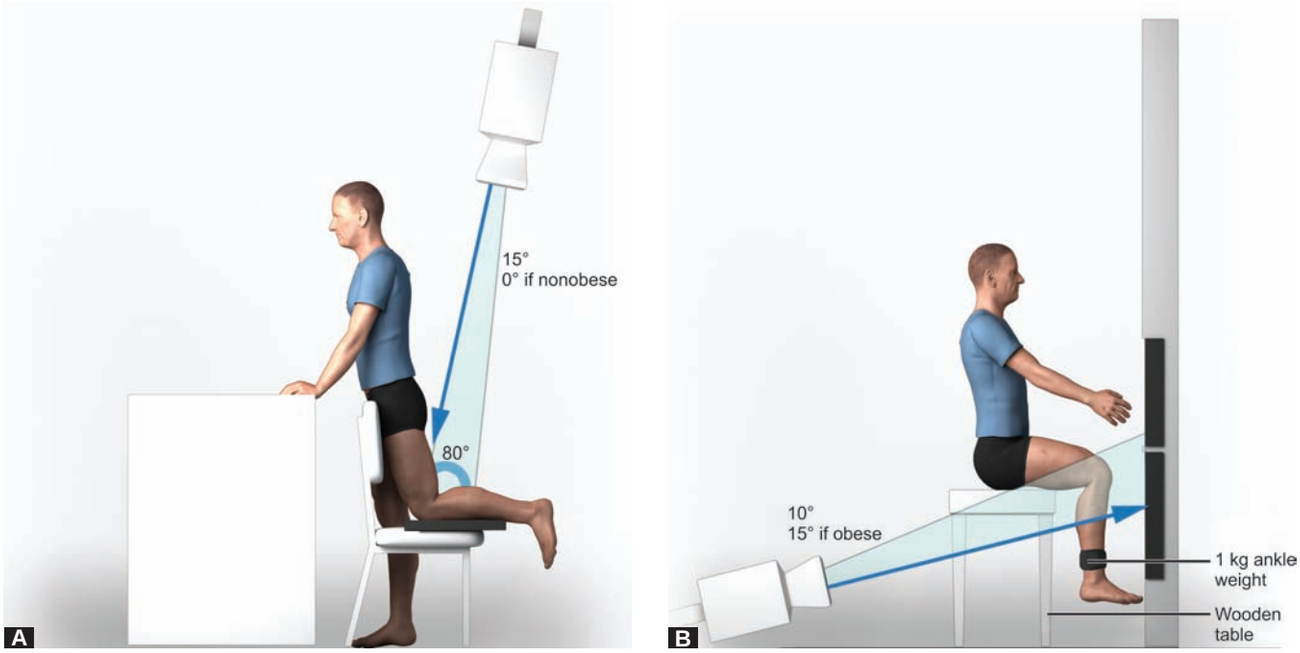
The patellar tilt angle (α) for the preoperative or unresurfaced patella is formed by a line drawn across the anterior limits of the femoral condyle or prosthesis in the skyline view and a line connecting the apex of the patellar articular surface (point where medial and lateral patellar facets join) with the lateral edge of the lateral patellar facet (Fig. 24 A). If the angle is positive as indicated in the drawing, the patellar angle is considered normal. If the angle is zero or reversed, patellar tilt is considered abnormal. Subluxation and dislocation are also indicated by this measurement, because a low or reversed angle indicates subluxation and displacement. If the reversed angle is high, complete dislocation will be present.

Patellar tilt (β) after a patellar prosthesis has been implanted is the angle between a line which connects the anterior limits of the condyles and a line drawn through the prosthesis bone-interface (Fig. 24 B).

Patellar thickness (T) pre- and postoperatively is the vertical distance from the anterior cortex of the patella to the depth of the femoral patellar sulcus. A cadaver study by Scott et al. pointed out that passive knee flexion decreases 3° for every 2 mm increment of patellar thickness in their model (Fig. 24 B).[16]

Symmetry of resection for a resurfaced patella is measured calculating the patellar prosthesis-bone angle (γ) at the intersection of a line drawn through the equator of the patellar bony remnant and a line drawn through the patellar prosthesis-bone interface (Fig. 24 C). With the use of a loaded axial patellofemoral view, the detrimental kinematics effects of asymmetric resection in patellar resurfacing are more evident, and it particularly increased the rate of maltracking and patellar bone-to-femoral trochlea contact.[8] The resultant oblique bone-implant interface could also lead to shear stress and jeopardize patellar component fixation and longevity.[74]

The medial-lateral position of the patella is the horizontal distance between two vertical lines perpendicular to a line drawn across the femoral condyles. One line is formed by the midpoint of the bony patella and the other line by a point in the depth of the femoral patellar sulcus. The later point can be estimated by visual inspection or by the intersection



Figures 25 A and B (A) Femoral axial views: "kneeling view" by Takay[102] and (B) "Sitting view" by Kanekasu[56]

of the medial and lateral tangent lines of the femoral condyles converging in the depths of the sulcus (Fig. 24 D).

Femoral Axial Views

Other than patellofemoral joint evaluation, a knee axial view can offer data on femoral component axial alignment. Rotational position of the femoral component is calculated by the condylar twist angle (CTA, angle between the posterior condylar axis and the clinical epicondylar axis). This data, commonly obtained using a CT scan of the knee (see next paragraph), can be obtained with plain radiograms. In the literature, there are two described radiographic methods to obtain an accurate knee axial view which enables the surgeon to evaluate the CTA.[56,102] Both methods were validated comparing their X-ray data with the CT data in the same cohorts, results showed a high correlation index.[56,102] The preoperative use of one of these views can anticipate the amount of degrees of external rotation respect to the posterior condyles that the surgeon should select in order to match the alignment over the transepicondylar axis (TEA). Postoperatively, the femoral component rotation can also be assessed in relationship to the TEA.

Takai's view (Kneeling view): Position of the patient for this view is with the examined knee of the patient lying down in the kneeling position on a radiographic cassette which is held by a support represented by a chair or a wooden frame. The angle of knee flexion should be 80° and the beam is perpendicular to the patient's tibial shaft. The resultant radiogram is a posteroanterior of the flexed knee (Fig. 25 A). In order to obtain a satisfactory quality of the film, the authors suggested to use 100% amplitude, 120% voltage (140% for obese), and 100% time, compared with the usual anteroposterior views of the knee.[102]

Kanekasu's view: The patient is sitting on a wooden frame with the lower legs hanging down and bent 90°. The X-ray beam is directed at a 10° upward angle. The angle is increased at 15° in obese subjects to minimize the effect of soft tissue overlap. The close contact between the table and the posterior thigh minimizes soft tissue overlap and ensures good quality to the view. The distance between the X-ray tube and the cassette is 1 m.[56]

The same authors realized that this patient position with legs hanging from the table generates a tibial distraction force which was useful to analyze the configuration of the flexion gap (Fig. 25 B). They modified the original position by adding 1.5 kg distraction to the examined leg and were able to assess preoperative and postoperative tibiofemoral gap configuration. Dimension of the gap was not related to the weight, and 1.5 kg was selected because it was comfortable for the patient.[105]

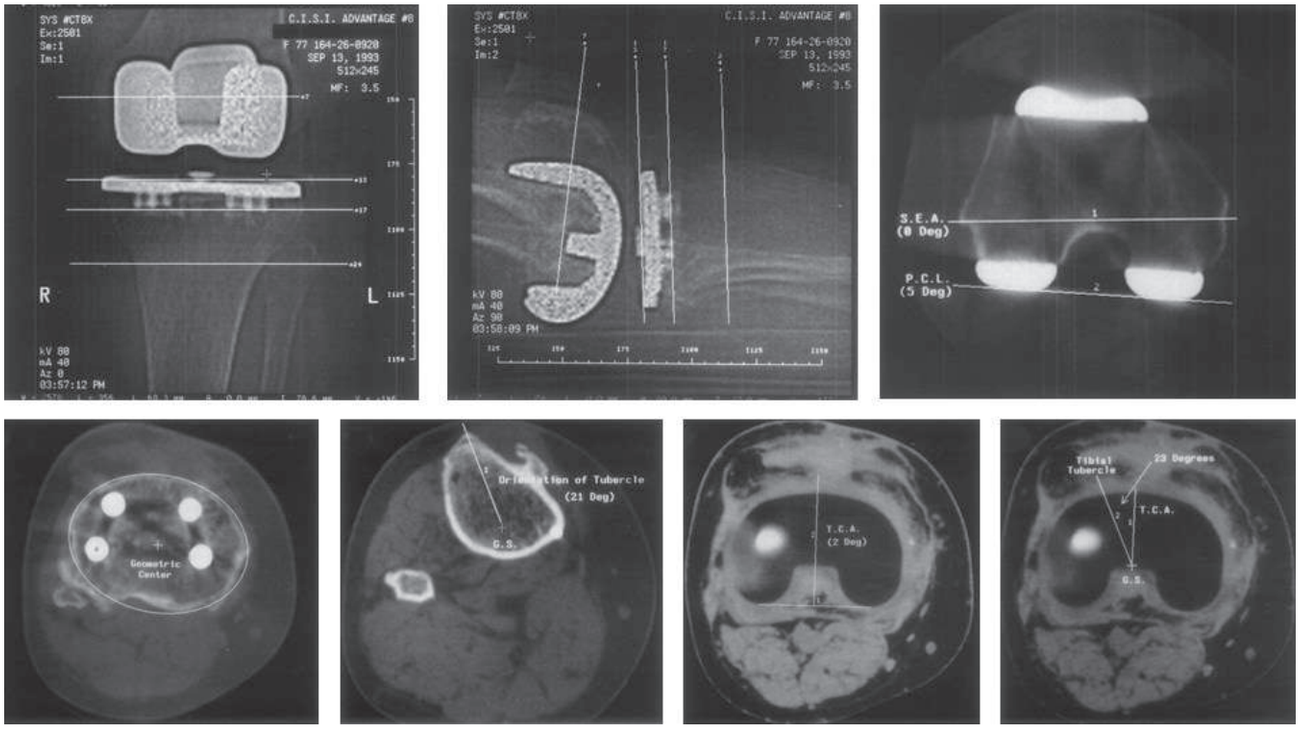


Figure 26 Image sequence for the CT scan rotational evaluation of the tibial and femoral component according to Berger et al[17]

CT-Scan Protocol

Complete measurement of the axial plane before and after TKA can be performed only by using CT or MRI. Both techniques need to reduce the metal artifact scatters from the implant with special metal artifact reduction sequences.[86,98] CT scans are more widely utilized for TKA evaluation so far, and the protocol for axial rotational alignment assessment has been developed on CT by Berger et al. several years ago (Fig. 26).[17] It should be taken into account that identification of these CT anatomic landmarks has an inherent methodological error as pointed out by Victor et al.[107]

Berger's Protocol

The patient is positioned supine with the examined limb in full extension, adjusted to allow the scans to be perpendicular to the MA of the knee. With the lateral scout view, the scans are taken perpendicular to the long axis of the femur for the femoral scan and perpendicular to the long axis of the tibia for the tibial scans (Fig. 26). This is achieved by tilting the scanner's gantry. CT images, 1.5 mm in thickness, are obtained at the following four locations: through the epicondylar axis on the femur, the tibial tubercle, the top of the tibial plateau, and the tibial component itself.

Femoral component rotation: The best level to identify both the epicondyles in the same scan is on average at 30 mm from the joint line.[100] At this level, two lines are drawn: one tangent to the posterior condyles and one connecting the prominence of the lateral epicondyle to the sulcus of the medial epicondyle (surgical TEA). The angle between these two lines is the posterior condylar angle (PCA). Postoperatively, the value of this angle should be as close as possible to the zero. Romero et al. suggested to refer the clinical TEA connecting the lateral epicondyle to the ridge of the medial epicondyle because it is a more accurate landmark to visualize.[100] This will calculate the CTA which is on average externally rotated to the PCA by 3–4°.[100]

Tibial component rotation: To determine rotation of the tibial component, the geometric center (GC) of the proximal tibial plateau is located and axially transposed distal to the level of the tibial tubercle. Then, the GC of the proximal tibial plateau and the junction of the medial-to-middle third of the tibial tubercle are connected, giving the orientation of the tubercle. The AP tibial component

axis (TCA) is drawn on the single axial scan through the tibial component. The tibial component rotation is subtended by the orientation of the tibial tubercle and the AP TCA.

CONCLUSION

Measurements of lower limb alignment after TKA require knowledge of radiographic landmarks in the three planes. Conventional radiographic assessment can be obtained only with a series of proper films made with accurate technique and patient positioning. Multiple references for axes description are reported in the literature. This variability is a natural consequence of the multitude of sizes, shapes and deformities which is typical of the human skeleton. A disciplined approach to radiographic analysis of TKA allows the surgeon to accurately plan the procedure and to obtain a high range of information which can be transferred into the surgical field. Postoperatively, TKA assessment needs accurate measurements in order to understand the influence of surgical technique on clinical and functional results. However, all these measurements have a limit: they are bidimensional. Rotational assessment of components, combined components position under load, kinematics relationships between components and between bones, will be possible to be understood only when 3D evaluation of the entire lower limb will be possible on a routine basis.[5,61]

Research in transferring two-dimensional images in three-dimensional models is reaching an advanced phase. The so-called "2D–3D" registration method is used in many medical areas to create 3D information on the inside of human bodies by aligning 3D data, such as CT or MRI, to 2D radiograph.[60] The area where 2D–3D registrations are most frequently used is in image-guided therapy. Their purpose of it is mainly to align preoperative CT data with intraoperative 2D radiographs in order to determine accurate positions and orientations of the patient's anatomy during an operation. Such 2D–3D registrations are divided into two categories: edge-based and intensity-based registrations. Edge-based registrations use gradient information of radiographs, while intensity-based registrations are made through comparisons of intensities between actual intraoperative radiographs and digitally reconstructed radiograph.[60] Other means are employing three-dimensional digital models of reference bones which are projected onto AP and lateral or oblique computed radiographs of the patient's tibia and femur. The projected images of the reference bones are then mathematically "deformed" by an image-fitting technique so that the surface shape and reference points of the reference bones approximated the surface shape and reference points of the patient's images.[89] With this method, the lower extremity skeletal landmarks precision relates to the quality of the corresponding 3D reconstructions. Except for tibial rotation, all the translation and rotation parameters are estimated within a mean error margin inferior to within a millimeter or a degree.[90] Biplanar low-dose X-ray systems may represent a tool of the future to generate 3D knee X-rays that can improve the evaluation and follow-up of total knee arthroplasty.

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