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Kinematically Aligned TKA with MRI-based Cutting Guides

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INTRODUCTION

There is general agreement that restoring kinematics after total knee arthroplasty (TKA) as close to normal is the best option for preserving knee stability, restoring movement, and reducing wear.^{10,20,52} Traditionally, TKA strives to restore the mechanical axis of the leg (i.e. hip-knee-ankle angle) to a straight line, but this alignment target does not restore knee kinematics to normal.¹⁴ This lack of restoration of normal knee kinematics, may in part explain the high prevalence of patient dissatisfaction with mechanically aligned total knee arthroplasties. At one year postoperatively, only 75% of 253 subjects were either 'very satisfied' or 'satisfied' in a single center study in the United States.⁴¹ In other reports, 82% of 8095 subjects were satisfied in the National Joint Registry for England and Wales² and 81% of 1703 subjects were satisfied in a study of the Ontario Joint Replacement Registry in Canada.⁶ Although computer-assisted instrumentation aligns the limb closer to the straight line mechanical axis than conventional instruments, this alignment target has not necessarily improved the clinical outcome or range of motion (ROM) of TKAs in multiple randomized clinical trials.^{4,12,31,32,37,51}

Studies have questioned the goal and outlined the penalties of mechanically aligning the limb with a TKA to a straight line.^{13,14,17,20-24,50} The goal and necessity of striving for a postoperative mechanical axis of $0^\circ \pm 3^\circ$ was questioned in a study of 398 modern TKAs at 15-year follow-up. They found that the prevalence of revision for aseptic loosening, mechanical failure, and wear was no greater in the mechanically aligned group ($0^\circ \pm 3^\circ$) than in the outlier group ($> 3^\circ, < -3^\circ$).⁴⁴ The potential penalty from mechanically aligning the components to the knee to form a limb with a straight line is an undesirable change in the obliquity and level of the joint line from normal and kinematic malalignment¹⁴ (Fig. 1). In many cases, the change in obliquity and level of the joint line creates an uncorrectable ligament imbalance.^{25,26,36} The ligament imbalance may cause abnormal knee kinematics, increase the risk of wear, and potentially lead to a high rate of patient dissatisfaction due to unexplained pain, stiffness, and instability.^{14,23,25,26,36}

There is renewed interest in restoring normal knee kinematics with the goal of improving the clinical outcome of the close to one out of five patients dissatisfied with their TKA.^{20-24,50} Patients with mechanically aligned TKAs have reported more pain and longer return to excellent function when compared to total hip arthroplasty (THA) patients in the early, intermediate, and 5-8 year postoperative periods.^{42,55} A potential

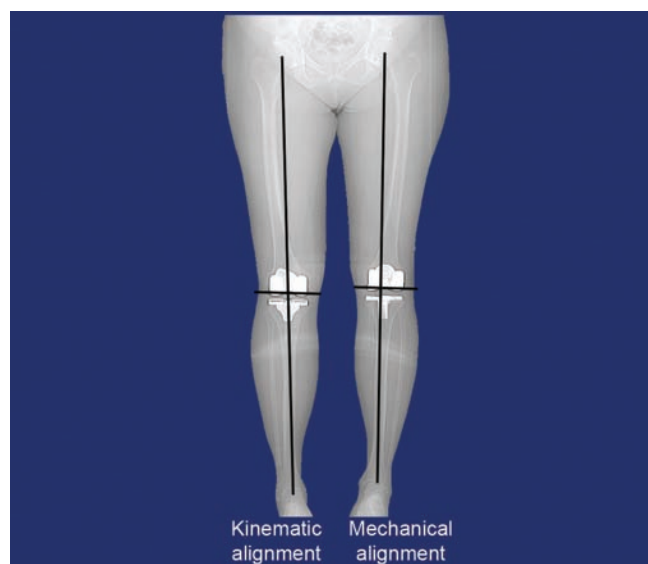


Figure 1 This is a scanogram of a kinematically and mechanically aligned total knee arthroplasty (TKA) in the same patient. In the kinematically aligned TKA (left), the thickness of the distal femoral bone resections after correcting for cartilage and bone loss from wear as well as kerf of the saw were adjusted intraoperatively until they equaled the thickness of the condyle of the femoral component, which confirmed the obliquity and level of the femoral joint line which was restored to normal. In the mechanically aligned TKA (right), the obliquity of the femoral component has been changed from normal to varus and the joint line has been raised, which is indicated by a thicker tibial insert. The penalty from mechanically aligning the TKA and changing the obliquity and level of the joint line can be kinematic malalignment of the femoral component and knee instability as evidenced by the lift-off of the medial femoral condyle.^{25,26,36} The weight-bearing line from the center of the femoral head to the ankle passes closer to the center of the kinematically aligned TKA than the mechanically aligned TKA

explanation for the difference in recovery between THA and mechanically aligned TKA may be that THA strives to restore normal hip kinematics whereas mechanically aligned TKA does not.^{13,20,23}

Based on the kinematic analyses, clinical evidence, and the current literature, we initiated the routine use of kinematic alignment in all patients requiring TKA beginning in January 2006 with the goal of improving clinical outcomes and patient satisfaction. As of August 2009, 23,000 kinematically aligned TKAs have been implanted with patient-specific cutting guides nationwide with one author implanting 1,096 (SMH). From September 09 through October 2010, one author (SMH) implanted over 400 kinematically aligned TKAs with modified conventional instruments because the patient-specific cutting guides were not approved by

the Food and Drug Administration (FDA). This five-year developmental and clinical experience forms the basis for the concepts that will be shared in this chapter with the primary goals of stimulating debate and advancing the understanding of kinematic alignment in TKA.

This chapter introduces kinematic alignment and describes the location and the importance of the three axes responsible for normal knee kinematics.^{9,13,14,17} A diagrammatic knee model is used to demonstrate an easy method for finding these kinematic axes with the use of surface landmarks on the knee.^{9,13,14,17,21,23} The use of shape-matching methodologies to kinematically align the femoral component is described, which follows the principle of equal measured resection.^{25,26,36} Equal measured resection is achieved when the thickness of the distal and posterior bone resections, equal the thickness of the condyle of the femoral component. The penalty from aligning the femoral component perpendicular to the mechanical axes of the femur is kinematic malalignment of the knee as a result of changing the obliquity and level of the joint line from normal,^{25,26,36} which often creates an uncorrectable ligament imbalance, as graphically illustrated. The methods for virtual planning and aligning the components as well as and intraoperatively kinematically positioning a TKA with patient-specific femoral and tibial guides-based on a magnetic resonance image (MRI) of the arthritic knee will be detailed.²⁰⁻²² A step-by-step algorithm with a defined end-point for restoring motion and balancing the kinematically aligned TKA that relies on osteophyte removal and modification of the plane of the tibial cut without releasing collateral and the posterior cruciate ligaments is provided. Finally, a paired study of limb, knee, and component alignment of subjects with a kinematically aligned and a mechanically aligned TKA in conjunction with published studies will be used to justify the opinion that the predisposition of wear, loosening, and aseptic revision should be no greater in the kinematically aligned TKA than in the mechanically aligned TKA.

THE THREE AXES THAT DESCRIBE THE KINEMATICS OF THE KNEE

The biomechanical rationale for kinematic alignment is based on the understanding that three kinematic axes in the native knee determine the relative position of the femur, patella, and tibia at any angle of flexion without force applied to the knee.^{9,17} The term kinematics is derived from the Greek word 'kinein' which means to move, and is the branch of classical mechanics that describes the motion of objects without consideration of the forces leading to the motion.

Knee kinematics are described by three axes: the transverse axis in the femur about which the tibia flexes and extends, the transverse axis in the femur about which the patella flexes and extends, and the longitudinal axis in the tibia about which the tibia internally and externally rotates on the femur^{9,13,14,17,29} (Table 1). Historically, Hollister et al. was the first to identify the transverse axis in the femur about which the tibia flexes and extends and the longitudinal axis in the tibia about which the tibia flexes and extends by ingeniously applying an axis finder to a cadaveric knee in 1993.¹⁷ Ten years later Coughlin et al. confirmed the existence of Hollister's two axes and identified the transverse axis in the femur about which the patella flexes in cadaveric knees.⁹ More recent image-based studies have confirmed the existence of three axes that define normal knee kinematics.^{13,14,29}

The transverse axis of the femur about which the tibia flexes and extends passes through the center of a

Table 1

Three kinematic axes	Description of location	Image
Transverse axis in the femur about which the tibia flexes and extends	Axis passes through the center of a circle fit to the articular surface of the femoral condyles 15-115° of flexion	
Transverse axis in the femur about which the patella flexes and extends	Axis is parallel, 10 ± 1.6 mm anterior, 12 ± 2.1 mm proximal to the transverse axis in the femur about which the tibia flexes and extends	
Longitudinal axis in the tibia about which the tibia internally and externally rotates on the femur	Axis is located anteriorly and remains nearly perpendicular to the two transverse axes in the femur from 0-90 degrees of knee flexion	

circle fit to the articular surface of the femoral condyles from 15 to 115° of flexion.^{9,13,14,17,21,29} The transverse axis of the femur about which the patella flexes and extends is parallel and approximately 10 mm anterior and 12 mm proximal to the transverse axis in the femur about which the tibia flexes and extends. The longitudinal axis in the tibia about which the tibia internally and externally rotates on the femur is anterior and remains nearly perpendicular to the transverse axes in the femur from 0 to 90° of knee flexion.^{9,17} Each of the three axes are aligned either parallel or perpendicular to one another, however they are not aligned to the anatomic sagittal, coronal, or axial planes. Therefore, the kinematic axes are best found by the use of articular surface landmarks on the knee and not by the use of imaging studies obtained in the anatomic sagittal, coronal, and axial planes.^{13,14,17,21,23,29}

A SIMPLE METHOD FOR FINDING THE THREE KINEMATIC AXES

The three-dimensional orientation of the transverse axis of the femur about which the tibia flexes and extends is found by viewing the lateral and medial projections

of the femoral condyles with the articular surface superimposed (Fig. 2). This view projects the femur in a plane perpendicular to the transverse axis of the femur about which the tibia flexes and extends.²¹ The best-fit circle is shape-matched on the articular surface of each femoral condyle from 15 to 115° of flexion.^{9,13,14,21} In the typical varus and valgus knee with end-stage osteoarthritis, the radii of best-fit circles on the medial and lateral femoral condyles are the same.²¹ A line connecting the center of the circles defines the three-dimensional orientation of the transverse axis in the femur about which the tibia flexes and extends.

The three-dimensional orientation of the transverse axis of the femur about which the patella flexes and extends is also found by viewing the lateral and medial projections of the femoral condyles with the articular surface superimposed (Fig. 3). The patella tracks in a nearly circular arc in a plane perpendicular to the transverse axis in the femur about which the tibia flexes and extends.^{9,29}

The three-dimensional orientation of the longitudinal axis of the tibia about which the tibia internally and externally rotates on the femur is found based on the transverse axes in the femur about which the tibia flexes and extends (Fig. 4). The longitudinal axis is anterior

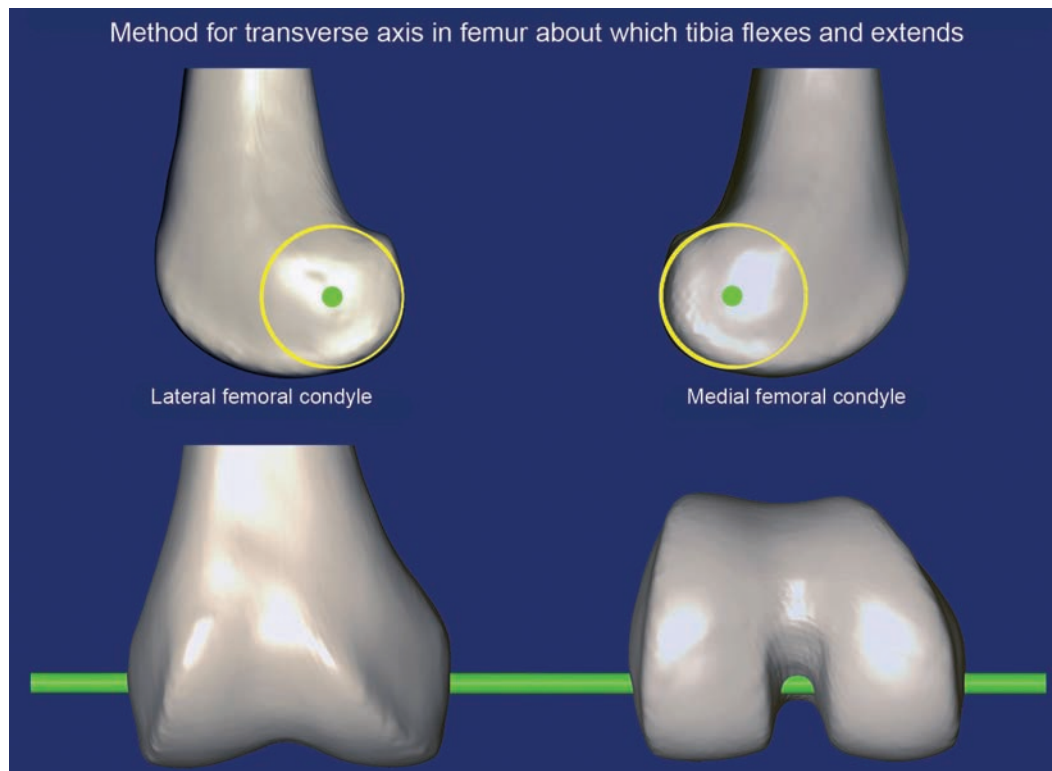


Figure 2 Shows the best-fit circle (yellow) shape-matched to the articular surface on the medial and lateral femoral condyles from 15 to 115° of flexion. The center of each circle (green dot) is connected with a line (green line), which locates the three-dimensional orientation of the transverse axis of the femur about which the tibia flexes and extends

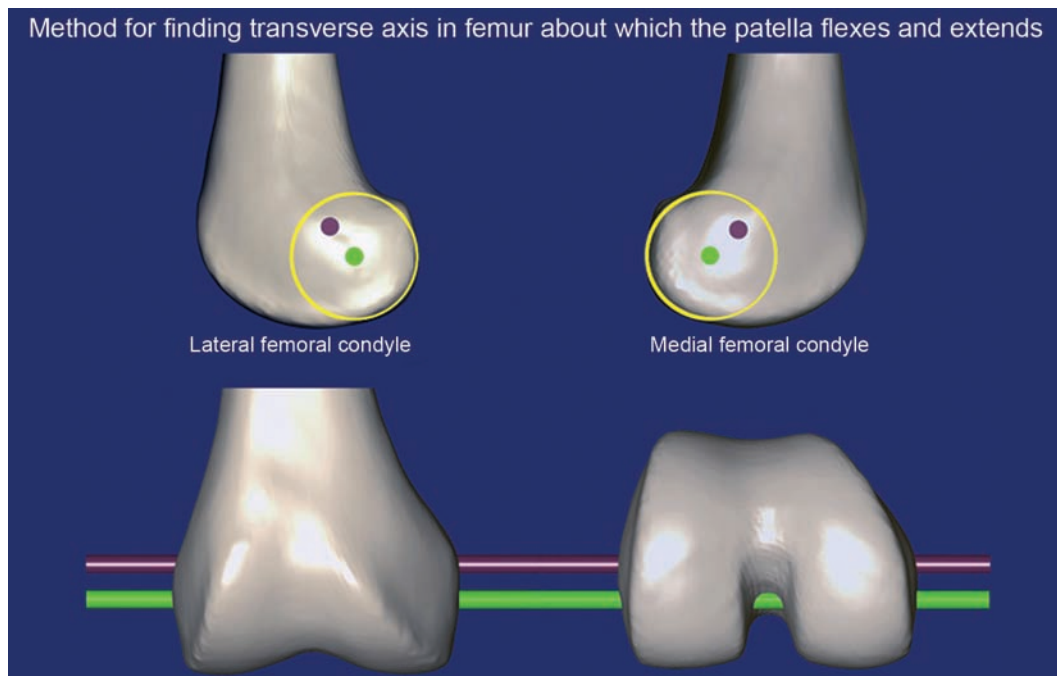


Figure 3 Shows the transverse axes of the femur about which the patella (magenta line) moves. The transverse axis of the femur about which the patella flexes and extends is parallel and 10 mm anterior and 12 mm proximal to the transverse axis in the femur about which the tibia flexes and extends

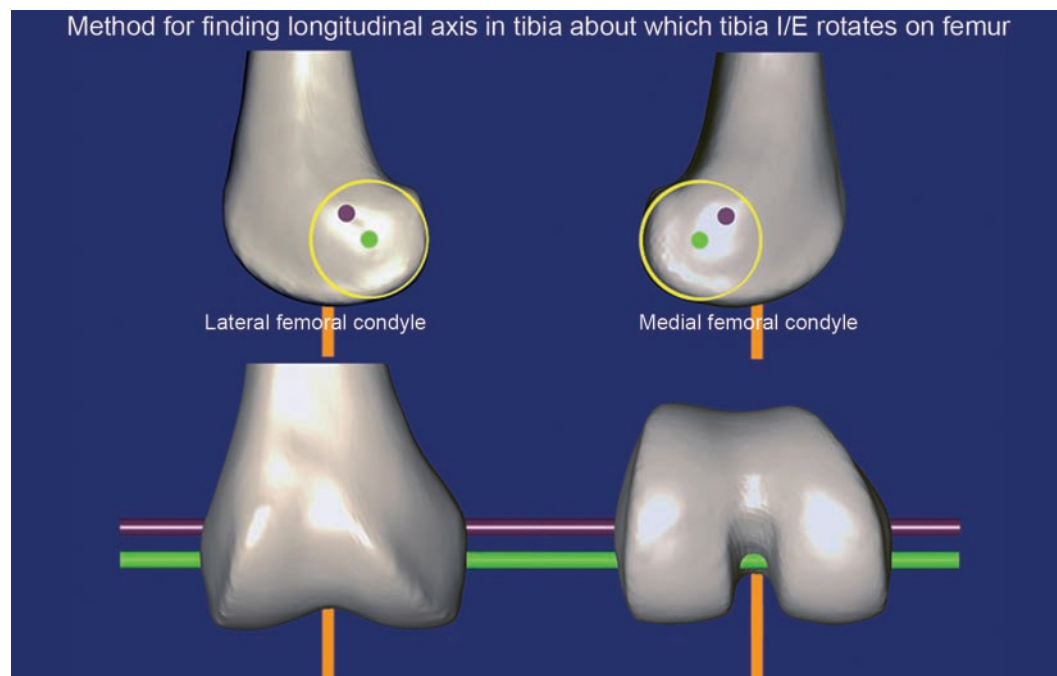


Figure 4 Shows the longitudinal axis of the tibia (orange line) about which the tibia internally and externally (I/E) rotates on the femur. The longitudinal axis of the tibia is aligned anterior and perpendicular to the transverse axes of the femur about which the tibia (green line) and patella (magenta line) flexes and extends

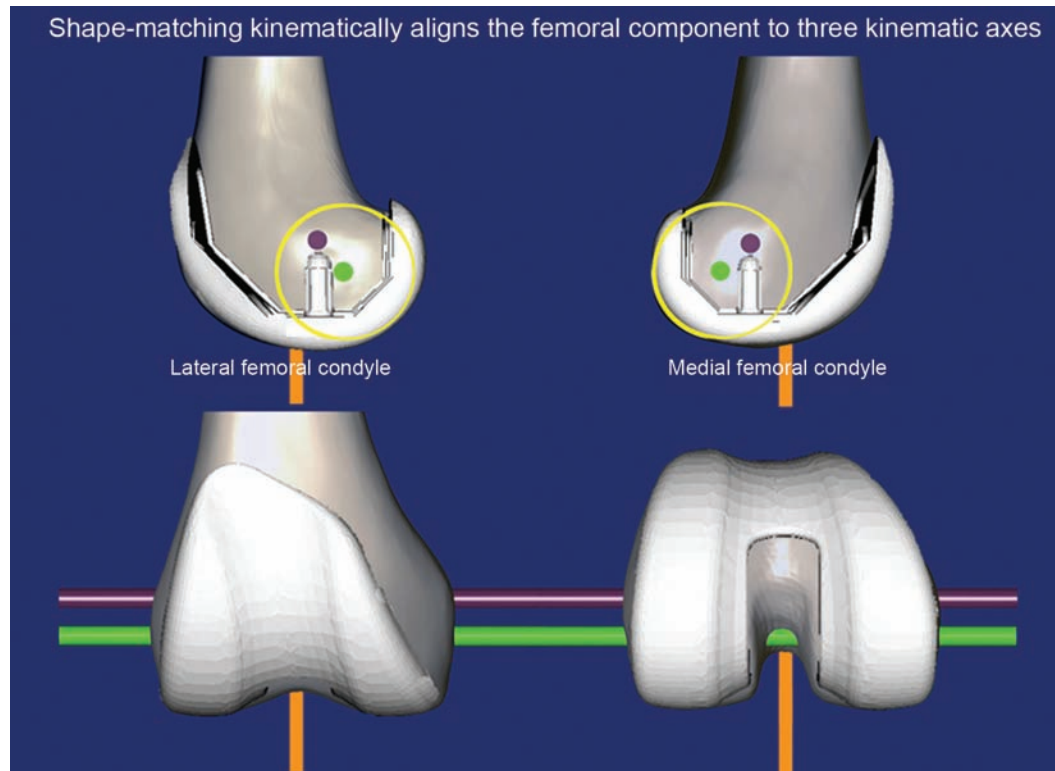


Figure 5 Shows a single-radius, symmetric, femoral component shape-matched to the restored articular surface of the femoral condyles, which theoretically maintains the orthogonal three-dimensional orientation of the three kinematic axes

and remains nearly perpendicular to the transverse axes in the femur from 0 to 90° of knee flexion.⁹ This axis passes through the anterior cruciate ligament at the joint line.¹⁷

USE OF SHAPE-MATCHING TO KINEMATICALLY ALIGN THE FEMORAL COMPONENT

The principle for kinematically aligning the femoral component is to shape-match it to the articular surface of the femur on a 3-dimensional model of the knee that has been restored to 'normal' by 'filling-in' the worn articular surfaces (Fig. 5). Because the difference in the radii of the medial and lateral femoral condyles in varus and valgus knees with end-stage osteoarthritis is small enough to be considered clinically unimportant when aligning a total knee prosthesis, the use of a symmetric, single radius femoral component is an optimal design for shape-matching and restoring kinematics.²¹ Shape-matching a symmetric, single radius femoral component to the femur coaligns the transverse axis of the femoral component with the transverse axis in the femur about which the tibia flexes and extends, which is requisite to restoring

the normal parallel/perpendicular interrelationships between the three axes.^{20,22}

The intraoperative method for determining whether the femoral component is kinematically aligned before cementing the components is to follow the concept of 'measured resection' with the use of calipers to measure the thicknesses of the distal and posterior bone resections from the femur^{25,26,36} (Fig. 6). The femoral component is kinematically aligned when the four distal and posterior femoral bone resections equal the thickness of the femoral component after correcting for cartilage and bone wear as well as the kerf (bone removed by the saw blade).¹⁹ For a femoral articular surface without cartilage and bone wear and a femoral component with 8 mm thick condyles, the thickness of each of the four bone resections should be 6.5 to 7.0 mm when a 1.27 mm saw blade is used.

To account for wear of the knee with osteoarthritis, the distal and posterior resections on the worn femoral condyle should be thinner than those of the unworn femoral condyle (Fig. 7). The typical wear is 1.5 to 2.5 mm on the distal resection and 0 to 1 mm on the posterior resection. Adjusting the thickness of the distal and posterior bone resections to account for cartilage and bone wear and kerf corrects the coronal and axial angular deformities in the femur, respectively.²¹

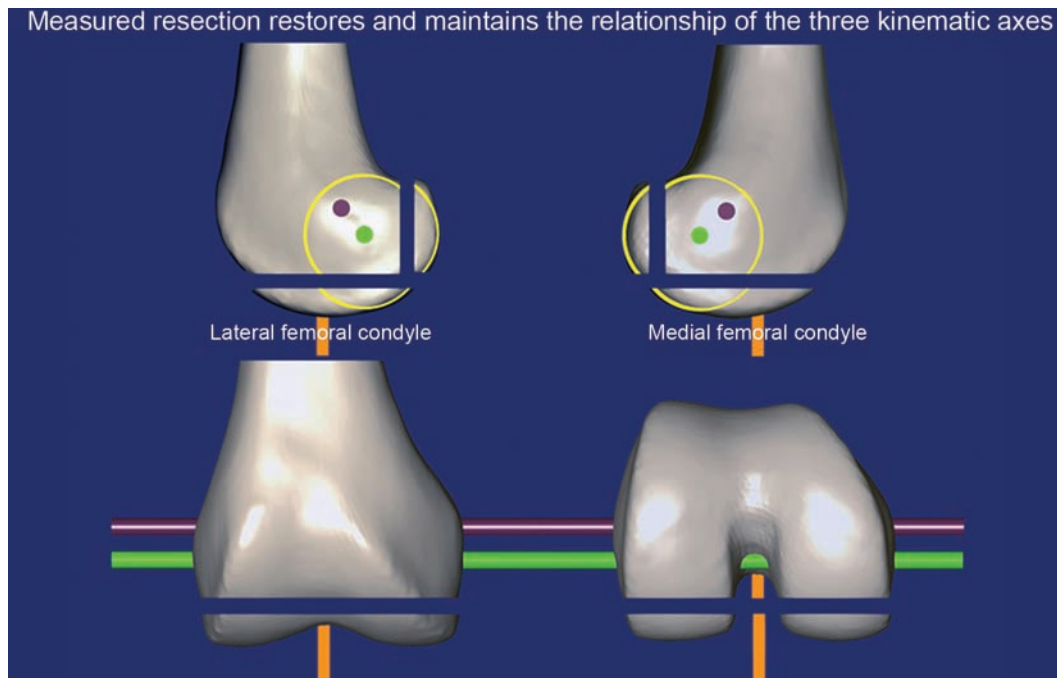


Figure 6 Shows the principle of equal measured resection as a useful intraoperative method to confirm that the femoral component is kinematically aligned. The thickness of the distal and posterior resections should equal the thickness of the condyles on the femoral component after correcting for the thickness from wear and the kerf of the saw blade. Correcting the thickness of the bone resections for wear and kerf also corrects coronal and axial deformities in the femur

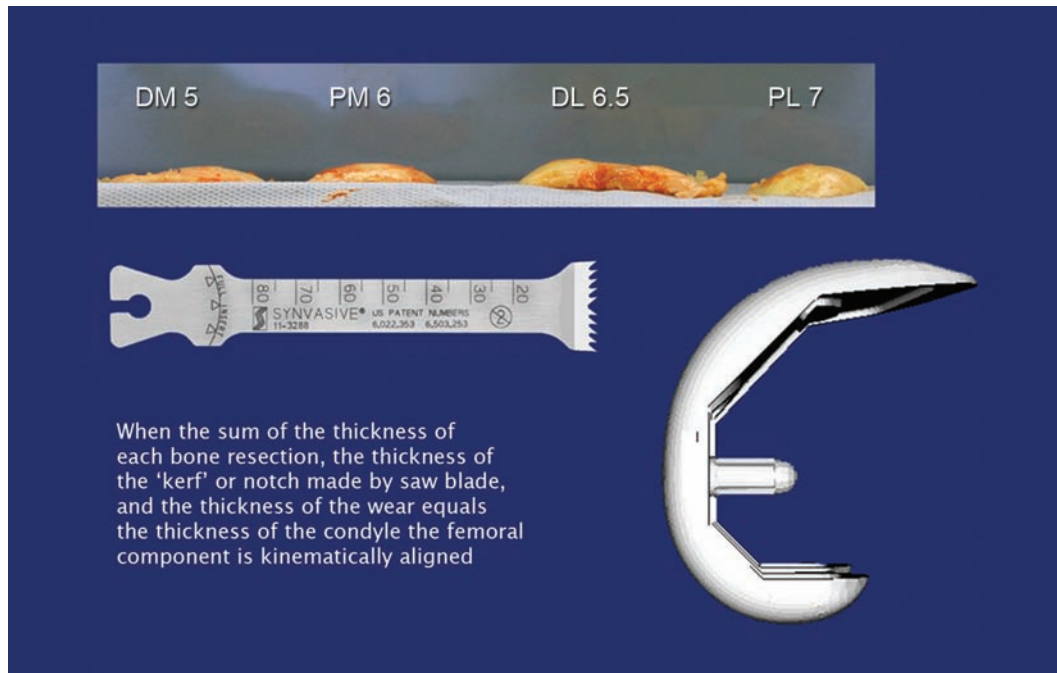


Figure 7 Shows the typical bone resections expected for a varus knee with 2 mm of distal medial (DM) wear and 1 mm of posterior medial (PM) wear when a symmetric single-radius femoral component with 8 mm thick condyles is used for shape-matching. The thickness of the distal medial (DM) resection is 5 mm, the posterior medial (PM) resection is 6 mm, the distal lateral (DL) resection is 6.5 mm, and the posterior lateral (PL) resection is 7 mm thick. The kerf created by the saw blade is 1 to 1.25 mm thick. When the sum of the bone resection, kerf, and wear equal the thickness of the condyle, the femoral component is kinematically aligned and the obliquity of the joint line is restored to normal in both the coronal and axial planes

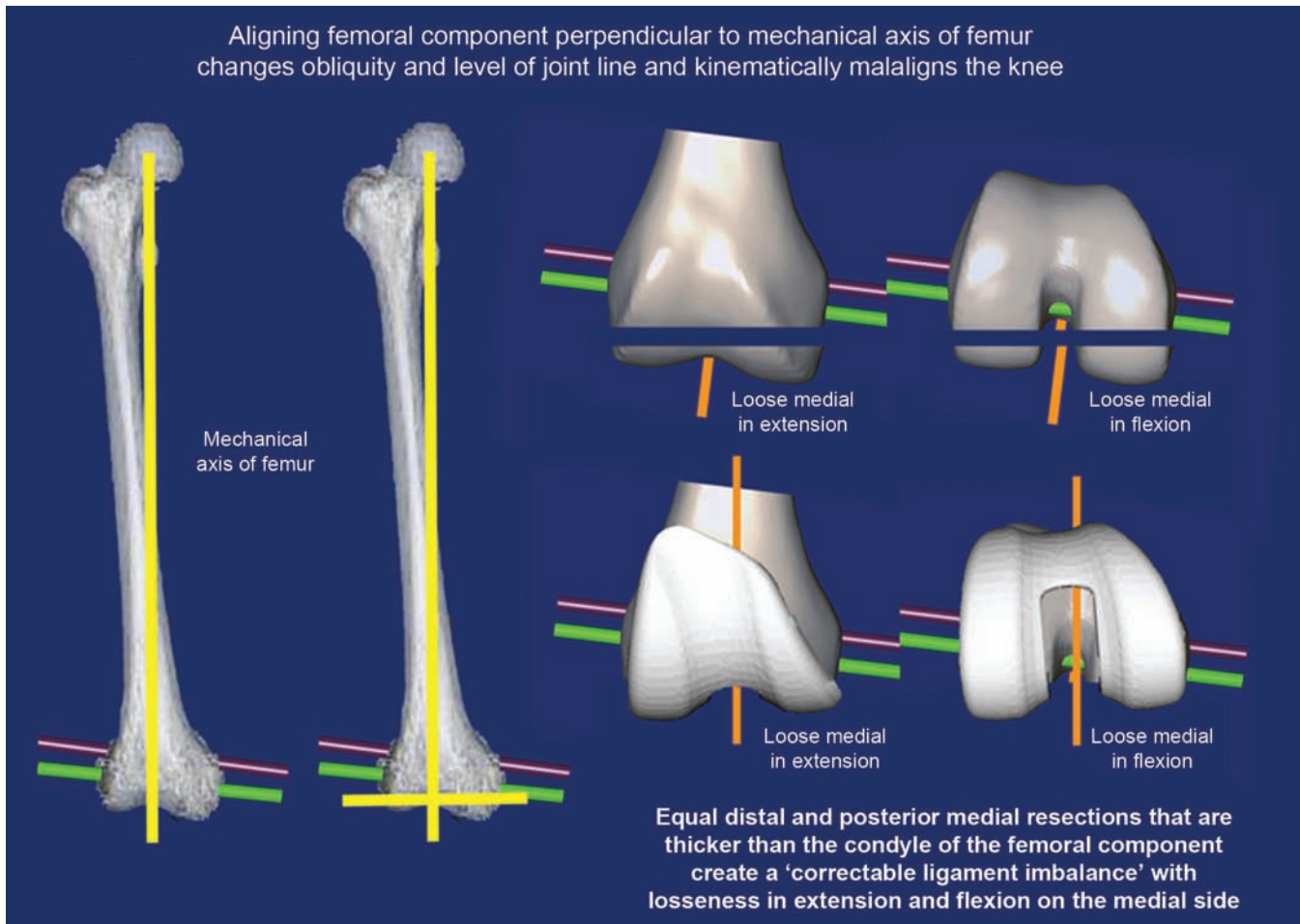


Figure 8 Shows the penalty from aligning the femoral component perpendicular to the mechanical axis of the femur, which is a change in the obliquity and level of the joint line and kinematic malalignment the knee. In this example, the thickness of the distal and posterior-medial femoral condyles are equal but thicker than the condyle of the femoral component, which creates equal slack in the collateral ligament on the medial side in extension and 90° of flexion. The use of a thicker liner tightens up the slack on the medial side, but tightens the collateral ligament on the lateral side, which requires a release of the lateral collateral ligament to restore motion. However, because of the change in the obliquity and level of the joint line the TKA remains kinematically malaligned because the joint line in both the coronal and axial planes is not parallel to the two transverse axes in the femur (green and magenta line) or perpendicular to the longitudinal axis in the tibia (orange line)

PENALTY FROM ALIGNING THE FEMORAL COMPONENT PERPENDICULAR TO THE MECHANICAL AXIS OF THE FEMUR IS 'KINEMATIC MALALIGNMENT'

Because the distal femoral joint line forms an average angle of 2 to 3° of valgus inclination with respect to the mechanical axis of the femur, a resection perpendicular to the femoral mechanical axis results in asymmetric distal bony resections^{34,43} (Figs 8 and 9). The penalty from femoral bone resections that do not equal the thickness

of the condyle of the femoral component after correcting for the thickness of the arthritic wear and kerf from the saw (i.e. corrected bone resection) is a change in the obliquity and level of the joint line that leads to imbalance of the collateral ligaments and kinematic malalignment of the knee.^{13,14,36} In the coronal plane, unequal distal bone resections change the varus-valgus rotation of the femoral component and level of the joint line from normal, which slackens the collateral ligament on the side where the bony resection is thicker than the condyle of the femoral component, and tightens the collateral ligament on the side where the bone resection is thinner than the condyle of the femoral component. In the axial

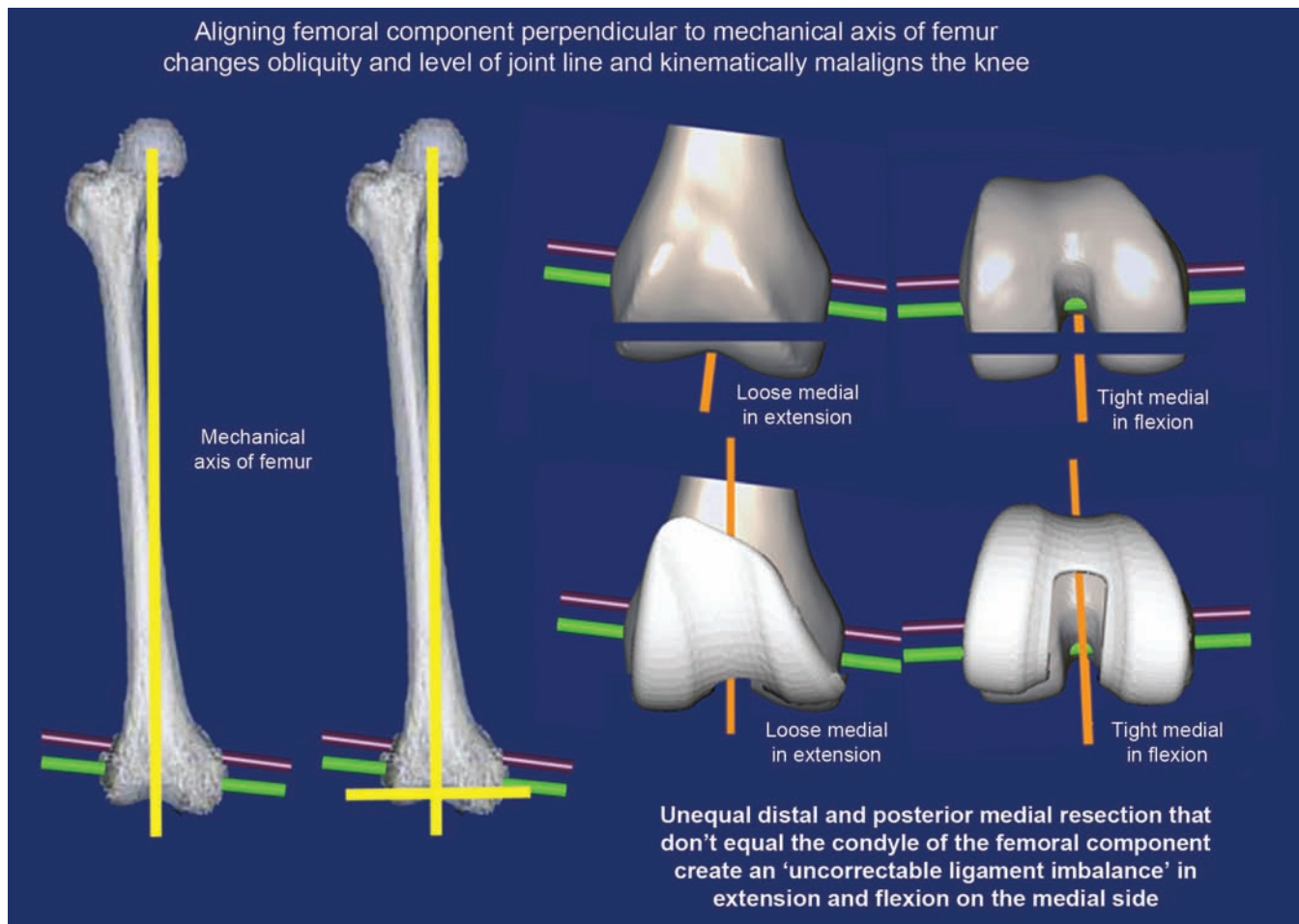


Figure 9 Shows how aligning the femoral component perpendicular to the mechanical axis of the femur and independently setting the axial rotation of the femoral component results in an 'uncorrectable ligament imbalance.' In this example, the thickness of the distal and posterior medial femoral condyles are unequal and do not equal the thickness of the condyle of the femoral component. The medial collateral ligament is loose in full extension, but tight in 90 degrees of flexion. Releasing the collateral ligament to reduce the tightness in flexion increases the slackness in extension, but re-establishes the original imbalance. Ensuing attempts to establish knee stability by modifying bone cuts and/or re-releasing ligaments results in the circuitous and unending experience of 'chasing one's tail' with no defined endpoint

plane, unequal posterior bone resections change the internal-external rotation of the femoral component and the anterior-posterior level of the joint line from normal, which slackens the collateral ligament on the side where the bone resection is thicker than the condyle of the femoral component, and tightens the collateral ligament on the side where the bone resection is thinner than the condyle of the femoral component.

The one scenario where a ligament release can 'balance' a knee with a mechanically aligned femoral component is when the distal and posterior resections from one condyle equal the thickness of the condyle of the femoral component and the thickness of the distal and posterior bone resections in the other condyle are

equal, but are either thinner or thicker than the condyle of the femoral component (Fig. 8). In this scenario, the knee has a 'correctable ligament imbalance' because the laxity in the collateral ligament attached to the condyle with corrected distal and posterior bone resections that equal the condyle of the femoral component is normal from full extension to full flexion, whereas, the laxity in the collateral ligament on the other condyle with corrected distal and posterior bone resections that are equal but thinner or thicker than the condyle of the femoral component is either too tight or too slack from full extension to full flexion, respectively. When the corrected thickness of the distal and posterior bone resections on one condyle is equal, but thinner than the

condyle of the femoral component, then a release of the collateral ligament corrects the tightness caused by the change in the obliquity and level of the knee joint line. When the corrected thickness of the distal and posterior bone resections on one condyle is equal but thicker than the condyle of the femoral component, then the use of a thicker liner on the overresected side reduces the slack, but a release of the collateral ligament on the opposite side of the knee is required to reduce the tightness from the use of the thicker liner, which corrects the slack caused by the change in the obliquity and level of the joint line. In either case, the penalty for making distal and posterior resections thinner or thicker than the condyle of the femoral component is kinematic malalignment because the transverse axis of the femoral component is not coaligned with the transverse axis in the femur about which the tibia flexes and extends, is not coaligned with the transverse axis in the femur about which the patella flexes and extends, and is not perpendicular to the longitudinal axis in the tibia about which the tibia internally and externally rotates on the femur.

Unfortunately, the most common penalty from aligning the femoral component perpendicular to the mechanical axis of the femur is an 'uncorrectable ligament imbalance,' which occurs when the corrected distal and posterior resections are unequal and do not equal the thickness of the condyle of the femoral component (Fig. 9). If the distal resection is thicker than the posterior resection on one or both condyles and the thickness of the resections do not equal the condyle of the femoral component, then the collateral ligament is slacker in extension and tighter in flexion. Inserting a thicker tibial liner to eliminate slackness in extension increases the tightness in flexion, which then limits flexion. Releasing the collateral ligament to reduce the tightness in flexion increases the slackness in extension and re-establishes the original imbalance. In the knee with an 'uncorrectable imbalance,' any ensuing attempts to establish knee stability by modifying bone cuts and/or releasing ligaments results in a circuitous and unending experience with the surgeon 'chasing their tail' with no defined endpoint.

There are several reasons for uncorrectable ligament imbalances in mechanically aligned TKA. The primary surgical goal is not to align the femoral component kinematically. Mechanically aligned TKA does not rely on an intraoperative protocol that intentionally strives to make the corrected distal and posterior bone resections equal to the thickness of the condyle of the femoral component, which fosters non-kinematic alignment. Another reason is the use of non-kinematic landmarks to align the femoral component such as mechanical axis

of the femur in the coronal plane to align the femoral component, which as previously discussed, changes the obliquity and level of the joint line. There are several non-kinematic landmarks in the axial plane including the practice of externally rotating the femoral component 3° to the posterior condylar axis, and aligning the femoral component with the transepicondylar axis. The use of these two rotational landmarks kinematically malaligns the femoral component because they align the femoral component obliquely to the transverse axis in the femur about which the tibia flexes and extends.^{13,21} The further reason is the inherent error in the use of non-kinematic landmarks. When experienced total joint arthroplasty surgeons aligned the femoral component to the posterior condylar, transepicondylar, and anteroposterior axes in a cadaveric study the inherent error ranged from 13° of internal rotation to 16° of external rotation, which results in unequal posterior femoral bone resections.⁴⁸

Kinematic malalignment of the femoral component has many other adverse effects on knee function including abnormal patellar tracking, abnormal adduction, and reversal of rotation when standing and kneeling, as well as the described uncorrectable ligament imbalances.^{13,14,23} We believe that the uncorrectable ligament imbalance is an important cause of the high rate of patient dissatisfaction due to unexplained pain, stiffness, and unmet patient expectations with mechanically aligned total knee arthroplasty.

METHOD OF KINEMATICALLY ALIGNING THE TOTAL KNEE ARTHROPLASTY WITH USE OF PATIENT SPECIFIC CUTTING GUIDES

With a goal of improving on the 18 to 25% prevalence of patient **dis-satisfaction** from mechanically aligned TKA with conventional and computer-assisted instruments,^{2,6,41} we began developing the method for performing kinematic alignment with patient-specific femoral and tibial cutting guides in 2005. Software was designed to create a 3-dimensional (3-D) model of the arthritic knee from a non-weightbearing magnetic resonance image (MRI) or computer tomography (CT) arthrogram of the knee (OtisKnee, OtisMed, Inc, Alameda, CA, <http://www.otismed.com>).

Proprietary software first creates an 'arthritic' knee model, and then transforms the 'arthritic' knee model to a 'normal' knee model by restoring the worn surfaces. The 'normal' knee model is then used to plan the position of the femoral tibial components. Shape-matching the best-fitting femoral and tibial components

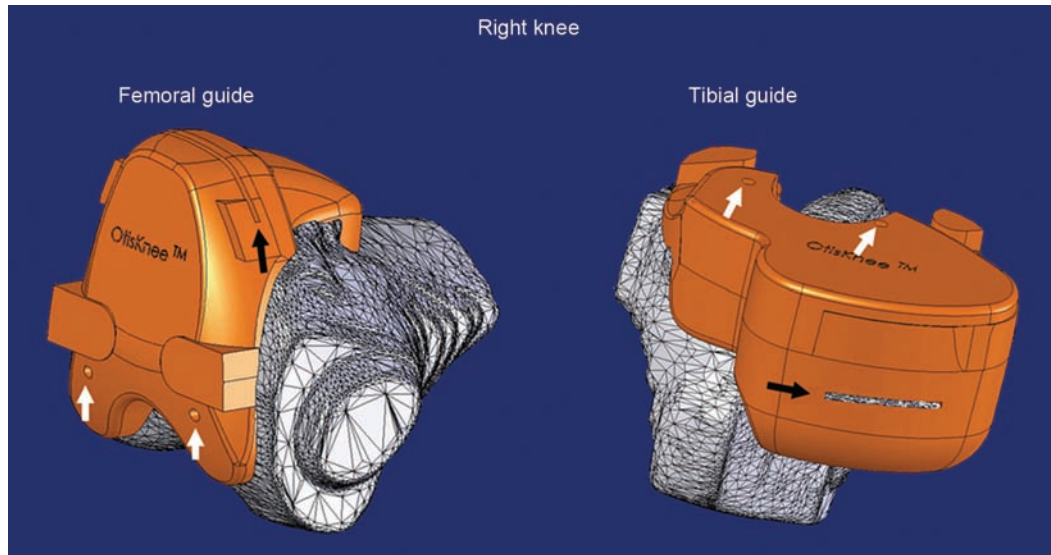


Figure 10 The diagram of a right knee shows the femoral (left) and tibial (right) patient-specific cutting guides (orange) on the 'arthritic' model of a right knee made from a magnetic resonance image (MRI). The saw slot (black arrow) in each guide sets proximal-distal translation, flexion-extension rotation, and varus-valgus rotation. The two holes (white arrows) in each guide set internal-external rotation and anterior-posterior translation. The surgeon visually sets the medial-lateral translation of the components after removal of medial and lateral osteophytes

to the 'normal' knee model kinematically aligns the femoral and tibial components. The 3-D position of each component is then transferred from the planned position on the 'normal' knee model to the 'arthritic' knee model. Patient-specific femoral and tibial cutting guides incorporating the cut planes of each component are machined to mate to the arthritic knee model (Fig. 10). The cutting guides are used intraoperatively to transfer five of the 6° of-freedom (6 DOF) positions of the femoral and tibial component from the computer to the patient (that is varus-valgus, internal-external, and flexion-extension rotations, as well as anterior-posterior, proximal-distal, and medial-lateral translations). However, since the removal of marginal osteophytes to restore ligament length changes the width of the femur and tibia the surgeon can visually center the medial-lateral translation of each component.^{20,22,24,50}

PROTOCOL FOR ALIGNING AND OBTAINING MRI OF THE KNEE

Kinematic alignment requires that the MRI projects the knee in a plane perpendicular to the transverse axis in the femur about which the tibia flexes and extends, which is close to but does not coincide with the true sagittal plane.^{9,13,14,17,21,22,24,29} To obtain the kinematic projection, the knee is placed in a position of comfort

inside a dedicated knee coil. The knee with a severe varus or valgus deformity, or a flexion contracture can be successfully imaged without forcing the knee into extension or an uncomfortable rotation. Imaging the knee in a comfortable position lowers the risk of knee movement during image acquisition, which would create a motion artifact and adversely affect the accuracy of the 3-D model. Contraindications for MRI imaging of the knee for patient-specific cutting guides are: (1) a pacemaker; (2) an inability to remain still; (3) a tremor; (4) a history of claustrophobia; (5) a large knee that does not fit into a dedicated knee coil; (6) any metal hardware about the knee that distorts the image and subsequent 3-dimensional model; and (7) any metal in the body that might move in the magnetic field such as brain aneurysm clips, metal in the eye, and shrapnel near vital structures.

A non-orthogonal, oblique, sagittal MRI scan of the treated knee is obtained with the use of a 1.5 or 3.0 Tesla scanner. Coronal and axial locator images are used to customize the orientation of the sagittal imaging plane to obtain a kinematic projection of the femur perpendicular to the transverse axis in the femur about which the tibia flexes and extends (Fig. 11).²¹ Coronal, axial, and sagittal high-resolution locator images are obtained with the use of 4 mm slice thicknesses, 1 mm spacings/gap, 256 x 224 matrices, 1 number of excitations (NEX), and 24 cm fields of view that yield nine slices in all three planes. The

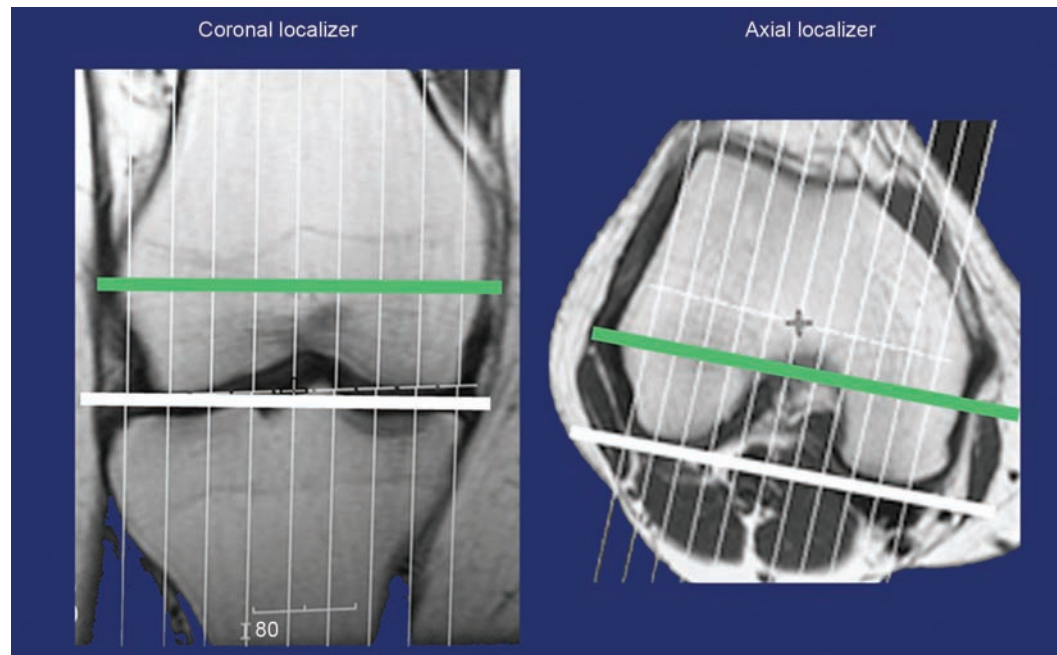


Figure 11 This depicts the use of the coronal (left) and axial (right) localizer to align the image plane perpendicular to the transverse axes in the femur about which the tibia flexes and extends (green line). In the coronal localizer, the image plane (parallel, thin lines) is adjusted perpendicular to a transverse line drawn at the subchondral-cancellous bone interface of the distal articular surface of the femur (thicker white line). In the axial plane, the image plane is adjusted perpendicular to a transverse line drawn at the subchondral-cancellous bone interface of the posterior articular surface of the femur

locator image in the coronal and axial planes that shows the largest projection of the distal femoral condyles is used to adjust the varus-valgus and internal-external rotation of the image plane, respectively. In the coronal plane, the image plane is aligned perpendicular to a line connecting the cortical-cancellous bone interface of the distal femoral condyles. In the axial plane, the image plane is aligned perpendicular to a line connecting the cortical-cancellous bone interface of the posterior femoral condyles. Because the contour of the posterior femoral condyles from 10 to 160° forms a single radius of curvature, and because the transverse axis in the femur about which the tibia flexes and extends is approximately equidistant from the distal and posterior articular surfaces of the femoral condyles, the femoral condyles are projected as both circular in a plane perpendicular to the transverse axis in the femur about which the tibia flexes and extends.^{13,14,21}

A near-sagittal MRI of the knee is acquired with this customized image plane. Imaging parameters are selected to provide contrast between fat, joint fluid, cartilage, degenerative and normal menisci, subchondral bone, cancellous bone, and cortical bone. For a 1.5 Tesla scanner and a dedicated knee coil (General Electric Medical Systems, Milwaukee, Wisconsin), the following

parameters work well: FRFSE PD, 30 to 35 TE, 2800 to 3400 TR, 31.25 Hz bandwidth, and minimum of two excitations with use of a 16-cm field of view centered at the joint line of the knee, 256 matrix, 2-mm slice thickness, with no spacing/gap. The length of each side of a pixel in the oblique sagittal image is 0.31 mm.²¹

VIRTUAL CONSTRUCTION OF THE 3-DIMENSIONAL 'ARTHRITIC' AND 'NORMAL' KNEE MODEL

The process of virtual kinematic alignment of the femoral and tibial components begins once the near-sagittal MRI of the knee has been received electronically at the manufacturing facility from the imaging center. The boundary of the articular cartilage and bone on each of the 40 to 60, 2 mm wide MRI slices is segmented and then compiled to make a 3-D 'arthritic' model of the femur (OtisMed Corp, Alameda, California) (Fig. 12). The 'arthritic' model is transformed into a 3-D 'normal' model of the femur by 'filling-in' articular and bone defects and removing osteophytes. Flexion-extension and varus-valgus rotational malalignments are corrected by adjusting these rotations until the normal model

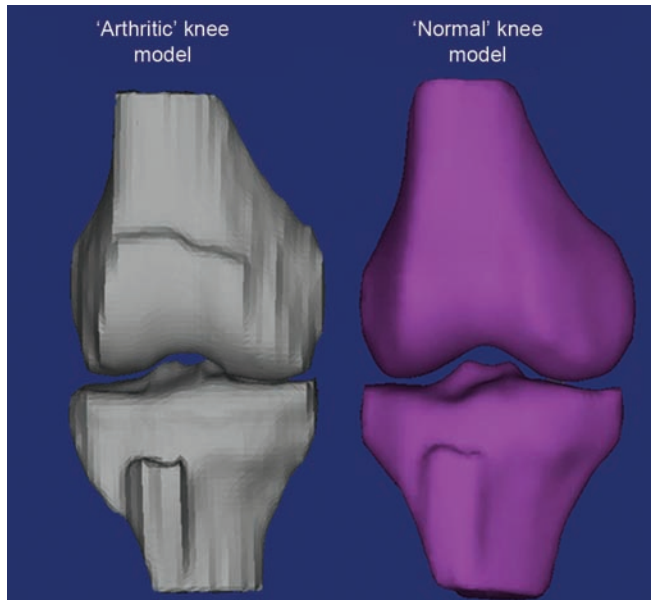


Figure 12 The diagram shows the 3-dimensional 'arthritic' knee model (left) and 'normal' knee model (right) created with software from an MRI of the knee. Software creates the 'normal' knee model from the 'arthritic' knee model by "filling-in" articular and bone defects and removing osteophytes. Setting the tibial-femoral separation distance equal between the medial and lateral hemi-joints in the 'normal' knee model corrects any varus or valgus deformity

of the knee is in full extension and the tibial-femoral separation distance is equal between the medial and lateral hemi-joints.^{20,22} This principle of restoring the joint line to normal is consistent with the concept of measured resection TKA, which has been shown to avoid mid-flexion instability.^{25,26,36,45}

VIRTUAL SHAPE-MATCHING THE FEMORAL AND TIBIAL COMPONENTS

Proprietary software selects the 3-D model of the femoral and tibial component that best fits the 'normal' knee model (Fig. 13). Algorithms shape match the femoral component to the restored articular surface of the femur from 15 to 115°, which theoretically kinematically aligns the femoral component by co-aligning the transverse axis of the femoral component with the primary transverse axis of the femur about which the tibia flexes and extends. The internal-external rotation of the anterior-posterior axis of the tibial component is set perpendicular to the transverse axis of the femur and femoral component, which kinematically aligns the tibial component to the femoral component. The tibia is centered under the tibial component, which theoretically kinematically aligns the tibia to the tibial component.^{1,9,14,17} In theory, kinematic alignment restores

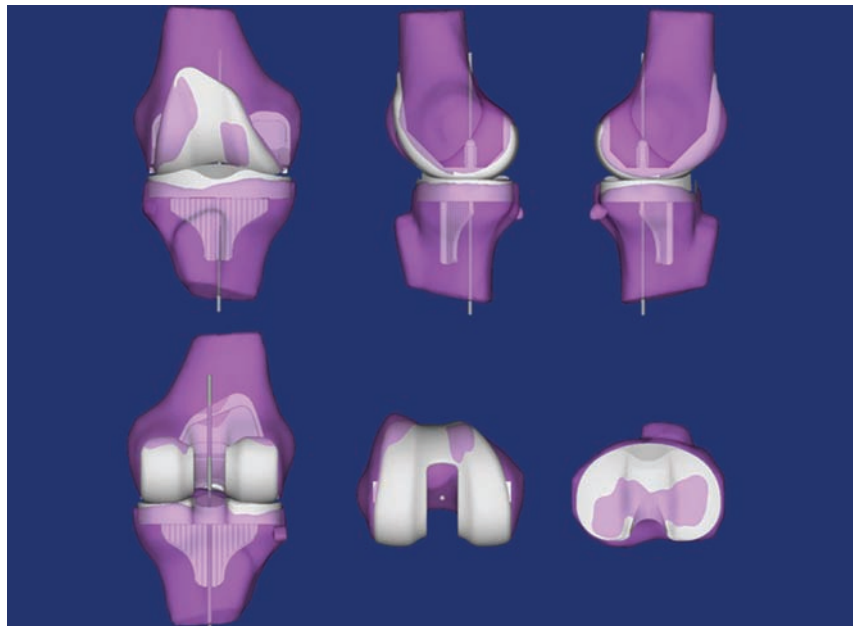


Figure 13 The diagram shows the plan of the best fitting femoral and tibial components shape-matched to the 'normal' knee model in various orientations. Software shape-matches the femoral component to the restored articular surface of the femur from 15 to 115°, which theoretically kinematically aligns the femoral component by co-aligning the transverse axis of the femoral component with the primary transverse axis in the femur about which the tibia flexes and extends. The tibial component is aligned with the femoral component, which sets the internal-external rotation of the tibial component on the tibia

the normal parallel and perpendicular inter-relationships between the three kinematic axes of the pre-arthritic knee.²¹

FUNCTION, DESIGN, AND MACHINING OF PATIENT SPECIFIC CUTTING GUIDES

A common function of all computer-generated patient-specific cutting femoral and tibial cutting guides, whether they are made to kinematically or mechanically align the TKA, is to accurately transfer the position of each component in 3-D space from the computer to the operating room. Each cutting guide sets 5° of freedom of component position in 3-D space, which is comprised of three rotations (flexion-extension, varus-valgus, and internal-external) and two translations (proximal-distal and anterior-posterior) (Fig. 10). Because the removal of osteophytes changes the width of the femur and tibia, the surgeon has the option to visually adjust the medial-lateral position of the femoral and tibial component.

The patient-specific cutting guides must fulfill several criteria simultaneously. The guides need to be small enough to fit in the knee with the use of minimally invasive incisions and yet large enough to register enough knee topography so that the surgeon can accurately seat the guide in the intended position. In the event that a cutting guide is inadvertently dropped on the floor, the guide must be both sturdy enough to avoid breakage and be able to retain its initial cavity shape during resterilization with heat. Rapid manufacturing is required to make production of patient-specific cutting guides cost effective and to limit the turnaround time between receiving the MRI and shipping the finished guides. Currently, the turnaround time is approximately 10 business days, but might be shortened to a single day with technological improvements.

Patient-specific femoral and tibial cutting guides are presently machined from bio-compatible plastic (Delrin™, Dupont, Wilmington, DE) to fit the 'arthritic knee' model. There is one saw slot and four holes for fixation pins in each guide (Fig. 10). The saw slot in each guide sets proximal-distal translation, flexion-extension, and varus-valgus rotations of the femoral and tibial components. The two pin holes on the articular surface of each guide reference the conventional chamfer block and the tibial component alignment instrument thereby setting the anterior-posterior translation and the internal-external rotation of the femoral and tibial components. Each guide provides the surgeon with the size and position of the femoral and tibial components and efficiently and accurately transfers five of the 6°

of-freedom positions of each component from the computer to the patient.^{20-24,50}

SIMPLE ALGORITHM FOR RESTORING MOTION AND BALANCING THE KINEMATICALLY ALIGNED TOTAL KNEE ARTHROPLASTY

In contrast to balancing the mechanically aligned total knee arthroplasty, where surgeons often have the undesirable circuitous and unending experience of 'chasing their tails' with no endpoint, the algorithm for restoring motion and balance to the kinematically aligned TKA is simpler, has a logical progression, and has a defined end-point (Fig. 14). The predicate step is kinematically aligning the femoral component, which is assessed by an intraoperative measurement of the distal and posterior bone resections with calipers. Distal and posterior bone resections that equal the thickness of the condyle of the femoral component after correcting for cartilage and bone wear as well as saw kerf confirm kinematic alignment of the femoral component.

Predicting the thickness of each bone resection can be complicated in the arthritic femur because of variability of the location and extent of focal cartilage wear (typically 1 to 2 mm) and bone wear (usually no more than 1 mm). A rotationally controlled MRI can be used to predict the resection thickness on the worn side by reviewing the location and amount of wear (Fig. 15).²¹ The image that projects the largest radius of each femoral condyle is selected with the use of image-analysis software (Osirix DICOM Viewer, www.osirix-viewer.com), and the best-fit circle is placed on the unworn femoral condyle and then propagated across the slices to the worn condyle. The thickness of the distal and posterior bone resection on the worn condyle is computed as the difference in distance between the circle and worn area which is then subtracted from the thickness of the femoral condyle of the femoral component minus the thickness of the saw cut.

On the occasion in which the thickness of the distal and posterior bone resections do not equal the thickness of the condyle of the femoral component after correcting for cartilage and bone wear and kerf, fine adjustments in the position of the femoral component are required. When too little bone is removed from the medial or lateral distal condyles, the resection should be increased. When excessive bone is removed from the medial or lateral distal condyles, distract the chamfer guide the thickness of the overresection from the overresected femoral condyle. Before making the anterior and two chamfer cuts, make and measure the thickness of the

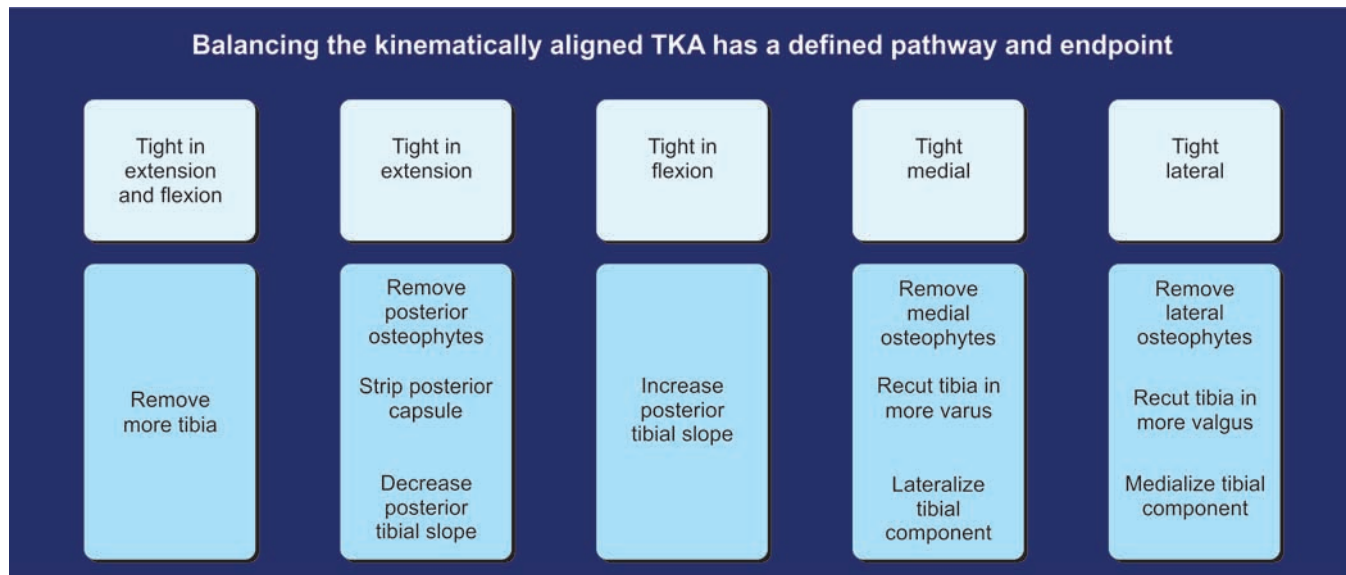


Figure 14 Flowchart shows the decision tree and step-by-step actions for balancing the knee with a kinematically aligned femoral component. The predicate step is kinematically aligning the femoral component, which is assessed by an intraoperative measurement of the distal and posterior bone resections with calipers. Equal thickness of the distal and posterior bone resections after correcting for wear and kerf that equal the thickness of the condyle of the femoral component confirms kinematic alignment

two posterior cuts. When too little or too much bone is removed from both posterior femoral condyles, translate the chamfer guide anteriorly or posteriorly the thickness of the under or over-resection, respectively. When excessive bone is removed from one of the posterior femoral condyles, rotate the chamfer guide the thickness of the over-resection from the over-resected condyle. These small gaps between the femoral component and femur can then be filled with bone cement.

Once the femoral component is kinematically aligned, all subsequent steps to restore motion and to balance the knee are limited to just four options; removing osteophytes, adjusting the plane of the tibial cut, releasing the posterior capsule from the femur, and medializing or lateralizing the tibial component (Fig. 14). To determine which options are needed to restore motion and balance the knee, the knee is examined with trial components and assessed as to whether the knee fully flexes and extends, and whether the varus-valgus and the anterior-posterior stability is acceptable at 30° intervals from full extension to flexion. When the knee lacks both extension and flexion but has anterior-posterior and varus-valgus stability throughout the motion arc, remove more tibia. When the knee lacks extension, but fully flexes and has anterior-posterior and

varus-valgus stability through out the motion arc, remove posterior osteophytes, and release the posterior capsule. If removal of the posterior osteophytes and releasing the posterior capsule are ineffective, then decrease the posterior slope on the tibia. Additional resection of bone from the distal femur is not recommended to restore extension unless the distal bone resection is 2 mm or more thinner than the posterior bone resection or unless the PCL is inadvertently released. The penalty from additional resection of bone from the distal femur is proximal movement of the femoral component, which moves the proximal-distal position of the primary transverse axis of the femur proximally, but leaves the anterior-posterior position of the primary transverse axis of the femur unchanged, which loosens the collateral ligaments in extension but not in flexion, and which limits flexion and kinematically malaligns the knee.⁴⁹ When the knee lacks flexion but fully extends and has anterior-posterior and varus-valgus stability throughout the motion arc, increase the posterior slope on the tibia. A kinematically aligned femoral component does need recession or release of the posterior cruciate ligament to increase flexion.^{20,22,49} When the knee is tight medially throughout the motion arc and fully flexes and extends, remove medial femoral and tibial osteophytes.

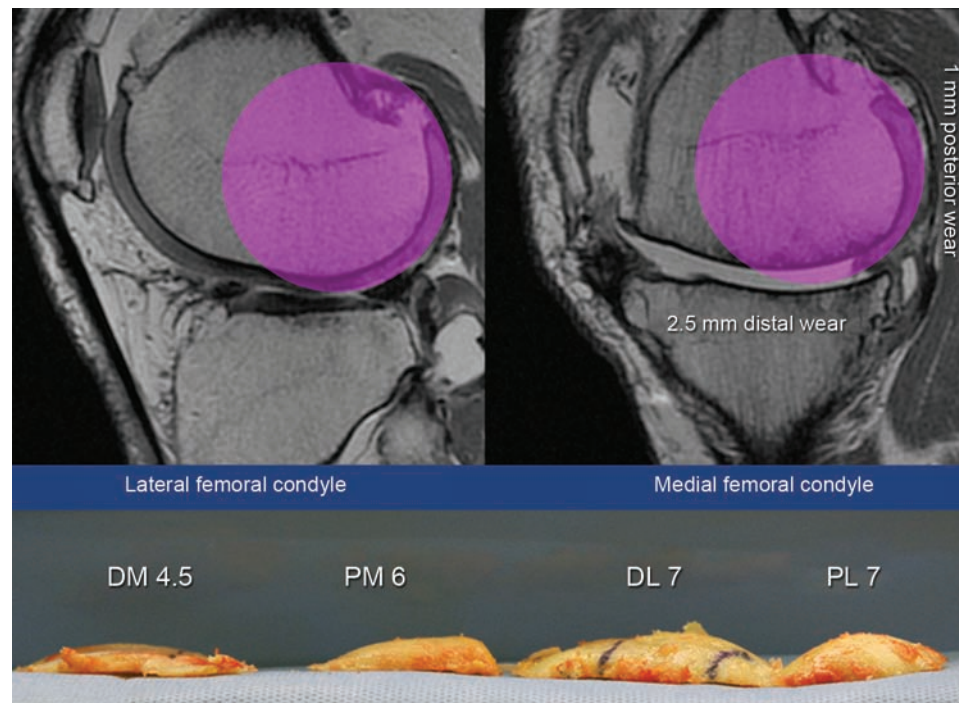


Figure 15 Shows the use of a rotationally controlled MRI to predict the resection thickness on the worn side of a knee with varus osteoarthritis to kinematically align the femoral component. The image that projects the largest radius of the unworn lateral femoral condyle is selected with use of image-analysis software and the best-fit circle (pink circle) is superimposed on the normal articular surface. The circle is propagated across the slices to the worn medial condyle, and the difference in distance between the circle and worn surface distally and posteriorly is computed. In this case, the wear on the distal medial femoral condyle is 2.5 mm, which means the intraoperative thickness of the distal medial (DM) resection should be 4.5 mm thick. The wear on the posterior condyle is 1 mm, which means the posterior medial (PM) resection should be 6 mm thick. The distal lateral (DL) and posterior lateral (PL) should both be 7 mm thick, which confirms the femoral component is kinematically aligned for a symmetric single-radius femoral component with an 8 mm thick distal and posterior condyle

When medial tightness persists, recut the tibia in 1 to 2° more varus as long as the overall visual alignment of the limb will be acceptable. Finally, if the medial side is still tight, then medialize the tibia on the tibial component and remove overhanging bone from the medial tibia³⁸ (Fig. 16). When the knee is tight laterally throughout the motion arc and fully flexes and extends, remove lateral femoral and tibial osteophytes. When the lateral tightness persists, recut the tibia in 1 to 2° more valgus as long as the visual alignment of the limb will be acceptable. In the case where the posterior cruciate ligament is insufficient due to inadvertent release or incompetency and there is anterior-posterior instability in 90° of flexion, but stability in full extension, resect 2 mm of bone from the distal femur and use a 2 mm thicker liner to increase the stability in 90° of flexion. If the knee still has anterior-posterior instability in 90° of flexion, then use either a liner with an increased anterior slope or use a posterior stabilized component.

SURGICAL TECHNIQUE FOR KINEMATICALLY ALIGNING THE TKA WITH PATIENT SPECIFIC CUTTING GUIDES

The range of motion, the presence of a fixed flexion contracture, and the magnitude of any uncorrectable varus-valgus deformity are assessed under anesthesia. Experience has shown that removal of posterior osteophytes and a posterior capsular release corrects a fixed flexion contracture of up to 40° without removing additional bone from the distal femur.⁴⁹ Removal of medial and/or lateral femoral and tibial osteophytes and adjusting the varus-valgus slope of the tibial resections corrects varus or valgus deformities without releasing the collateral ligaments.^{22,50}

The use of the patient-specific cutting guides simplifies the set up and execution of the surgery (Fig. 17).^{22,50} Confirm that the operating room technician

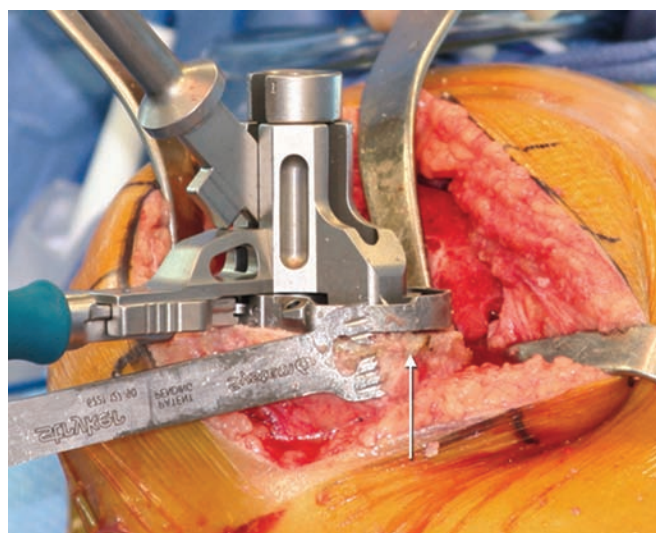


Figure 16 Intraoperative photograph of a right knee shows the technique of medializing the tibia on the trial baseplate and the use of a saw to trim overhanging bone to reduce medial tightness (arrow). The decision to medialize the tibia on the tibial component was made when medial tightness persisted after removing osteophytes from the medial femur and tibia and after verifying the plane of the varus-varus cut of the tibia was correct. This sequence of steps restores motion, stability, and alignment without releasing the medial collateral ligament in the knee with varus deformity

and circulating nurse have sterilized and assembled the guides, and that there are the correct subset of conventional instruments and trial components matching the size determined by computer planning. Cross-check with the operating room technician and circulating nurse that the patient's initials, surgeon's name, date of birth, component size, and the 'R or L' etched in the patient-specific femoral and tibial cutting guides match the patient and the knee being treated. The use of these guides reduces the number of instrument trays from 6 to 1, which should decrease operating time, turnover time, and the cost of processing instruments.²²

Although all TKA approaches can be used, a mid-vastus approach without patella eversion gives adequate exposure for use of the patient-specific cutting guides in most knees except for the large patient with a wide femur, thick patella, and well-developed non-compliant musculature. Fat is removed from the anterior surface of the femur proximal to the trochlear groove as are any prominent osteophytes extending from the proximal trochlea. The patient-specific femoral guide is seated on the anterior cortex, trochlear groove, and centered medial-laterally on the distal femur (Fig. 18). The guide is compressed and rotated in the axial or transverse plane



Figure 17 An intraoperative photograph that shows the one tray of instruments needed to perform a kinematic TKA with patient-specific cutting guides. The patient-specific femoral guide (FG) and tibial guide (TG) are sterilized with the instruments and trial components that match the size of the components determined by computer planning

until there is a sense that it 'locks' in place. The guide is secured with two articular and two anterior pins. The saw slot sets the varus-valgus, flexion-extension, and proximal-distal positions of the femoral component. The medial and the lateral distal pins are sequentially removed as the distal cut is made. Alternatively, the patient-specific femoral guide can be removed and the conventional distal femoral cutting guide can be placed over the two anterior pins, which allows visual assessment of the thickness of each of the distal resections before the cuts are made. The thickness of each distal femoral resection is measured with a caliper, and the thickness is corrected for cartilage and bone wear as well as kerf. The surgeon should know the kerf of their preferred blade when making this correction. The corrected medial and/or lateral distal resections should be equal to the thickness of the condyle of the femoral component. When too little bone is removed from the medial or lateral distal condyles, increase the resection. When excessive bone is removed from the medial or lateral distal condyles, distract the chamfer guide the thickness of the over-resection from the overresected femoral condyle and fill the gap with bone cement.

The chamfer guide from the conventional set of instruments that corresponds to the size of the femoral component is inserted into the two articular pin holes. The chamfer guide sets the internal-external rotation, the anterior-posterior, and the medial-lateral positions of the

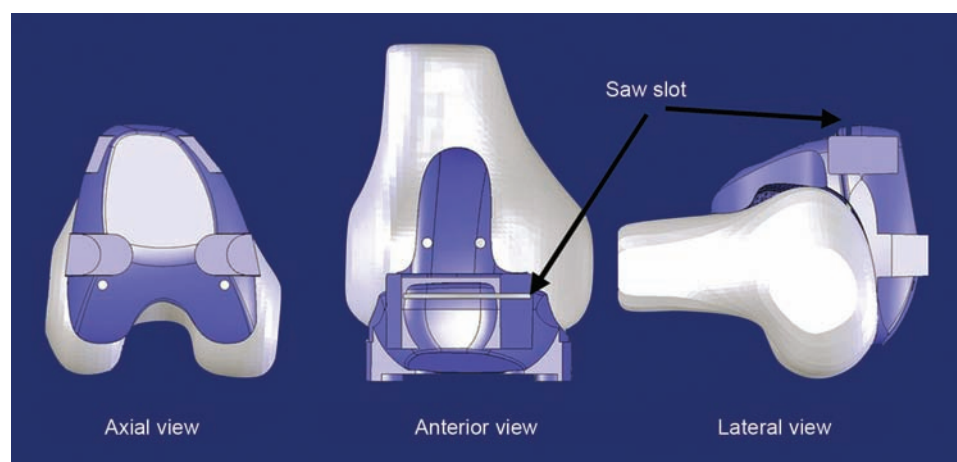


Figure 18 The diagram of the right knee shows the axial, anterior, and lateral view of the patient-specific femoral guide on the 'normal' knee model. The saw slot sets the varus-valgus, flexion-extension, and proximal-distal degrees of freedom of the femoral component. The axial view shows two articular pin holes through which pins are drilled to fix the femoral guide and reference the conventional chamfer block, which sets the internal-external rotation, and anterior-posterior positions of the femoral component. The surgeon visually centers the medial-lateral position of the femoral component after removing marginal osteophytes

femoral component. Before making the anterior and two chamfer cuts, cut and measure the thickness of the two posterior resections and correct the thickness for cartilage and bone wear and saw kerf. When too little or too much bone is removed from both posterior femoral condyles, translate the chamfer guide anteriorly or posteriorly the thickness of the under or over-resection, respectively. When excessive bone is removed from one of the posterior femoral condyles, rotate the chamfer guide the thickness of the over-resection from the over-resected condyle.

One major advantage of the femoral patient-specific cutting guides is that the use of an intramedullary alignment rod is avoided. Avoiding the use of an intramedullary rod prevents spraying fat emboli into the systemic circulation, which may cause hypoxemia and change the thrombolytic coagulation parameters making patients more susceptible to pulmonary embolism. Not using an intramedullary rod to align the femoral component avoids the limitations of trying to center the alignment rod in those femurs with wide variability in the longitudinal shape and diaphyseal diameter that might cause a varus-valgus error in aligning the femoral component.^{13,14,23}

The tibia is exposed while preserving the insertion of the posterior cruciate ligament. It is dislocated anteromedially, both menisci are removed, and anterior osteophytes are trimmed. The patient-specific tibial guide is seated on the articular surface and the anteromedial cortex of the tibia. The guide is compressed and rotated

in the axial or transverse plane until there is a sense that it 'locks' in place. The lateral anterior flange of the tibial guide needs to rest on the anterior lateral cortex of the tibia. The guide is secured with two articular and two anterior pins (Fig. 19). The medial and lateral articular pins are sequentially removed as the tibial cut is made. The medial-lateral thickness and anterior-posterior slope of the resected portion of the tibia are examined. The thickness of the worn side should be thinner than the unworn side by the amount of wear. The anterior-posterior slope of the proximal tibia should be neutral and conservative, which preserves both the insertion of the posterior cruciate ligament and the tibial bone. A long-alignment rod is not used to check the varus-valgus orientation of the tibial cut because the wide variability in the longitudinal shape of the tibia makes the use of the center of the ankle a sometimes unreliable landmark, and because referencing of the center of the ankle may kinematically malalign the knee.²³

We routinely replace the patella in all patients even when they are less than 60-year old based on our experience in 48 subjects, who had bilateral TKAs in which the patella was resurfaced in one knee, but not the other (Fig. 20). At one year, twelve of eighteen subjects with a mechanically aligned knee with the patella resurfaced and a kinematically aligned knee without the patella resurfaced preferred the kinematically aligned knee without the patella resurfaced, and three of fifteen thought both knees were the same ($p = 0.011$).

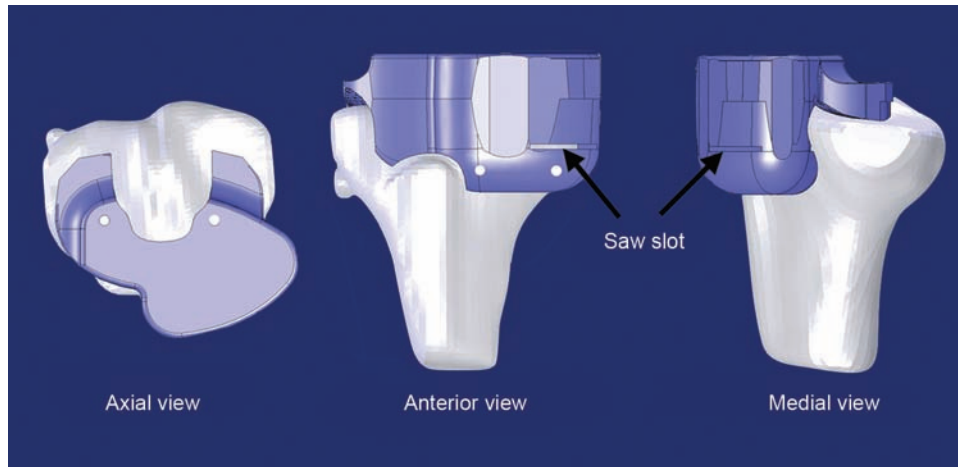


Figure 19 The diagram of a right knee shows the axial, anterior, and medial view of the patient-specific tibial guide on the 'normal' knee model. The saw slot sets the varus-valgus, flexion-extension, and proximal-distal position of the tibial component. The axial view shows two articular pinholes through which pins are drilled to fix the tibial guide. After making the tibial resection, these two holes are used to align the tibial positioning guide, which sets the internal-external rotation and anterior-posterior positions of the tibial component. The surgeon visually centers the medial-lateral position of the tibial component after removing marginal osteophytes

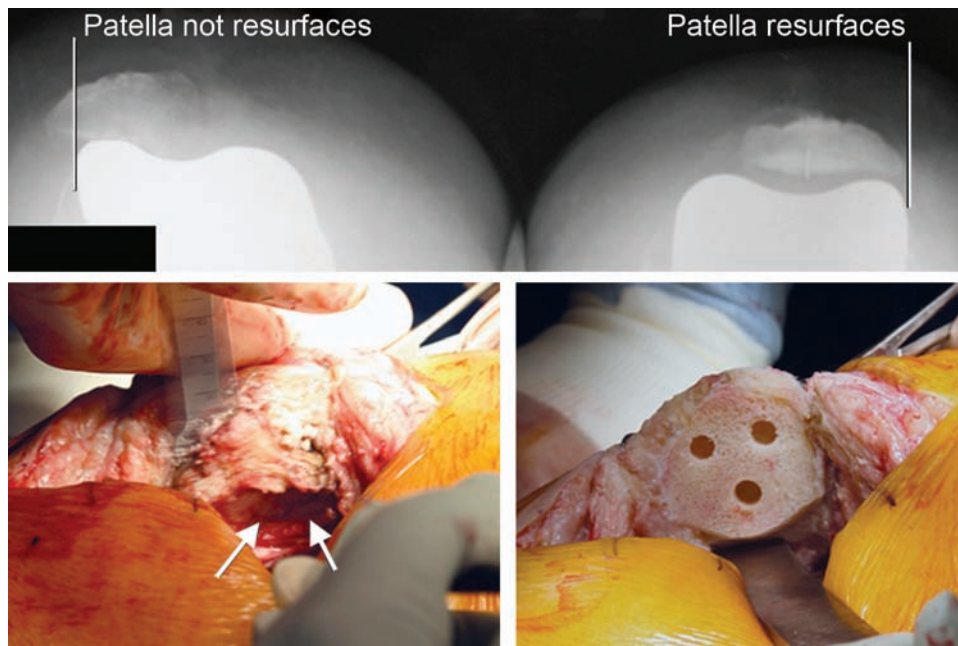


Figure 20 Composite of a skyline radiograph (top row) and intraoperative images of the patella being treated with a delayed resurfacing in a patient (bottom row) with bilateral kinematically aligned TKA. The intraoperative photograph shows that the unresurfaced patella developed a late subluxation and an erosive groove in the lateral patella facet (two black arrows). Although studies of mechanically aligned TKA have shown that resurfacing the patella may not improve the clinical outcome,^{7,8,15,16} our patients with bilateral kinematically aligned TKA prefer the knee with the resurfaced patella

Sixteen of thirty subjects with two kinematically aligned knees, one with and one without the patella resurfaced, preferred the kinematically aligned knee with the patella resurfaced, and eleven of thirty thought both knees were the same ($p = 0.014$). In the kinematically aligned knee, the resurfaced patella tracks well because the transverse axis of the femoral component is aligned parallel to the transverse axis in the femur about which the patella flexes and extends.²² Rarely is a lateral release needed to improve patella tracking except in cases where the primary diagnosis is patellofemoral arthritis and the patella has been chronically subluxated laterally. Although studies of mechanically aligned TKA have shown that resurfacing the patella may not improve the clinical outcome,^{7,8,15,16} our experience suggests that the clinical outcome of the kinematically aligned TKA with the patella resurfaced is better than the kinematically aligned knee without the patella resurfaced, and both are better than the mechanically aligned TKA with the patella resurfaced.

The trial reduction is used to assess the range of motion as well as anterior-posterior and varus-valgus stability at 30° intervals from full extension to full flexion. During the motion and stability assessment a mental note is made of any loss of motion, instability, or tightness, which is then corrected with the use of the previously described algorithm for restoring motion and balancing the kinematically aligned TKA. Correction of a flexion contracture rarely requires additional resection of the distal femur as long as the sequence of removing posterior osteophytes, stripping of the posterior capsule from the femur, and making sure the tibial cut is not sloped anteriorly is followed.⁴⁹ The sequence of complete removal of medial osteophytes, moving the tibia medial on the tibial component, and removing more medial tibia,³⁸ and cutting the tibia in 1 to 2° of varus corrects the limb alignment with medial tightness without releasing the medial ligaments. The sequence of complete removal of lateral osteophytes (and if necessary, then recutting the tibia in 1 to 2° of valgus) corrects the limb alignment with lateral tightness without releasing the medial ligaments.²² The step of increasing the posterior slope of the tibial cut restores motion to the knee with loss of flexion.

The articular pinholes made by drilling through the tibial guide are used to set the internal-external rotation of the tibial component on the tibia. We prefer to use the articular pin holes to set internal-external rotation because: (1) the medial-lateral location of the tibial tubercle is an inconsistent landmark (ranges from 32 to 47 mm from the medial tibia); (2) the range-of-movement or 'floating trial' technique, which allows

the tibial component to orient itself in the best position relative to the femoral component, gives widely variable results; and (3) the registration of anatomical landmarks with conventional and computer-assisted techniques are not reliable or reproducible.^{18,28,47} The tibial template, corresponding to the size of the tibial component, is aligned with the articular pin holes. Small, 1 to 2 mm medial-lateral and anterior-posterior translation adjustments may be required to center the tibia on the tibial component. In the varus knee, moving the tibia medial on the tibial component and removing more medial tibia is effective in restoring coronal alignment and eliminating medial tightness.³⁸

KINEMATICALLY ALIGNED TKA ENABLES A HIGH LEVEL OF EARLY SATISFACTION AND RAPID RECOVERY

As of January 2011, the clinical experience with kinematic alignment with patient-specific guides spans five years and comprises over 23,000 TKAs. In a single-center study of 308 consecutive knees in 285 patients, one author used a hand-held computer (OrthoSight, Conshohocken, PA, www.orthosight.com) to prospectively collect preoperative and postoperative data to assess the level of patient satisfaction and rate of recovery. Each patient spent an average of 8 to 10 minutes filling out a survey of queries consisting of custom questions, Oxford Scores, SF-12 surveys, and Knee Society Scores on the hand-held computer. Requiring the patient to self-answer the survey helped to minimize interviewer bias. Hospital records were assessed to determine the hospital experience with a special analysis of operative time, transfusion rate, length of stay, and whether the patient was discharged home or to a rehabilitation facility.^{22,24}

Patients with a kinematically aligned TKA had a high level of satisfaction, a rapid return to daily activities and an independent lifestyle at 4 to 5 weeks after the surgery. Compared to the knee preoperatively, 88% of patients thought their operated knee was better than before surgery, 8% the same, and 4% worse. Compared to a normal knee, 93.5% of patients thought their treated knee was normal or nearly normal (19.5% normal, 74% nearly normal, 4.5% abnormal, and 2% severely abnormal). Ninety-eight percent thought their limb was aligned 'just right' and 2% thought their limb was too 'knock kneed' (i.e. valgus). By 4-5 weeks, 90% of subjects walked without a walker, 80% walked without a cane, and 54% of those that drove before surgery resumed driving. The hospital stay was short with 6% staying one night, 86% staying two nights, and 7%

staying three nights. Patients rarely required transfer to a nursing home or rehabilitation facility, with 98% of patients being discharged directly to home. By 4–5 weeks patient can expect a significant improvement from their preoperative knee extension and their Oxford, Knee Society, Knee Function, and SF-12 Physical scores.²⁴

A PREDICTION OF THE LONG-TERM CLINICAL OUTCOME OF KINEMATICALLY ALIGNED TKA

One concern of surgeons interested in kinematically aligned TKA is whether the postoperative alignment of the limb, knee, and components predisposes the knee to a higher rate of wear, loosening, and aseptic revision.^{22,33,50} Because long-term data is not available for new alignment techniques, insight about the rate of wear, loosening, and aseptic revision based on alignment can be predicted by comparing the new to established alignment methods that serves as a historical control.

To investigate whether the kinematically aligned TKA is predisposed to early failure, we studied limb, knee, and component alignment in 32 consecutive patients who had a mechanically aligned total knee replacement implanted with conventional instruments and who subsequently were treated with a kinematically aligned TKA in the other knee (Fig. 1). In each kinematically aligned case, the restoration of the obliquity and the level of the femoral joint line to normal was confirmed intraoperatively by creating distal femoral resections that equaled the thickness of the condyle of the femoral component after correcting for bone and cartilage wear and kerf (Fig. 7).

The values for the hip-knee-ankle angle, the anatomic knee angle (formed by the line that bisected the distal ¼ of the femur and the proximal ¼ of the tibia), and the angle formed by each component and the mechanical axis of the femur and tibia are shown in [Table 2](#) and

Fig. 21. The mean limb alignment of both the kinematically and mechanically aligned TKAs was quite close to a straight line mechanical axis, with a hip-knee-ankle angle of $-0.7^\circ \pm 2.8^\circ$ valgus for kinematic alignment and a $-0.2^\circ \pm 2.5^\circ$ valgus for mechanical alignment, the difference not being significant ($p = 0.789$). The mean knee alignment or anatomic knee angle was $-3.6^\circ \pm 2.4^\circ$ valgus for kinematic alignment and $-3.9^\circ \pm 3.1^\circ$ valgus for mechanical alignment (difference not significant ($p = 0.321$)). Based on the similarity of the limb and knee alignment of both alignment methods, the rate of wear, loosening, and aseptic revision as a function of limb and knee alignment should not be different for kinematically and mechanically aligned TKA.

The importance of aligning the femoral and tibial components to the mechanical axes of the femur and tibia for survivorship is controversial. One study of four patients without long-leg radiographs, clinical outcome, or long-term follow-up reported that kinematic alignment placed the components in more than 3° off of the mechanical axis of the femur in the coronal plane. This deviation of the components from perpendicular to the mechanical axes of the femur and tibia was thought to indicate malalignment of the components and to place the arthroplasty at high risk for early failure.³³ Our data describing the alignment of the kinematically and mechanically aligned TKA in the same subject (Table 2) showed that the angle formed by the femoral component and the mechanical axis of the femur was $-2.9^\circ \pm 1.9^\circ$ valgus for the kinematically aligned TKA and $-0.4^\circ \pm 2.4^\circ$ valgus for the mechanically aligned TKA, where the difference was highly significant ($p < 0.0001$). The angle formed by the tibial component and the mechanical axis of the tibia was $2.4^\circ \pm 2.4^\circ$ varus for the kinematically aligned TKA and $0.1^\circ \pm 1.6^\circ$ valgus for the mechanically aligned total knee arthroplasty, of which the difference was highly significant ($p < 0.0001$). The obliquity of the joint line shown by our data in the kinematically aligned TKA, which is not perpendicular to the mechanical axes of the femur and tibia, replicates

Table 16.2

Paired comparison of kinematically and mechanically aligned total knee replacement same patient	Kinematically aligned (N = 32) (Mean (SD))	Mechanically aligned (N = 32) (Mean (SD))	Difference equals kinematic-mechanical (95% CI), p-value
Measurements in Coronal Plane (+ varus/ -valgus in degrees)			
Hip-knee-ankle angle	-0.7 (2.8)	-0.2 (2.5)	-0.5 (-1.8 to 0.8), p = 0.7890
Anatomic angle of knee	-3.6 (2.4)	-3.9 (3.1)	0.3 (-1.1 to 1.8), p = 0.3210
Angle between femoral component and mechanical axis of femur	-2.9 (1.9)	-0.4 (2.4)	-2.5 (-3.5 to -1.4), p < 0.0001
Angle between tibial component and mechanical axis of tibia	2.4 (2.4)	0.1 (1.6)	2.3 (1.3 to 3.4), p < 0.0001

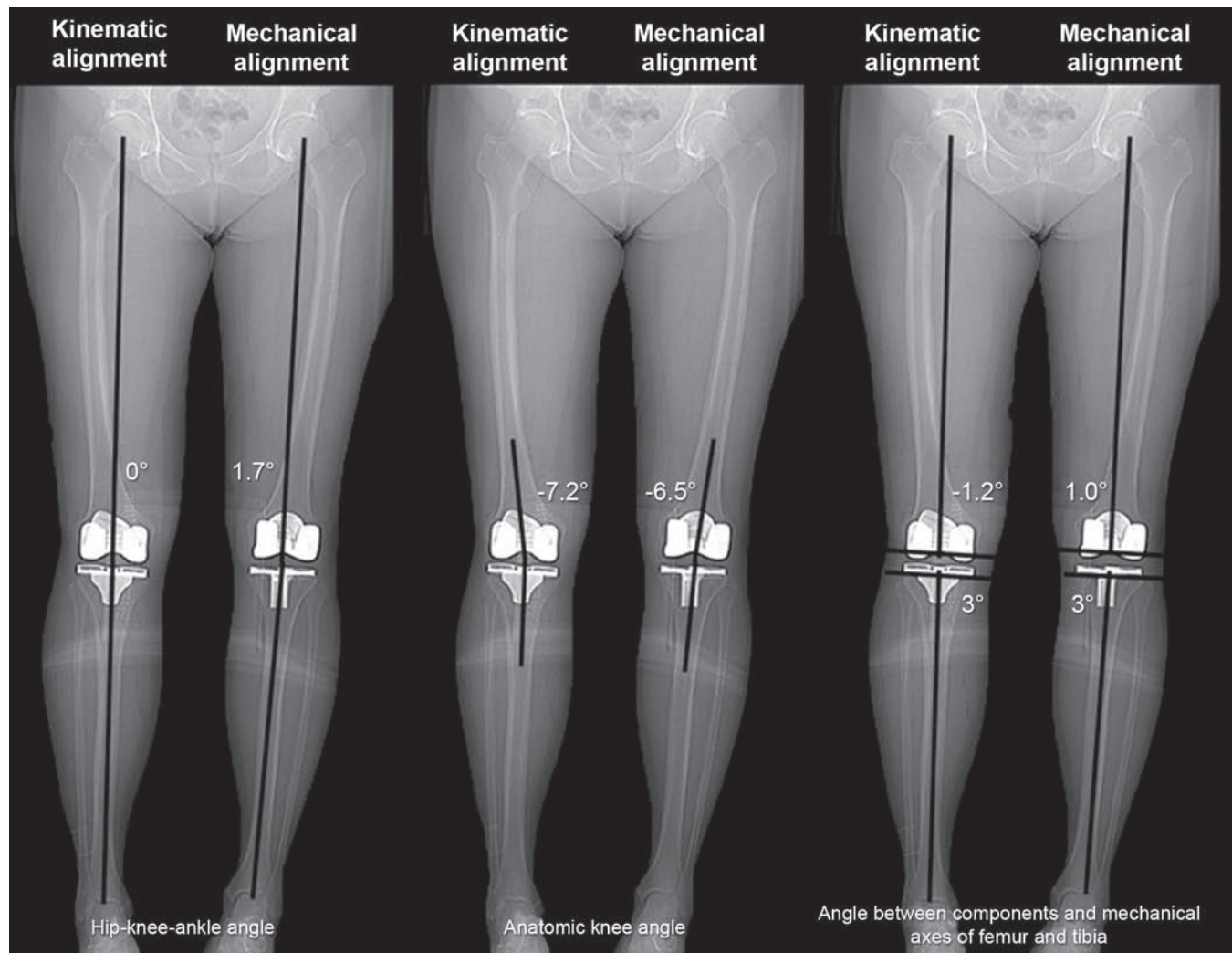


Figure 21 Composite shows the paired measurements of the four alignment parameters performed on the kinematically and mechanically aligned TKA in 32 consecutive subjects. In this case, the limb with the kinematically aligned TKA (0°) had a more neutral hip-knee-ankle angle than the mechanically aligned TKA (1.7° varus) and the anatomic knee angle was similar. However, in the mechanically aligned TKA the femoral component was malaligned in 2.2° more varus than the normal joint line in the kinematically aligned total knee arthroplasty

the normal 'anatomic' limb and the alignment of a TKA favored by Hungerford, Krackow, and Kenna.^{25-27,34} Restoring the normal obliquity and level of the joint line are needed to avoid varus-valgus and anterior-posterior instability in midrange flexion and kinematic malalignment.^{13,14,36,45} A 10-year follow-up study of a prosthesis with tibial component aligned in $3^\circ \pm 3^\circ$ varus similar to the $2.4^\circ \pm 2.4^\circ$ varus alignment of the tibial component in the kinematically aligned TKA showed a 96% survivorship.³⁵ The similarity of the component alignment in the kinematically aligned TKA to the joint line in the normal knee, to anatomic alignment of a TKA, to the component alignment in a study showing 96%

survivorship of the prosthesis at 10 years should allay the concern that the component alignment in kinematically aligned TKA has a high risk of wear, loosening, and aseptic revision.

The mean change in obliquity of 2.5° from the normal joint line with mechanically aligned TKA has two adverse effects on the normal orthogonal relationship of the three kinematic axes. One adverse effect is that the transverse axis of the femur about which the patella flexes and extends is no longer parallel to the transverse axis of the femur about which the tibia flexes and extends, which results in abnormal patello-femoral kinematics. Another adverse effect is that the longitudinal axis in the tibia

about which the tibia internally and externally rotates on the femur is no longer perpendicular to the transverse axis in the femur about which the tibia flexes and extends, which results in abnormal femoral-tibial kinematics. This loss of the normal orthogonal relationships between the three kinematic axes leads to imbalance of the collateral and retinacular ligaments leading to limited motion and altered patella tracking.^{9,13,14,17,21,29} The restoration of flexion-extension, internal-external rotation, and patella tracking often requires release of collateral and retinacular ligaments with the unintended complication of causing instability in other portions of the motion arc, maltracking of the patella, and abnormal contact kinematics with patient standing and kneeling.^{9,13,14,17,21}

CONTACT KINEMATICS APPROACH NORMAL IN KINEMATICALLY ALIGNED TKA

Another concern for surgeons interested in kinematically aligned TKA is whether the motion patterns or contact kinematics between the femoral and tibial components during standing and kneeling are normal.²⁰ Quantifying the contact kinematics of a TKA provides an early method for detecting safety and efficacy issues of a new alignment technique when long-term outcome data are not yet available.³

Motion patterns of lateral condylar lift off (adduction), external rotation of the tibial component, and anterior-posterior edge loading of the tibial liner are undesirable contact kinematics because they indicate component malalignment.^{10,11,52} Varus-valgus malalignment of the femoral and tibial components can result in lateral condylar lift-off of the femoral component and cause medial overload resulting in asymmetrical wear of the polyethylene liner, tibial component loosening, and mechanical failure.^{30,53,54} Internal-external rotational malalignment of the components can result in excessive external rotation of the tibial component during knee motion and cause pain, patellar tracking issues, increased patellar contact forces, and failure.^{5,39,40,46}

Mechanical alignment with conventional instruments often requires collateral ligament releases, which result in a high prevalence of adduction and reverse axial rotation (external rotation) of the tibial component during knee flexion with a variety of component designs. A study of mechanically aligned cruciate-retaining TKAs reported a high prevalence of lateral condylar lift-off (70%) and external rotation of the tibial component (24%) in a non-consecutive series of well-functioning subjects.^{10,11}

We used a radiographic image-matching technique to determine the contact kinematics during standing and kneeling at 90° and maximum flexion in a series of 32 subjects with a kinematically aligned TKA with a cruciate-retaining prosthesis²⁰ (Fig. 22). The kinematically aligned prosthesis had a minimal prevalence of lateral condylar lift off (adduction) (3%) and a low prevalence of external rotation of the tibia (8.5%). The antero-posterior contact positions of the lateral and medial femoral condyles did not edge load the tibial liner. These more normal contact kinematics in the kinematically aligned TKA were achieved without release of the collateral ligaments or lateral retinaculum. In contrast to historical reports of mechanical alignment with conventional surgical techniques,^{10,11} the use of kinematically aligned TKA with patient-specific cutting guides and a cruciate-retaining, symmetric medial and lateral femoral-tibial bearing surface minimizes the undesirable consequences of lateral condylar lift-off and external rotation of the tibia.

SUMMARY

The primary goals of this chapter were to advance the understanding of kinematic aligned TKA and stimulate debate. Kinematic alignment may possibly offer a much-needed alternative because mechanical alignment with conventional and computer-assisted techniques has a high prevalence of patient dissatisfaction (approximately 20%) due to continued pain and poor function in activities of daily living. The location, importance, and inter-relationships between the three axes responsible for normal knee kinematics were described and the fact that mechanical alignment ignores these axes when placing TKA components was highlighted.^{9,13,14,17} The use of shape-matching to kinematically align the femoral component was described. The intraoperative confirmation of kinematic alignment of the femoral component before cementation by creating equal thickness distal and posterior femoral bone resections that match the condyle of the femoral component after correcting for wear and kerf was detailed. The penalties from aligning the femoral component perpendicular to the mechanical axes of the femur are changes in the obliquity and level of the joint line from normal, which often creates an uncorrectable ligament imbalance. The methods for virtual planning and aligning the components, and intraoperatively kinematically positioning a TKA with patient-specific femoral and tibial guides based on an MRI of the arthritic knee were described. A step-by-step algorithm with a defined end-point for restoring motion and balancing the kinematically aligned TKA that relies

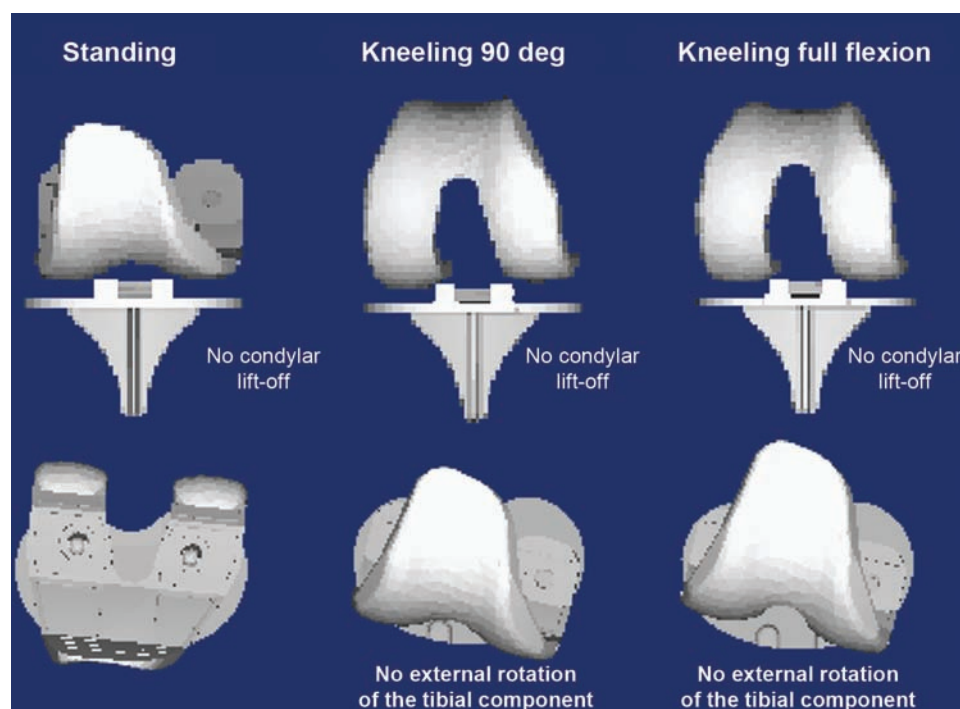


Figure 22 Composite of a right knee shows the relationship between the femoral and tibial components in a kinematically aligned TKA of a subject standing in extension (left), kneeling in 90° of flexion (middle), and kneeling in maximum flexion (right). The upper row shows the AP view and lower row shows the top or axial view. In this case, there was no condylar lift-off and no external rotation of the tibial component with knee flexion, which means the pattern of these contact kinematics closely match the normal knee

on osteophyte removal and modifying the plane of the tibial cut without releasing collateral ligaments and the posterior cruciate ligament was provided. A clinical study with short-term follow-up documented the high-level of early patient satisfaction and rapid recovery after kinematically aligned TKA. A paired study showed the limb and knee alignments of kinematically and mechanically aligned TKA are similar which justified the opinion that wear, loosening, and aseptic revision should be no greater in the kinematically aligned than in the mechanically aligned TKA. The kinematically aligned TKA restores more normal contact kinematics than mechanical alignment.

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