Kinematically Aligned Total Knee Arthroplasty Using Calipered Measurements, Manual Instruments, and Verification Checks

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24.1 Overview

This chapter presents the philosophy of kinematic alignment (KA) and the surgical technique for setting the positions of the components using ten calipered measurements, manual instruments, and nine verification checks. The adoption of kinematic alignment is increasing. Four meta-analyses, three randomized trials, and a national multicenter study showed that patients treated with KA total knee arthroplasty (TKA) reported significantly better pain relief, function, and flexion and a more normal feeling knee than patients treated with mechanically aligned (MA) TKA [1–8]. Two randomized trials that limited the severity of the preoperative knee deformities showed similar clinical outcomes [9, 10]. KA co-aligns the axes of the femoral and tibial components with the three axes of the native knee without restrictions on

the level of preoperative deformities [11]. The surgical goal of restoring the native alignments of the limb, Q-angle, and joint lines unique to each patient depends on accurately setting the components coincident to the native joint lines, which co-aligns the axes. The surgical goal of restoring the laxities, tibial compartment forces, knee adduction moment, and gait to those of the native knee without ligament release balances the TKA and promotes long-term implant survival [12–19]. A description of the calipered technique of KA with manual instruments, the sequence for measuring bone positions and resection thicknesses, the intraoperative recording of these measurements on the verification worksheet (Fig. 24.1), and the use of decision trees for balancing the TKA with the medial pivot CS and CR inserts are shown (Figs. 24.2 and 24.3). Calipered measurements of the thicknesses of the femoral and tibial bone resections restore the native joint lines with high reproducibility when they are adjusted within ±0.5 mm of the femoral and tibial components after compensating for cartilage and bone wear and the 1 mm kerf from the saw cut [20–22]. Because calipered measurements are a basic surgical skill, inexpensive, and highly reliable, they should be a required verification check when performing kinematic alignment with manual instruments, patient-specific guides, navigation,

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RECORD OF VERIFICATION CHECKS FOR CALIPERED KINEMATICALLY ALIGNED MEDACTA GMK SPHERE TKA

SURGEON _____ PATIENT CODE _____ DATE (DD/MM/YYYY) _____

KNEE ☐ RIGHT ☐ LEFT

OA DEFORMITY ☐ VARUS ☐ VALGUS ☐ PF

ACL CONDITION
☐ INTACT ☐ TORN ☐ GRAFT

A/P OFFSET
EXPOSURE _____ mm TRIALING _____ mm DIFFERENCE _____ mm

DISTAL FEMORAL RESECTION
Target Thickness: 8mm Unworn, 6mm Worn (No Cartilage)

MEDIAL CONDYLE		**LATERAL CONDYLE**	
☐ UNWORN	☐ WORN	☐ UNWORN	☐ WORN
RESECTION _____ mm		RESECTION _____ mm	
☐ RECUT _____ mm		☐ RECUT _____ mm	
☐ WASHER _____ mm		☐ WASHER _____ mm	

POSTERIOR FEMORAL RESECTION
Target Thickness: 7mm Unworn, 5mm Worn (No Cartilage)

MEDIAL CONDYLE		**LATERAL CONDYLE**	
☐ UNWORN	☐ WORN	☐ UNWORN	☐ WORN
RESECTION _____ mm		RESECTION _____ mm	
☐ RECUT _____ mm		☐ RECUT _____ mm	

TIBIAL RESECTION
Target: Equal Thickness Measured at Base of Tibial Spines

☐ M
☐ L

☐ M
☐ L

_____ mm _____ mm

PCL CONDITION
☐ INTACT ☐ TORN ☐ EXCISED

☐ TIBIAL V-V RECUT _____
☐ TIBIAL SLOPE RECUT _____

☐ NEGLIGIBLE V-V LAXITY IN EXTENSION WITH SPACER BLOCK

FEMUR SIZE	TIBIA SIZE	INSERT THICKNESS	PATELLA SIZE
		☐ CR ☐ CS	

Fig. 24.1 Verification checks consisting of serial calipered measurements of bone positions and resection thicknesses within ±0.5 mm of target are recorded intraoperatively on a worksheet. Recording these steps validates that the femoral and tibial components are kinematically aligned coincident to the native femoral and tibial joint lines before cementation

DECISION-TREE FOR BALANCING A CALIPERED KINEMATICALLY ALIGNED MEDACTA GMK SPHERE CR TKA					
Tight in Flexion & Extension	Tight in Flexion Well-Balanced in Extension	Tight in Extension Well-Balanced in Flexion	Well-Balanced in Extension and Loose in Flexion	Tight Medial & Loose Lateral in Extension	Tight Lateral and Loose Medial in Extension
Recut tibia and remove 1-2mm more bone.	Increase posterior slope until exposure A-P offset is restored at 900 of flexion.	Remove posterior osteophytes. Strip posterior capsule. Insert trial components & gently manipulate knee into extension.	Add thicker insert and recheck knee extends fully. When knee does not fully extend check PCL tension. When PCL is incompetent use GMK Sphere CS Insert.	Remove medial osteophytes. Reassess. Recut tibia in 1-2° more varus. Insert 1 mm thicker insert.	Remove lateral osteophytes. Reassess. Recut tibia in 1-2° more valgus. Insert 1 mm thicker insert.

Fig. 24.2 The decision tree lists six corrective measures for balancing the KA TKA with a posterior cruciate ligament-retaining (CR) sphere insert. The balancing steps adjust the proximal–distal level and varus–valgus and slope orientations of the tibial resection and insert thickness without recutting the femur or releasing the collateral, retinacular, and posterior cruciate ligaments

DECISION-TREE FOR BALANCING A CALIPERED KINEMATICALLY ALIGNED MEDACTA GMK SPHERE CS TKA					
Tight in Flexion & Extension	Tight in Flexion Well-Balanced in Extension	Tight in Extension Well-Balanced in Flexion	Well-Balanced in Extension and Loose in Flexion	Tight Medial & Loose Lateral in Extension	Tight Lateral and Loose Medial in Extension
Recut tibia and remove 1-2mm more bone.	Confirm complete resection of the PCL. Increase posterior slope until natural A-P offset is restored at 90° of flexion.	Remove posterior osteophytes. Strip posterior capsule. Insert trial components & gently manipulate knee into extension.	Add thicker insert and recheck knee extends fully. If still loose in flexion, then reduce slope or resect 1-2 mm bone from distal femur and add thicker GMK Sphere CS insert.	Remove medial osteophytes. Reassess. Recut tibia in 1-2° more varus. Insert 1 mm thicker insert.	Remove lateral osteophytes. Reassess. Recut tibia in 1-2° more valgus. Insert 1 mm thicker insert.

Fig. 24.3 The decision tree lists six corrective measures for balancing the KA TKA with a posterior cruciate ligament-substituting (CS) sphere insert. The balancing steps adjust the proximal–distal level and varus–valgus and slope orientations of the tibial resection and insert thickness without releasing collateral, retinacular, and posterior cruciate ligaments. When the posterior cruciate ligament is unintentionally transected with the saw or detached from the tibia the flexion space increases whereas the extension space does not. Bone grafting the posterior 1/3 rd of the tibial resection, recutting the tibia in less slope, and resecting 2 mm of bone from the distal femur and using a thicker insert are strategies for compensating for the increase in flexion space laxity

and robotics. Examples of treatment of patients with severe varus and valgus deformities and flexion contractures treated with KA TKA without ligament release are shown. Finally, the reasons for the low risk of tibial component failure, low risk of patellofemoral instability, and high implant survival at 10 years after KA TKA are explained [11, 23, 24].

24.2 Co-aligning the Axes of the Femoral and Tibial Components with the Three Axes of the Native Knee Is the Philosophy of Kinematic Alignment

The term "kinematic alignment" indicates the surgeon follows the philosophy of co-aligning the axes of the femoral and tibial components with the three axes of the native knee without ligament release and without restrictions on the degree of preoperative varus, valgus, flexion, and extension deformities [3, 21, 25–27]. Calipered measurements of femoral and tibial bone resections verify the alignment of the components coincident to the native joint lines and co-alignment of the axes of the components with the three "kinematic" axes of the native knee (Fig. 24.4) [22]. The first axis is in the native femur and connects the center of the best-fit circles to the posterior femoral condyles from 20° to 120° like an axle passing through two wheels. This axis controls the arc of flexion and extension of the tibia with respect to the femur [26, 28–31]. The second axis is in the native femur and lies parallel and averages 10 mm anterior and 12 mm proximal to the first axis. This axis controls the arc of flexion and extension of the patella

with respect to the femur [25, 27]. The flexion–extension plane lies perpendicular to the two femoral axes in the extended knee [32, 33]. The third axis is in the native tibia and lies perpendicular to the two femoral axes and native joint lines of the femur and tibia. This axis controls internal–external rotation of the tibia with respect to the femur [25, 26]. Because the orientations of three kinematic axes are closely parallel or perpendicular to the native joint lines, setting the femoral and tibial components coincident to the native joint lines after compensating for cartilage wear and the kerf of the saw cut closely co-aligns the axes of the components with those of the native knee, which preserves the native resting lengths of the collateral, posterior cruciate, and retinacular ligaments [21, 22, 34].

24.3 First Surgical Goal: Restore the Native Joint Lines, Q-Angle, and Limb Alignments Unique to Each Patient

Restoring the native joint lines, Q-angle, and limb alignments unique to each patient is the first surgical goal of calipered KA TKA [3, 21, 35].
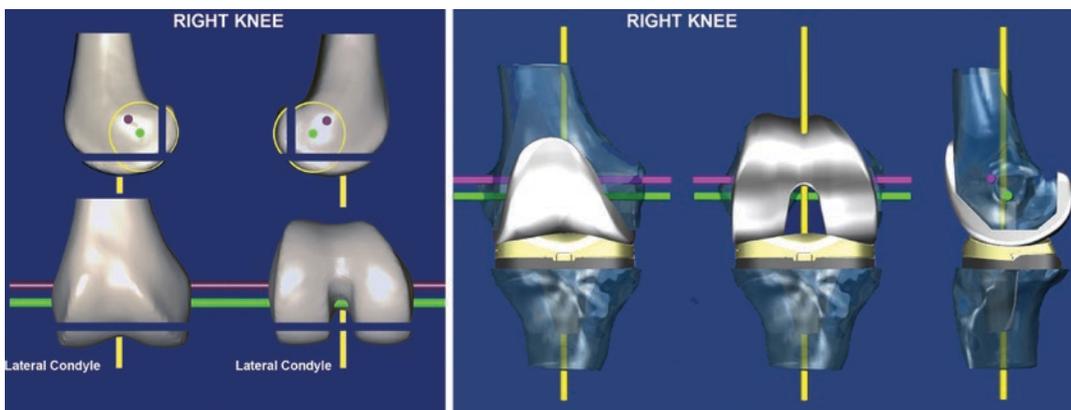
Fig. 24.4 Projections of the right distal femur (left) and KA TKA (right) show the parallel and perpendicular relationships between the three "kinematic" axes of the native knee show the anatomic basis of the philosophy of co-aligning the axes of the components with those of the native knee [48]. The flexion–extension axis of the tibia is the green line, the flexion–extension axis of the patella is the magenta line, and the internal–external axis of the tibia is the yellow line. All three axes are closely parallel or perpendicular to the joint lines of the native knee. Resecting bone from the distal and posterior femur condyles equal in thickness to the condyles of the femoral component after compensating for 2 mm of cartilage wear and 1 mm kerf of the saw cut sets the femoral component coincident to the native joint lines and co-aligns the axes

There is a growing body of evidence that a substantial number of native limbs do not have a neutral or 0° hip–knee–ankle (HKA) angle prior to the onset of osteoarthritis [12, 31, 35–38]. The maximum range reported for the HKA angle is 7°–12° for constitutional varus and −4° to −16° for constitutional valgus for people in the United States, Korea, India, and Belgium [31, 36–38]. Hence, when mechanical alignment changes constitutional varus and valgus alignment to a 0° HKA angle, the native joint lines and Q-angle are changed. Changing the native joint lines overly

tensions or slackens the collateral, retinacular, and posterior cruciate ligaments and frequently creates an extension–flexion imbalance in a compartment that is uncorrectable with a soft tissue release [18, 19, 35, 36, 39–42] (Figs. 24.5 and 24.6). The technique of kinematic alignment using ten calipered measurements is highly reproducible as the left to right symmetry of the distal lateral femoral angle (DLFA), proximal medial tibial angle (PMTA), Q-angle, and HKA angle is restored to that of the native limb in >95% of patients with negligible risk of varus

Fig. 24.5 Composite of a patient with a constitutional varus limb (left) shows calipered KA restored the native joint lines (light blue lines), Q-angle (dark blue lines), distal lateral femoral angle (pink lines), and proximal medial tibial angle (green lines) in the limb with the TKA without ligament release (right)

Fig. 24.6 Composite of a patient with a constitutional valgus limb (left) shows calipered KA restored the native joint lines (light blue lines), Q-angle (dark blue lines), distal lateral femoral angle (pink lines), and proximal medial tibial angle (green lines) in the limb with the TKA without ligament release (right)

alignment of the tibial component with respect to the native tibial joint line [20, 21].

24.4 Second Surgical Goal: Restore Laxities, Tibial Compartment Forces, and Knee Adduction Moment of the Native Knee Without Ligament Release

Restoring the native laxities, tibial compartment forces, knee adduction moment, and gait without ligament release is the second surgical goal of calipered KA TKA [12, 13, 16–19, 43]. The varus–valgus and internal–external rotation laxities of the native knee are looser at 45° and 90° of flexion than at 0° (Fig. 24.7). The penalty for performing gap-balancing TKA, which tightens the native laxities at 45° and 90° to match those at 0° of flexion, is overly tight ligaments relative to those of the native knee that patients might perceive as pain, stiffness, and limited extension and flexion [14, 19].

Most TKA techniques resect the ACL and replace the articular cartilage and menisci with implants of graduated sizes with conformities and stiffnesses different from the native knee. A study in cadaveric knees showed that kinematic alignment with a posterior cruciate ligament-retaining implant restored 35 of 40 measures of laxity (8 laxities × 5 flexion angles) to those of the native knee. The restoration of most of the native laxities suggests that femoral and tibial components aligned with KA compensate for the articular cartilage, menisci, and ACL [16].

KA without ligament release limits high compartment forces by restoring those of the native knee [17–19, 43]. There is no evidence of medial or lateral compartment overload even in the subset of patients with alignment of the tibial joint line and limb in a varus or valgus outlier range according to MA criteria [19]. In contrast, the medial and lateral tibial compartment forces after mechanical alignment and ligament release to a 0° hip–knee–ankle with measured resection and gap-balancing techniques are three to six times higher than those of the native knee at 0°, 45°, and 90° of flexion [17, 19, 42, 44]. Hence, KA without ligament release restores native medial and lateral tibial compartment forces, whereas MA with ligament release does not [17–19].

KA restores the native joint line obliquity [7, 12, 45], which reduces the peak knee adduction moment during gait and better restores normal gait when compared to MA TKA [12, 13]. A low knee adduction moment is one explanation for the negligible risk of varus failure of the tibial component 2–10 years after KA TKA [11, 23]. Hence, KA is a promising option in limbs with constitutional varus alignment and large coronal bowing of the tibial shaft as the low knee adduction moment and more normal gait lowers the risk of medial compartment overload [12].

24.5 Calipered Technique for Setting the Femoral Component Coincident to the Native Femoral Joint Line with Verification Checks

The following sequence of surgical steps, calipered measurements, and adjustments and the intraoperative recording of these measurements on a verification worksheet set the proximal–distal position and varus–valgus orientation of the femoral component coincident to the native distal joint line at 0° and the anterior–posterior position and internal–external orientation of the femoral component coincident to the native posterior joint line at 90° with high reproducibility (Fig. 24.4) [21, 24, 32]. The femoral mechanical axis, trans-epicondylar axis, and anterior–posterior axis (Whiteside's line) are not of interest or use when kinematically aligning the femoral component [26, 31, 39, 40, 46, 47].

Flex the knee to 90°. Expose the knee using a medial approach. Position the short arm of the offset caliper against the distal medial femoral condyle and the long arm against the anterior tibia (Fig. 24.8). Orient the long arm
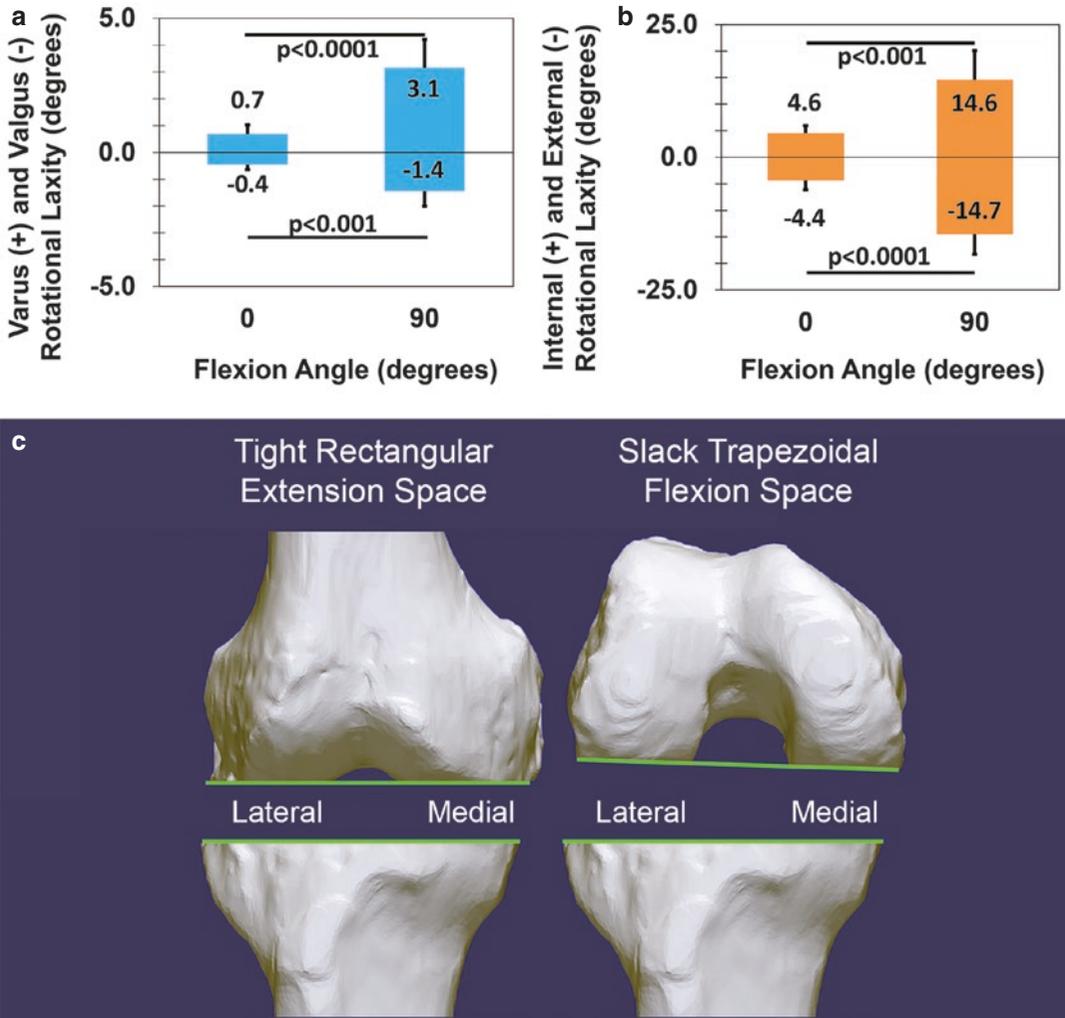
Fig. 24.7 Column graphs show the varus–valgus and internal–external rotational laxities of the native knee are greater at 90° than at 0° of flexion (**a**, **b**) [14, 15]. During knee arthroscopy, the surgeon notices these relative differences in laxity as a tight rectangular space when the knee is in extension and a slack trapezoidal space with more laxity laterally than medially when the knee is in flexion. The schematic shows that the resections of the femur and tibia with calipered KA restore the tight rectangular extension space and slack trapezoidal flexion space of the native knee (**c**). Hence, calipered KA restores 35 of 40 measures of laxity of the native knee [16], whereas the MA concept of gap balancing overtightens the flexion space that patients may perceive as pain, stiffness, and limited flexion [14]

parallel to the patellar tendon. Measure the distance of the offset. Subtract 2 mm when cartilage is worn to bone on the medial femoral condyle [48].

Verification Check 1: Record the offset measurement on an electronic or paper version of the verification worksheet (Fig. 24.1). During final balancing before cementation of the components, adjustments are made to the slope of the tibial resection and insert thickness until the offset is

matched within 0 ± 1 mm, which restores the native laxities and tibial compartment forces of the flexion space (Fig. 24.7) [15, 16, 48].

Expose the knee fully and assess the locations of cartilage wear on the distal femur. Remove any partially worn cartilage to bone with a ring curette. Set the flexion–extension orientation of the femoral component by starting the diameter hole for the positioning rod midway between the top of the intercondylar notch and the anterior
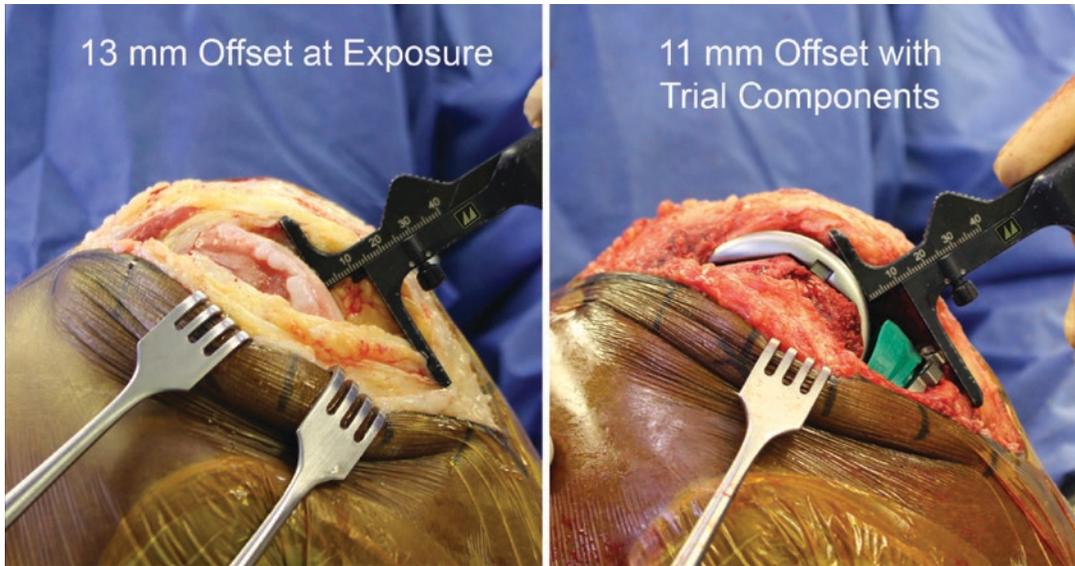
Fig. 24.8 Intraoperative photographs of a right knee in 90° of flexion show the caliper measurement of the "offset" of 13 mm between the distal medial femur and the anterior tibia at the time of exposure with the longer arm of the caliper-oriented parallel to the patellar tendon in the sagittal plane (left). When cartilage is worn to bone, subtract 2 mm from the measurement. During final balancing before cementation of the components, the slope of the tibial resection and insert thickness are adjusted until the offset with trial components matches the corrected offset of the knee at the time of exposure of 11 mm and passive internal–external rotation of the tibia ~±14° like the native knee (right) (Fig. 24.7) [14]. A 2° increase in the posterior slope and a 2 mm decrease in the insert thickness translates the tibia ~3 mm posterior [17, 53]

cortex (Fig. 24.9). Keep a 5–10 mm bridge of bone between the posterior rim of the drill hole and the top of the intercondylar notch. Orient the drill perpendicular to a plane coincident to the distal surface of the femur and parallel with the anterior cortex of the femur. Drill and then insert a positioning rod 8–10 cm.

Verification Check 2: Keeping a 5–10 mm bridge of bone between the posterior rim of the drill hole and the top of the intercondylar notch limits flexion of the femoral component to within 1° ± 2° with respect to the anatomic axis of the distal femur resulting in a negligible risk of patellofemoral instability [49–51].

Set the proximal–distal position and varus–valgus orientation of the femoral component by using an offset distal referencing guide (Fig. 24.10). Select the offset of the guide so that a compensation of 2 mm is added to the distal femoral condyle(s) with cartilage wear. Do not correct for distal femoral bone wear as it is negligible even in the most arthritic knees [34, 48].

Slide the selected offset distal referencing guide over the intramedullary rod. Confirm the offset surface of the guide contacts both distal femoral condyles. Pin the guide and resect the distal femur. Measure the thicknesses of the distal medial and lateral bone resections with a caliper. Adjust the resections of the distal femur until their thicknesses match the distal condyles of the femoral component within ±0.5 mm after compensating for 2 mm of cartilage wear and a 1 mm kerf from the saw cut.

- Correct a 1 or 2 mm underresection of the distal femoral condyles by removing more bone from the distal femur with use of a 1 mm distal recut guide or by repositioning the distal femoral resection guide 2 mm more proximal.
- Correct a 1 or 2 mm overresection of a distal femoral condyle by filling the gap by placing a 1 or 2 mm-thick washer on the corresponding fixation peg of the 4-in-1 block.
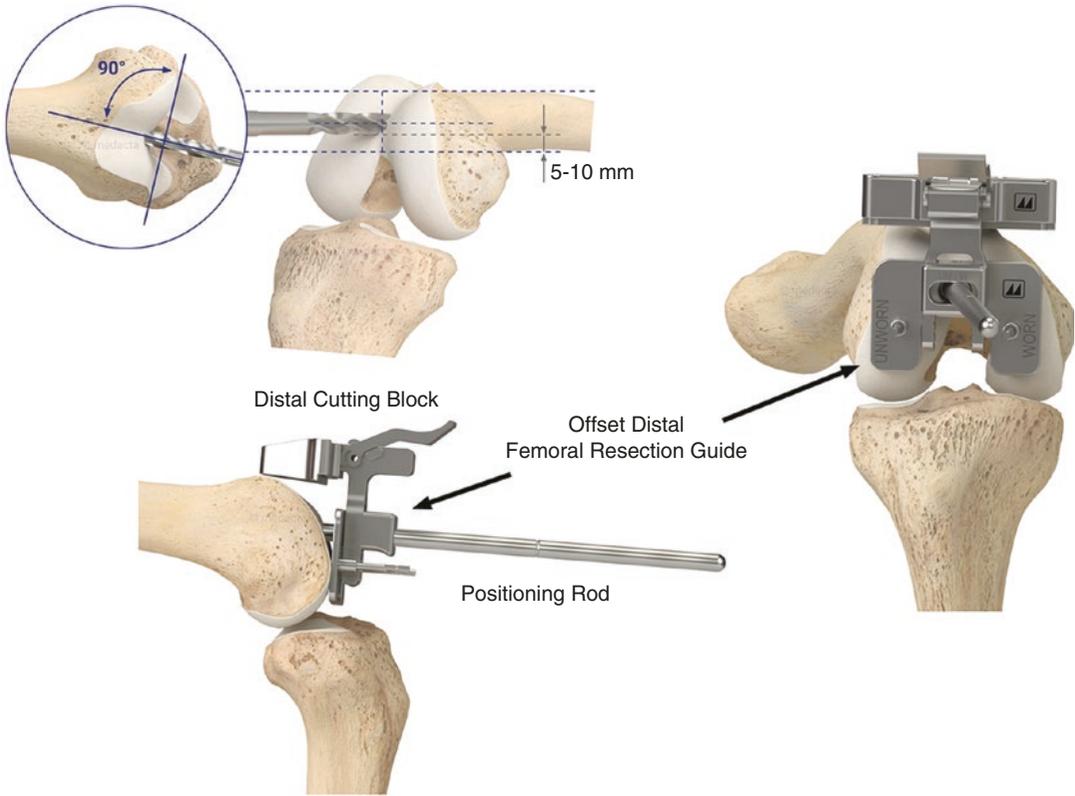
Fig. 24.9 Schematic shows the method for limiting flexion of the femoral component, which results in a negligible risk of patellofemoral instability [49–51]. Start the drill hole midway between the anterior limit of the notch and the anterior cortex of the femur (short blue-dotted line). Orient the drill perpendicular to a plane coincident to the distal surface of the femur and parallel with the anterior cortex of the femur. A starting point that keeps a 5–10 mm bone bridge between the posterior rim of the drill hole and the top of the intercondylar notch limits flexion of the femoral component to within $1° \pm 2°$ with respect to the anatomic axis of the distal femur [50]

Verification Check 3: Record the calipered measurements on the verification worksheet (Fig. 24.1). The calipered measurements restore the varus–valgus orientation of the femoral component to the contralateral native limb in 97% of subjects [21].

Set the anterior–posterior position and internal–external orientation of the femoral component by selecting a posterior referencing guide set in 0° rotation and positioning the feet of the guide in contact with the posterior femoral condyles (Fig. 24.11). In the most varus osteoarthritic knee, the use of the 0° posterior referencing guide is correct because complete cartilage wear is rare on the posterior medial femoral condyles. In the most severe valgus osteoarthritic knee, the 0° posterior referencing guide occasionally requires rotation of the foot of the guide 1–2 mm posterior from the worn posterior lateral femoral condyle. Do not correct for posterior femoral bone wear as it is negligible even in the most arthritic knees [34, 48].

Size the femoral component by positioning the stylus on the anterior femur. Drill the holes for the 4-in-1 chamfer block. Insert the 4-in-1 chamfer block remembering to place a 1 or 2 mm-thick washer on the corresponding fixation peg to correct for a 1 or 2 mm overresection of a distal femoral condyle. Make the posterior resections before making the anterior and chamfer cuts. Measure the thicknesses of the distal medial and lateral bone resections with a caliper. Adjust the resections of the posterior femur until their
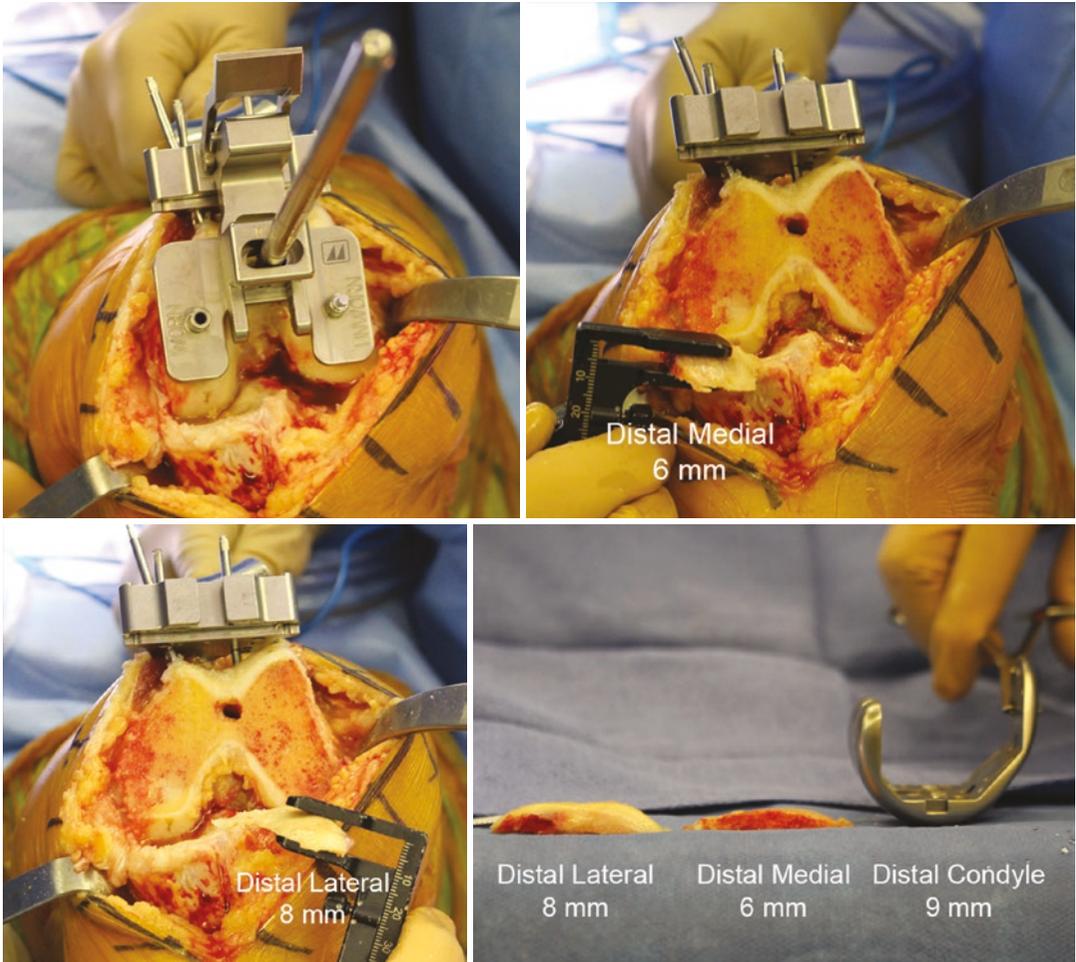
Fig. 24.10 Composite of a left varus osteoarthritic knee shows the steps for kinematically aligning the femoral component coincident to the distal joint line of the native femur. Pin the offset distal femoral resection guide with the "WORN" mark overlying the medial femoral condyle and the "UNWORN" mark overlying the lateral femoral condyle (upper left). Measure the distal medial resection with a caliper (upper right). Measure the distal lateral resection with a caliper (lower left). The distal condyles of the femoral component are 9 mm thick (lower right). Hence, the distal medial and lateral femoral resections should be 6 and 8 mm thick, which compensate for the 1 mm of kerf of the saw and the 2 mm of cartilage wear on the distal medial femoral condyle. Recording these calipered measurements verifies the varus–valgus orientation of the femoral component is coincident to the native joint line and matches the contralateral native limb in 97% of the subjects [21]
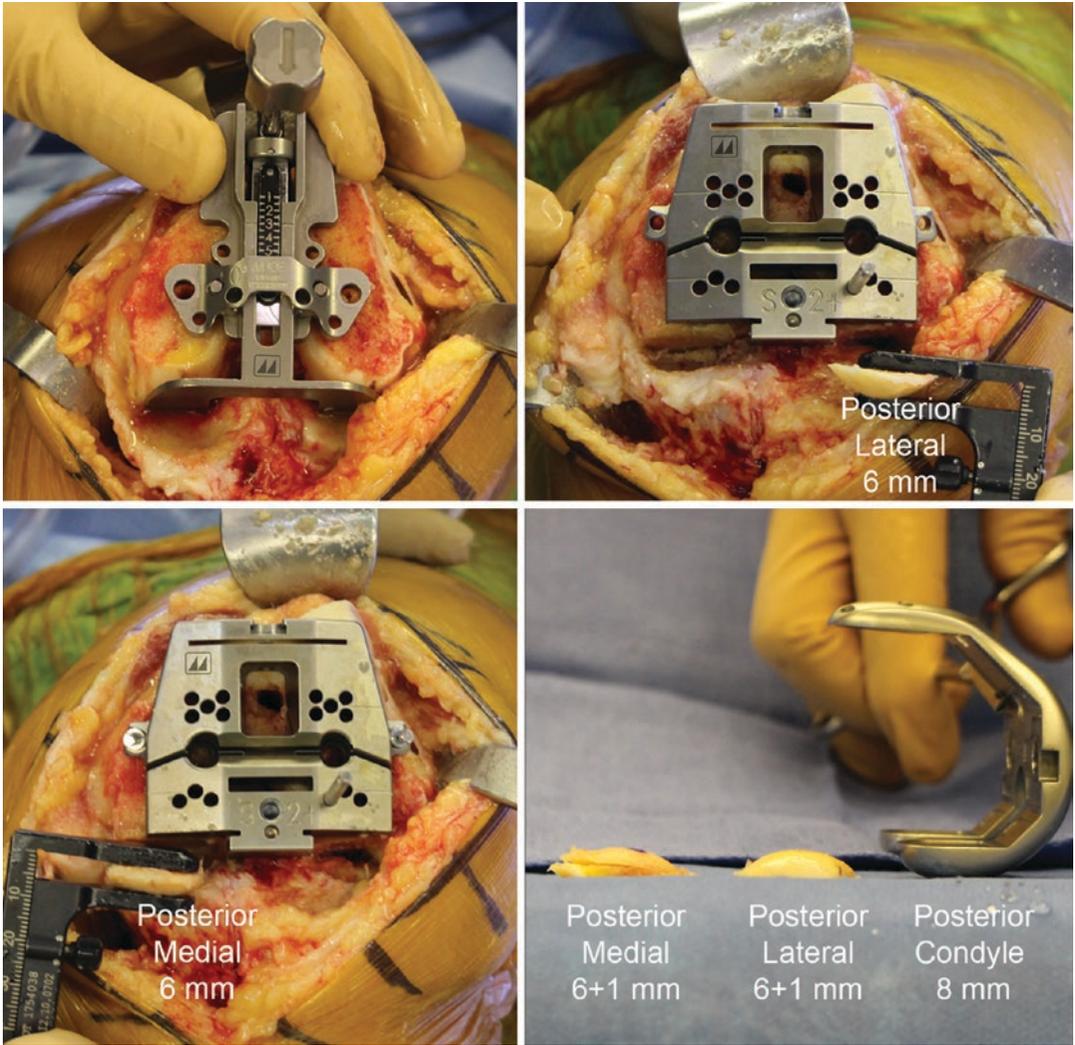
Fig. 24.11 Composite of a left varus osteoarthritic knee shows the steps for kinematically aligning the femoral component coincident to the posterior joint line of the native femur. Insert a posterior referencing guide set at 0° rotation and drill holes for the 4-in-1 chamfer block (upper left). Measure the posterior lateral resection with a caliper (upper right). Measure the posterior medial resection with a caliper (lower left). Hence, the posterior medial and lateral resections should be 7 mm thick, which compensates for the 1 mm kerf of the saw (lower right). The +1 indicates 1 mm of additional bone was resected to correct a saw blade that skived during the initial posterior resection. Recording these calipered measurements verifies the internal–external orientation of the femoral component is coincident to the posterior joint line of the native knee within 0° ± 1.1 [32]

thicknesses match the posterior condyles of the femoral component within ±0.5 mm after compensating for 2 mm of cartilage wear when present and a 1 mm kerf from the saw cut. When a posterior femoral resection is 1–2 mm too thick or too thin, elongate the pin hole in the direction of the correction and translate the 4-in-1 chamfer block as needed. Insert the oblique compression screws and secure the reposition of the chamfer block. Make the anterior and chamfer femoral resections.

Verification Check 4: Record the calipered measurements on the verification worksheet (Fig. 24.1).The calipered measurements reproducibly restore the internal–external orientation of the femoral component within 0° ± 1.1° of the posterior joint line and the flexion–extension plane of the native knee [32].

24.6 Calipered Technique for Setting the Tibial Component Coincident to the Native Tibial Joint Line with Verification Checks

The following sequence of surgical steps, calipered measurements, and adjustments verify the proximal–distal position and the varus–valgus, flexion–extension, and internal–external orientations of the tibial component are coincident to the native tibial joint line. The tibial mechanical axis, intramedullary canal, and tibial tubercle are not of interest or use when KA the tibial component [11, 21, 40, 47, 52].

Use an extramedullary tibial guide as a support for positioning the tibial resection guide and not as a method for referencing the ankle (Fig. 24.12). Set
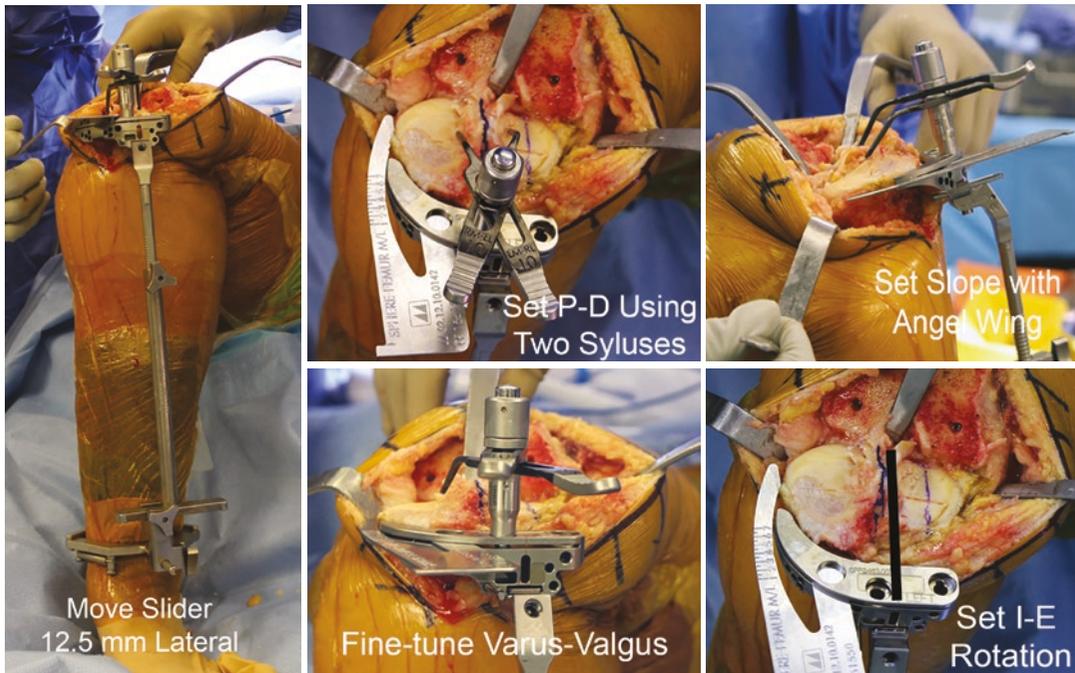
Fig. 24.12 Composite of a right knee shows the steps for KA the tibial component. Set the varus–valgus position of the tibial resection by applying a conventional extramedullary tibial resection guide to the ankle and moving the slider 12.5 mm lateral from the 0 mm position (left). Set the proximal–distal position by registering the tips of the two styluses at the base of each tibial spine in an area with intact cartilage (upper middle). Set the slope by adjusting the anterior–posterior slider at the ankle until the plane of the angel wing parallels the medial tibial joint line after compensating for cartilage and bone wear (upper right). Fine-tune the varus–valgus and slope orientation of the tibial resection guide to compensate for cartilage and bone wear (lower middle). Set internal–external orientation by rotating the tibial cutting guide until the line on the top of the guide is parallel to a line drawn between the tibial spines (black line) and a line representing the major axis of the elliptical-shaped lateral tibial condyle (faint blue line) (lower right)

the varus–valgus orientation of the tibial resection guide parallel to the articular surface of the native tibia by translating the medial–lateral slider at the ankle 12.5 mm lateral, which achieves an anatomic or ~2–3° varus orientation to the tibial mechanical axis in most patients [3, 10]. Set a conservative proximal–distal position for the tibial resection by positioning the tips of the two styluses with the 8 mm offset at the base of each tibial spine in an area with intact cartilage. Insert an angel wing on the medial side of the tibial cutting guide. Set the slope of the resection of the medial tibial plateau by adjusting the anterior-posterior slider at the ankle until the plane of the angel wing parallels the medial tibial joint line after compensating for cartilage and bone wear. Set internal–external orientation by rotating the tibial cutting guide until the line on the top is parallel to a line drawn between the tibial spines and a line representing the major axis of the elliptical-shaped lateral tibial condyle [32]. Visually fine-tune the varus–valgus and slope orientation of the tibial resection guide to compensate for cartilage and bone wear. Pin the guide and resect the proximal tibia. Examine the medial edge of the tibial resection and confirm the plane of the tibial resection parallels the plane of the articular surface of the tibia after compensating for wear. Use a caliper and measure the thickness of the medial and lateral tibial condyles at the base of the tibial spines, which should be similar within 0 ± 0.5 mm (Fig. 24.13).

Verification Check 5: Record the calipered measurements on the verification worksheet (Fig. 24.1).

Flex the knee to 90°. Insert the tightest-fitting spacer block (choose from 10, 11, 12, 13, and 14 mm) between the femur and tibia. Recut the tibia using the 2 mm recut guide when the flexion space is too tight for a 10 mm spacer.

Verification Check 6: With the knee in 90° of flexion, internally and externally rotate the spacer and assess the relative tightness between the medial and lateral compartments. Confirm the spacer fits tighter in the medial compartment, fits looser in the lateral compartment, and pivots about the medial compartment, which restores a trapezoidal flexion space like the native knee (Fig. 24.7) [14].

Place the knee in full extension. Reinsert the spacer. Retract the soft tissues and visually examine the varus–valgus laxity between the femoral resection and spacer block and between the spacer block and tibial resection. Confirm the varus–valgus laxity is negligible and the difference in the gaps between the medial and lateral compartments is within 0 ± 0.5 mm, which restores the varus–valgus laxity of the native knee in full extension and native limb and joint line alignments with high reproducibility [14, 21]. Remember to account for over-resections of the distal femoral condyle. Perform one of the corrective steps listed in the decision trees when the varus–valgus laxity is greater in either the medial or lateral compartment (Figs. 24.2 and 24.3).

- When the lateral compartment is 2 mm tighter, recut the tibia using the 2° valgus recut guide.

Fig. 24.13 Composite of a right knee shows a caliper measuring a 6 mm-thick medial tibial condyle and an 8 mm-thick lateral tibial condyle at the base of the tibial spines. Expect the medial side to be tight and the lateral side loose when visually examining the varus–valgus laxity between the femoral resection, spacer block, and tibial resection with the knee in full extension. In this case, the use of a 2° varus recut guide removed 2 mm of bone from the medial tibial condyle and restored the negligible varus–valgus laxity and tight rectangular space of the native knee in extension (Fig. 24.7) [13, 15]. The negligible varus–valgus laxity verifies the orientation of the tibial component matches the contralateral native limb in 97% of subjects [14, 16, 21]
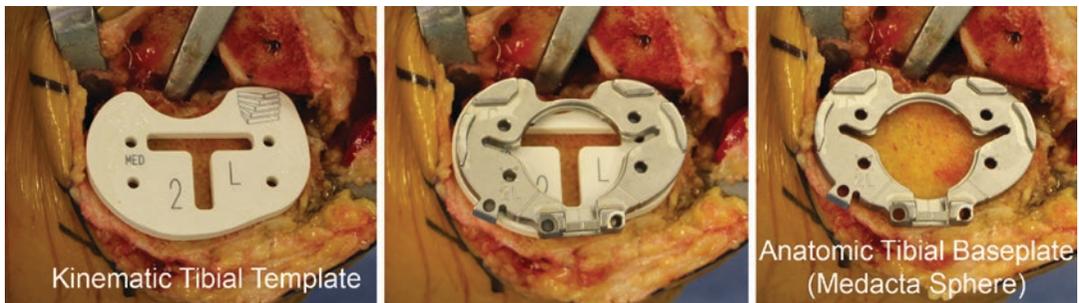
Fig. 24.14 Composite of a right knee shows the steps for KA internal–external rotation of the tibial component. Best-fitting the largest kinematic tibial template within the cortical boundary of the tibial resection assists the surgeon in accurately setting the I–E rotation of the tibial component parallel to the F–E plane of the knee when performing KA TKA (left) [33]. The anatomic shape of the trial tibial baseplate (Medacta) matches the kinematic tibial template (middle). Best fitting the largest trial tibial baseplate within the cortical boundary of the tibial resection verifies the internal–external rotation of the tibial component is within 0° ± 4° of the flexion–extension plane of the knee, which restores high-level knee function (right) [32, 33]

- When the medial compartment is 2 mm tighter, recut the tibia using the 2° varus recut guide.
- When a 1 mm correction is required, place the ~1 mm-thick angle wing between the recut guide and the tibia resection and make a 1° recut.

Verification Check 7: Negligible varus–valgus laxity restores the native rectangular space in full extension with a negligible mean varus–valgus laxity of <±1° and tibial joint line, knee, and limb alignment (Fig. 24.7) [14, 20, 21, 32, 43].

View the entire surface of the proximal tibial resection to size and position the anatomic tibial baseplate (Medacta) (Fig. 24.14). The anatomic shapes of the six trial tibial baseplates match closely those of seven kinematic tibial templates, which reproducibly set internal–external rotation of the tibial component within 0° ± 4° of the flexion–extension plane of the native knee [33]. Select the largest trial tibial baseplate that fits within the cortical boundary of the tibial resection. Rotate the trial tibial baseplate until the edge is parallel with the cortex. Pin the trial tibial baseplate and create the slot for the stem.

Verification Check 8: Setting the internal–external orientation of the anatomic tibial baseplate to within 0° ± 4° of the flexion–extension plane of the knee restores high-level knee function [32, 33]. Because the mediolateral location of the tibial tubercle varies, the medial border and medial one-third of the tibial tubercle are unreliable landmarks for setting the rotation of the tibial component on the tibia [52].

Finally, insert trial components and assess the varus–valgus laxities with the knee in full extension and 15–20° of flexion and the anterior offset of the tibia on the medial femur, internal–external rotation, and posterior and distraction translation of the tibia with the knee in 90° of flexion while referring to the corrective measures in the Sphere CR and Sphere CS decision trees (Figs. 24.2 and 24.3). The common principle of these decision trees is that fine-tuning the proximal–distal position and the varus–valgus and flexion–extension (slope) orientations of the tibial resection balances the knee. Balancing is accomplished without ligament release.

24.6.1 Final Verification with Trial Components Check 9

- *Place the knee in full extension:* Retract the soft tissues and visually examine the varus–valgus laxity between the femoral component and tibial insert, which should be negligible like the native knee (Fig. 24.7) [14, 15].
  - Correct a 1° varus or 1° valgus instability because this degree of laxity is greater than the native knee and is associated with instability in extension [14].

- *Place the knee in 15–20° of flexion:* Check varus–valgus laxity. The medial side should open ~1 mm and the lateral side ~2–3 mm and be looser than in full extension (Fig. 24.7).
  – When the lateral side opens more than ~3–4 mm, verify the tibial resection is not in excessive valgus by remeasuring the tibial resection at the base of the tibial spines.
- *Place the knee in 90° of flexion:*
  – When the posterior cruciate ligament is intact and the CR insert is used, adjust the slope of the tibial resection and thickness of the insert until the anterior offset of the tibia from the distal medial femoral condyle matches the knee at the time of exposure. A 2° increase in the posterior slope and a 2 mm decrease in the insert thickness translates the tibia ~3 mm posterior [17, 53]. Confirm the tibia internally and externally rotates ~±14° like the native knee (Figs. 24.2 and 24.7) [14, 48].
  – When the posterior cruciate ligament is resected and the sphere CS insert for a medial ball and socket implant is used, check the posterior drawer and distract the tibia. When the insert rides too posterior on the femoral component and the flexion space is slack, use a thicker insert and tighten the flexion space. When the thicker insert limits knee extension, recut 1–2 mm more bone from the distal femur. Refer to the corrective steps in the fourth column of the Sphere CS decision tree (Fig. 24.3).

24.7 Kinematic Alignment Corrects Severe Varus Deformities Without Ligament Release

Since 2006, all patients suitable for a primary total knee replacement were treated following the principles of kinematic alignment which are to co-align the axes and joint lines of the components with the three "kinematic" axes and joint lines of the pre-arthritic or native knee without placing restrictions on the preoperative deformity and postoperative correction and without ligament release. During these 13 years, there were over 5000 primary KA TKAs from which all patients with severe deformities secondary to post-traumatic arthritis, progressive osteoarthritis post high tibial osteotomy, and patients with multiple-level deformity were included.

Surprisingly, intrinsic contracture and stretching of the collateral and posterior cruciate ligaments were exceedingly uncommon. Preoperatively, the AP radiographs of chronic varus or valgus deformities often showed a joint space larger than typical suggesting intrinsic stretching or laxity of the lateral or medial collateral ligament, whereas intraoperatively these ligaments were not lax. The AP radiograph of a knee with a fixed flexion contracture explains the inconsistency. The lateral and medial laxity of a flexed knee is several millimeters more than the extended knee, which is why flexion is the preferred position for performing an arthroscopic meniscectomy. When treating a patient with extrinsic laxity of a collateral or posterior cruciate ligament secondary to trauma, components are still aligned coincident with the native joint lines with use of the kinematic principles, and added constraint with use of implants that offer a box in the femoral component and a post on the tibial insert compensates for the extrinsic laxity. The use of cones and short stem extensions enables positioning of components coincident with the native joint line with a low risk of stem impingement of the femoral and tibial cortex.

24.7.1 Case Example, History

A 58-year-old male tore his ACL and PCL in his right knee in a motorcycle injury at age 24 and had an open medial meniscectomy. Preoperatively, the knee had advanced post-traumatic, postsurgical osteoarthritis with a 20° varus deformity and 15° fixed flexion contracture and limited range of motion from 15° to 90° of flexion (Fig. 24.15). Varus–valgus

Fig. 24.15 Composite shows the preoperative radiographs of a post-traumatic knee with a severe varus deformity, flexion contracture, and chronic posterior cruciate ligament insufficiency; an intraoperative photograph of the varus deformity; and a postoperative computer tomographic scanogram of the limb and axial views of the femoral and tibial components. The AP radiograph shows a lateral joint space larger than typical suggesting intrinsic laxity of the lateral collateral ligament. Intraoperatively, the lateral collateral ligament was not lax. The AP radiograph of a knee with a fixed flexion contracture explains the inconsistency. The lateral laxity of a flexed knee is several millimeters more than the extended knee, which is why flexion is the preferred position for performing an arthroscopic lateral meniscectomy. Following the principles of kinematic alignment, the TKA restored the native alignment and laxities of the knee without a release of the medial collateral ligament and was performed with the posterior cruciate ligament substituting implants because of the torn posterior cruciate ligament

laxity testing at 0° and 30° indicated an intact MCL and LCL. Lachman and posterior drawer tests indicated chronic ACL and PCL insufficiency. His Oxford Knee Score was 11 points (48 best, 0 worst), Knee Society Score was 31 points, and Knee Society Function Score was 40 points.

24.7.2 Postoperative Result

KA with use of a posterior cruciate ligament substituting implant because of the torn PCL corrected this severe varus deformity of 20° and flexion contracture of 15° without ligament release. Postoperatively, the patient had a 6° varus hip–knee–ankle angle. The 6° angle between the transverse axes of the components was less than 106°, which is compatible with high function [24, 32]. At 2 years, the patient ambulated without difficulty or pain, range of motion improved to 0°–115°, and the Oxford Knee Score increased from 11 to 45 points, the Knee Society Score increased from 31 to 98 points, and Knee Society Function Score increased from 40 to 70 points.

24.8 Kinematic Alignment Corrects Severe Valgus Deformities Without Ligament Release

24.8.1 Case Example, History

A 68-year-old female with a prior arthroscopic meniscectomy developed osteoarthritis of the knee with a 25° valgus deformity, 17° fixed flexion contracture, and limited range of motion from 20° to 105° of flexion (Fig. 24.16). Varus–valgus laxity testing at 0° and 30° indicated an intact MCL and LCL. Lachman and posterior drawer tests indicated an intact ACL and PCL. Her Oxford Knee Score was 13 points (0 worst, 48 best), Knee Society Score was 24 points, and Knee Society Function Score was 30 points.

24.8.2 Postoperative Result

KA with use of a posterior cruciate ligament retaining implant corrected this severe valgus deformity and flexion contracture without ligament release. Postoperatively, the patient had a 3°

Fig. 24.16 Composite shows the preoperative radiographs of the knee with severe valgus deformity, intraoperative photograph of the severe valgus deformity, postoperative computer tomographic scanogram of the limb, and axial views of the femoral and tibial components. The AP radiograph shows a medial joint space larger than typical suggesting intrinsic laxity of the medial collateral ligament. Intraoperatively, the medial collateral ligament was not lax. The AP radiograph of a knee with a fixed flexion contracture explains the inconsistency. The medial laxity of a flexed knee is several millimeters more than the extended knee, which is why flexion is the preferred position for performing an arthroscopic medial meniscectomy. Following the principles of kinematic alignment, the TKA restored the alignments of the tibial joint line, knee, Q-angle, and limb close to those of the contralateral or native limb without release of the lateral collateral or lateral retinacular ligament in this patient with an intact posterior cruciate ligament

valgus hip–knee–ankle angle. The transverse axes of the femoral and tibial components were within 3° of parallel, which is compatible with high function [24, 32]. At 2 years, the patient ambulated without difficulty or pain, range of motion improved to 0°–119°, and the Oxford Knee Score increased from 13 to 44 points, Knee Society Score increased from 41 to 98 points, and Knee Society Function Score increased from 30 to 70 points.

24.9 Kinematic Alignment Has a Low Risk of Tibial Component Failure, Low Risk of Patellar Instability, and High Implant Survival at 10 Years

Accurately setting the slope of the tibial component in the sagittal plane results in negligible failure of the tibial component after KA [11, 23, 54, 55]. At 2–9 years of follow-up, the 0.3% incidence of tibial component failure (8 of 2725 prostheses) of patients treated with KA TKA was comparable if not lower than the 1.0% (54 of 5342 prostheses) incidence of failure from aseptic loosening of the femoral and/or tibial component for patients treated with MA TKA (Fig. 24.17) [56]. In kinematic alignment, posterior subsidence or posterior edge wear is the mechanism of tibial component failure, which is caused by resecting the tibia in 7° greater slope than the native [23]. In MA, varus or medial overload is the mechanism of tibial component failure, which is caused by uncorrectable instability in a compartment from changing the constitutional limb alignment to neutral and a high knee adduction moment during gait [12, 35, 39, 40]. Hence, restoring the slope of the native tibial joint line lowers the risk of posterior subsidence and posterior edge wear of the tibial component when performing KA TKA [11, 23].

Three biomechanical advantages explain the negligible risk of varus tibial loosening after kinematically aligned TKA. First, KA provides more physiological strains in the collateral ligaments than MA TKA by restoring the native joint lines and constitutional alignment without releasing ligaments [41]. Second, KA provides medial and lateral tibial compartment forces comparable to those of the native knee with no evidence of

KA Restores the Coronal and Sagittal
Alignment of the Native Joint Lines
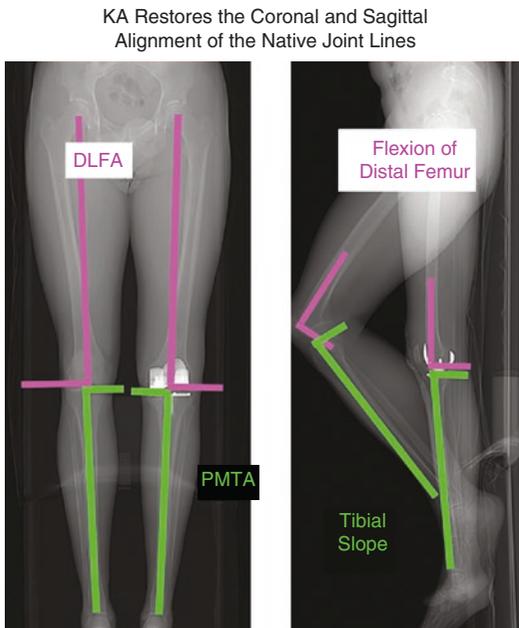
Fig. 24.17 Composite shows calipered KA restored the distal lateral femoral angle (DLFA) and proximal medial tibial angle (PMTA) of the TKA to those of the native knee in the sagittal plane (left) and the flexion–extension orientation of the distal femoral joint line and proximal tibial joint line of the TKA to those of the native knee in the coronal plane (right)

tibial compartment overload even when the postoperative alignments of the limb, knee, and tibial component are within the varus or valgus outlier range according to mechanical alignment criteria [17–19]. Third, KA is an especially promising option for patients with large varus coronal bowing of the tibia because the knee adduction moment and risk of varus overload are lower than after MA TKA [12].

Accurately setting the flexion of the femoral component in the sagittal plane results in negligible patellofemoral instability after KA [49–51]. At 1–10 years of follow-up, there is a 0.4% incidence of patellofemoral instability (13 of 3212 prostheses) in patients treated with kinematically aligned TKA. In KA, flexion of the femoral component greater than 10° with respect to the anatomic axis of the distal femur increased the risk of patellofemoral instability by downsizing the femoral component ~1–2 sizes, reducing the cross-sectional area of the trochlea, reducing the

proximal reach of the flange by ~8 mm, and delaying the engagement of the patella during early flexion [49, 51]. A change in the native Q-angle does not cause patellofemoral instability as KA restores the native Q-angle, whereas mechanical alignment increases or decreases the native Q-angle in limbs with varus or valgus constitutional alignment, respectively (Figs. 24.5 and 24.6) [35]. The design of the femoral component does not cause patellofemoral instability as KA more closely restores the groove location and the sulcus angle of the native trochlea and trochlea morphology without overstuffing than mechanical alignment [57, 58]. Internal rotation about the center of the femoral component of ~3 relative to mechanical alignment does not cause patellofemoral instability as the ~1.5 mm increase in the distance between the lateral prosthetic trochlea and lateral femur is negligible [49]. The use of a distal referencing guide attached to an intraosseous positioning rod limits flexion of the femoral component to $1 \pm 2°$ with respect to the femoral anatomic axis, which is 9° less than patients with patellofemoral instability (Fig. 24.9) [50]. Hence, limiting flexion of the femoral component lowers the risk of patellofemoral instability when performing kinematically aligned TKA [51].

The 10-year implant survivorship of a single-surgeon series of KA TKAs performed without restricting the degree of preoperative varus–valgus and flexion deformity is comparable if not higher than two single-surgeon series of MA TKAs. Using aseptic revision at 10 years as the end point, the 98.5% implant survival after 220 KA TKAs was 5.5% higher than the ~93% implant survival after 398 MA TKAs in the United States [59] and 4.5% higher than the ~94% implant survival after 270 MA TKAs in the United Kingdom [60]. The estimated number of revisions for 1000 patients is 15 for KA TKA and 70 and 60, respectively, for the US and UK studies of MA TKA. In the study of KA, four of seven revisions were associated with excessive flexion of the femoral component ($N = 3$) and reverse slope of the tibial component ($N = 1$) in the sagittal plane. Limiting flexion of the femoral component and restoring the slope of the native tibia could have lowered the incidence of these revisions [23,

49–51]. The postoperative alignment of the tibial component, knee, and limb in varus and valgus outlier ranges according to mechanical alignment criteria does not adversely affect the 10-year implant survival, yearly revision rate, and level of function as measured by the Oxford Knee and WOMAC scores [11]. Hence, restoring the native joint lines, Q-angle, and limb alignments unique to each patient results in high long-term implant survival regardless of the degree of preoperative varus-valgus and flexion deformity and postoperative alignment.

24.10 Summary

This chapter presented the philosophy of calipered KA and the surgical technique for setting components coincident to the native joint lines using ten calipered measurements, manual instruments, and nine verification checks. KA co-aligns the axes of the femoral and tibial components with the three axes of the native knee without ligament releases and without restricting the level of preoperative deformities and postoperative correction. The surgical goals are (1) restoration of the native alignments of the limb, Q-angle, and joint lines unique to each patient and (2) restoration of the laxities, tibial compartment forces, knee adduction moment, and gait of the native knee without ligament release. Measurement of the thicknesses of the femoral and tibial bone resections with a caliper and adjustment of the resections until they match those of the components after compensating for cartilage and bone wear and the 1 mm kerf from the saw cut restores the native joint lines with high reproducibility. These measurements are recorded intraoperatively on a worksheet, which verifies kinematic positioning of the components before cementation. Decision trees for balancing the TKA with CR and CS medial pivot tibial inserts balance the knee by adjusting the varus–valgus and slope of the tibial resection and not by releasing ligaments. Finally, the restoration of native alignment and tibial compartment forces lowers the risks of tibial component failure and patellofemoral instability and results in high implant sur-

vival at 10 years regardless of the level of preoperative deformity and whether the postoperative alignments of the tibial component, knee, and limb are within varus and valgus outlier ranges according to MA criteria.

References

1. Calliess T, Bauer K, Stukenborg-Colsman C, Windhagen H, Budde S, Ettinger M. PSI kinematic versus non-PSI mechanical alignment in total knee arthroplasty: a prospective, randomized study. Knee Surg Sports Traumatol Arthrosc. 2017;25(6):1743.
2. Courtney PM, Lee GC. Early outcomes of kinematic alignment in primary total knee arthroplasty: a meta-analysis of the literature. J Arthroplast. 2017;32(6):2028.
3. Dossett HG, Estrada NA, Swartz GJ, LeFevre GW, Kwasman BG. A randomised controlled trial of kinematically and mechanically aligned total knee replacements: two-year clinical results. Bone Joint J. 2014;96-B(7):907.
4. Lee YS, Howell SM, Won YY, Lee OS, Lee SH, Vahedi H, Teo SH. Kinematic alignment is a possible alternative to mechanical alignment in total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2017;25(11):3467.
5. Nam D, Nunley RM, Barrack RL. Patient dissatisfaction following total knee replacement: a growing concern? Bone Joint J. 2014;96-B(11 Supple A):96.
6. Li Y, Wang S, Wang Y, Yang M. Does kinematic alignment improve short-term functional outcomes after total knee arthroplasty compared with mechanical alignment? A systematic review and meta-analysis. J Knee Surg. 2018;31(1):78.
7. Matsumoto T, Takayama K, Ishida K, Hayashi S, Hashimoto S, Kuroda R. Radiological and clinical comparison of kinematically versus mechanically aligned total knee arthroplasty. Bone Joint J. 2017;99-B(5):640.
8. Nakamura S, Tian Y, Tanaka Y, Kuriyama S, Ito H, Furu M, Matsuda S. The effects of kinematically aligned total knee arthroplasty on stress at the medial tibia: a case study for varus knee. Bone Joint Res. 2017;6(1):43.
9. Waterson HB, Clement ND, Eyres KS, Mandalia VI, Toms AD. The early outcome of kinematic versus mechanical alignment in total knee arthroplasty: a prospective randomised control trial. Bone Joint J. 2016;98-B(10):1360.
10. Young SW, Walker ML, Bayan A, Briant-Evans T, Pavlou P, Farrington B. The Chitranjan S. Ranawat award: no difference in 2-year functional outcomes using kinematic versus mechanical alignment in TKA: a randomized controlled clinical trial. Clin Orthop Relat Res. 2017;475(1):9.

11. Howell SM, Shelton TJ, Hull ML. Implant survival and function ten years after kinematically aligned total knee arthroplasty. J Arthroplast. 2018;33:3678.

12. Niki Y, Nagura T, Nagai K, Kobayashi S, Harato K. Kinematically aligned total knee arthroplasty reduces knee adduction moment more than mechanically aligned total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2018;26(6):1629.

13. Blakeney W, Clément J, Ing M, Desmeules F, Hagemeister N, Rivière C, Vendittoli P. Kinematic alignment in total knee arthroplasty better reproduces normal gait than mechanical alignment. Knee Surg Sports Traumatol Arthrosc. 2019;27:1410–7.

14. Roth JD, Howell SM, Hull ML. Native knee laxities at 0 degrees, 45 degrees, and 90 degrees of flexion and their relationship to the goal of the gap-balancing alignment method of total knee arthroplasty. J Bone Joint Surg Am. 2015;97(20):1678.

15. Roth JD, Hull ML, Howell SM. The limits of passive motion are variable between and unrelated within normal tibiofemoral joints. J Orthop Res. 2015;33(11):1594.

16. Roth JD, Hull ML, Howell SM. Analysis of differences in laxities andneutral positions from native after kinematically aligned TKA using cruciate retaining implants. J Orthop Res. 2019;37:358–69.

17. Shelton TJ, Howell SM, Hull ML. A total knee arthroplasty is stiffer when the intraoperative tibial force is greater than the native knee. J Knee Surg. 2019;32:1008–14.

18. Shelton TJ, Howell SM, Hull ML. Is there a force target that predicts early patient-reported outcomes after kinematically aligned TKA? Clin Orthop Relat Res. 2019;477:1200–7.

19. Shelton TJ, Nedopil AJ, Howell SM, Hull ML. Do varus or valgus outliers have higher forces in the medial or lateral compartments than those which are in-range after a kinematically aligned total knee arthroplasty? Limb and joint line alignment after kinematically aligned total knee arthroplasty. Bone Joint J. 2017;99-B(10):1319.

20. Johnson JM, Mahfouz MR, Midillioglu MR, Nedopil AJ, Howell SM. Three-dimensional analysis of the tibial resection plane relative to the arthritic tibial plateau in total knee arthroplasty. J Exp Orthop. 2017;4(1):27.

21. Nedopil AJ, Singh AK, Howell SM, Hull ML. Does calipered kinematically aligned TKA restore native left to right symmetry of the lower limb and improve function? J Arthroplast. 2018;33(2):398.

22. Riviere C, Iranpour F, Harris S, Auvinet E, Aframian A, Chabrand P, Cobb J. The kinematic alignment technique for TKA reliably aligns the femoral component with the cylindrical axis. Orthop Traumatol Surg Res. 2017;103(7):1069.

23. Nedopil AJ, Howell SM, Hull ML. What mechanisms are associated with tibial component failure after kinematically-aligned total knee arthroplasty? Int Orthop. 2017;41(8):1561.

24. Nedopil AJ, Howell SM, Rudert M, Roth J, Hull ML. How frequent is rotational mismatch within 0 degrees +/−10 degrees in kinematically aligned total knee arthroplasty? Orthopedics. 2013;36(12):e1515.

25. Coughlin KM, Incavo SJ, Churchill DL, Beynnon BD. Tibial axis and patellar position relative to the femoral epicondylar axis during squatting. J Arthroplast. 2003;18(8):1048.

26. Hollister AM, Jatana S, Singh AK, Sullivan WW, Lupichuk AG. The axes of rotation of the knee. Clin Orthop Relat Res. 1993;(290):259.

27. Iranpour F, Merican AM, Baena FR, Cobb JP, Amis AA. Patellofemoral joint kinematics: the circular path of the patella around the trochlear axis. J Orthop Res. 2010;28(5):589.

28. Pinskerova V, Iwaki H, Freeman MA. The shapes and relative movements of the femur and tibia at the knee. Der Orthopade. 2000;29(Suppl 1):S3.

29. Iwaki H, Pinskerova V, Freeman MA. Tibiofemoral movement 1: the shapes and relative movements of the femur and tibia in the unloaded cadaver knee. J Bone Joint Surg Br. 2000;82(8):1189.

30. Weber WE, Weber EFM. Mechanik der menschlichen Gehwerkzeuge. Göttingen: Verlag der Dietrichschen Buchhandlung; 1836.

31. Eckhoff DG, Bach JM, Spitzer VM, Reinig KD, Bagur MM, Baldini TH, Flannery NM. Three-dimensional mechanics, kinematics, and morphology of the knee viewed in virtual reality. J Bone Joint Surg Am. 2005;87(Suppl 2):71.

32. Nedopil AJ, Howell SM, Hull ML. Does malrotation of the tibial and femoral components compromise function in kinematically aligned total knee arthroplasty? Orthop Clin North Am. 2016;47(1):41.

33. Paschos NK, Howell SM, Johnson JM, Mahfouz MR. Can kinematic tibial templates assist the surgeon locating the flexion and extension plane of the knee? Knee. 2017;24(5):1006.

34. Nam D, Lin KM, Howell SM, Hull ML. Femoral bone and cartilage wear is predictable at 0 degrees and 90 degrees in the osteoarthritic knee treated with total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2014;22(12):2975.

35. Singh AK, Nedopil AJ, Howell SM, Hull ML. Does alignment of the limb and tibial width determine relative narrowing between compartments when planning mechanically aligned TKA? Arch Orthop Trauma Surg. 2017;138(1):91.

36. Bellemans J, Colyn W, Vandenneucker H, Victor J. The Chitranjan Ranawat award: is neutral mechanical alignment normal for all patients? The concept of constitutional varus. Clin Orthop Relat Res. 2012;470(1):45.

37. Shetty GM, Mullaji A, Bhayde S, Nha KW, Oh HK. Factors contributing to inherent varus alignment of lower limb in normal Asian adults: role of tibial plateau inclination. Knee. 2014;21(2):544.

38. Song MH, Yoo SH, Kang SW, Kim YJ, Park GT, Pyeun YS. Coronal alignment of the lower limb and

the incidence of constitutional varus knee in Korean females. Knee Surg Relat Res. 2015;27(1):49.

39. Gu Y, Howell SM, Hull ML. Simulation of total knee arthroplasty in 5 degrees or 7 degrees valgus: a study of gap imbalances and changes in limb and knee alignments from native. J Orthop Res. 2017;35(9):2031.

40. Gu Y, Roth JD, Howell SM, Hull ML. How frequently do four methods for mechanically aligning a total knee arthroplasty cause collateral ligament imbalance and change alignment from normal in white patients? J Bone Joint Surg. 2014;96(12):e101.

41. Delport H, Labey L, Innocenti B, De Corte R, Vander Sloten J, Bellemans J. Restoration of constitutional alignment in TKA leads to more physiological strains in the collateral ligaments. Knee Surg Sports Traumatol Arthrosc. 2015;23(8):2159.

42. Meneghini RM, Ziemba-Davis MM, Lovro LR, Ireland PH, Damer BM. Can intraoperative sensors determine the "target" ligament balance? Early outcomes in total knee arthroplasty. J Arthroplast. 2016;31(10):2181.

43. Roth JD, Howell SM, Hull ML. Kinematically aligned total knee arthroplasty limits high tibial forces, differences in tibial forces between compartments, and abnormal tibial contact kinematics during passive flexion. Knee Surg Sports Traumatol Arthrosc. 2018;26(6):1589.

44. Verstraete MA, Meere PA, Salvadore G, Victor J, Walker PS. Contact forces in the tibiofemoral joint from soft tissue tensions: implications to soft tissue balancing in total knee arthroplasty. J Biomech. 2017;58:195.

45. Ji HM, Han J, Jin DS, Seo H, Won YY. Kinematically aligned TKA can align knee joint line to horizontal. Knee Surg Sports Traumatol Arthrosc. 2016;24(8):2436.

46. Eckhoff D, Hogan C, DiMatteo L, Robinson M, Bach J. Difference between the epicondylar and cylindrical axis of the knee. Clin Orthop Relat Res. 2007;461:238.

47. Howell SM, Kuznik K, Hull ML, Siston RA. Longitudinal shapes of the tibia and femur are unrelated and variable. Clin Orthop Relat Res. 2010;468(4):1142.

48. Howell SM, Papadopoulos S, Kuznik KT, Hull ML. Accurate alignment and high function after kinematically aligned TKA performed with generic instruments. Knee Surg Sports Traumatol Arthrosc. 2013;21(10):2271.

49. Brar AS, Howell SM, Hull ML, Mahfouz MR. Does kinematic alignment and flexion of a femoral component designed for mechanical alignment reduce the proximal and lateral reach of the trochlea? J Arthroplast. 2016;31(8):1808.

50. Ettinger M, Calliess T, Howell SM. Does a positioning rod or a patient-specific guide result in more natu-
ral femoral flexion in the concept of kinematically aligned total knee arthroplasty? Arch Orthop Trauma Surg. 2017;137(1):105.

51. Nedopil AJ, Howell SM, Hull ML. What clinical characteristics and radiographic parameters are associated with patellofemoral instability after kinematically aligned total knee arthroplasty? Int Orthop. 2017;41(2):283.

52. Howell SM, Chen J, Hull ML. Variability of the location of the tibial tubercle affects the rotational alignment of the tibial component in kinematically aligned total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2013;21(10):2288.

53. Christen B, Heesterbeek P, Wymenga A, Wehrli U. Posterior cruciate ligament balancing in total knee replacement: the quantitative relationship between tightness of the flexion gap and tibial translation. J Bone Joint Surg Br. 2007;89(8):1046.

54. Howell SM, Howell SJ, Kuznik KT, Cohen J, Hull ML. Does a kinematically aligned total knee arthroplasty restore function without failure regardless of alignment category? Clin Orthop Relat Res. 2013;471(3):1000.

55. Howell SM, Papadopoulos S, Kuznik K, Ghaly LR, Hull ML. Does varus alignment adversely affect implant survival and function six years after kinematically aligned total knee arthroplasty? Int Orthop. 2015;39(11):2117–24.

56. Ritter MA, Davis KE, Meding JB, Pierson JL, Berend ME, Malinzak RA. The effect of alignment and BMI on failure of total knee replacement. J Bone Joint Surg Am. 2011;93(17):1588.

57. Lozano R, Campanelli V, Howell S, Hull M. Kinematic alignment more closely restores the groove location and the sulcus angle of the native trochlea than mechanical alignment: implications for prosthetic design. Knee Surg Sports Traumatol Arthrosc. 2019;27:1504–13.

58. Riviere C, Iranpour F, Harris S, Auvinet E, Aframian A, Parratte S, Cobb J. Differences in trochlear parameters between native and prosthetic kinematically or mechanically aligned knees. Orthop Traumatol Surg Res. 2018;104(2):165.

59. Parratte S, Pagnano MW, Trousdale RT, Berry DJ. Effect of postoperative mechanical axis alignment on the fifteen-year survival of modern, cemented total knee replacements. J Bone Joint Surg Am. 2010;92(12):2143.

60. Bonner TJ, Eardley WG, Patterson P, Gregg PJ. The effect of post-operative mechanical axis alignment on the survival of primary total knee replacements after a follow-up of 15 years. J Bone Joint Surg Br. 2011;93(9):1217.