Mako Robotic-Arm Assisted Total Knee Arthroplasty: Updated Software

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ABSTRACT

Recently, robotic-arm assisted total knee arthroplasties have become popular because of their promise to lead to enhanced accuracy and efficient planning of the procedure, as well as improved radiographic and clinical outcomes. One robotic system is based on computed tomography (CT) to help with preoperative planning, intraoperative adjusting, and bone cutting for these procedures. The purpose of this article is to describe the second-generation iteration of this CT-based robotic technique by describing the new features using an actual total knee arthroplasty case. This article then becomes a step-by-step guide to performing the procedure, as well as describing the new features of this upgraded system.

INTRODUCTION

The use of robotic technology in total knee arthroplasty (TKA) has recently dramatically increased, owing to its ability to provide real-time intraoperative feedback and assist surgeons in more easily quantifying the balancing and rotation of the arthroplasty procedure.[1,2] Recent studies suggest that robotic-assisted total knee arthroplasty has increased five-fold with predictions for even higher robotic usage in the future. The Mako Robotic-Arm Assisted Surgical System (Mako Surgical Corp. [Stryker], Fort Lauderdale, Florida) incorporates a virtual model of the knee joint with patient-specific mapping via computed tomography (CT) imaging. The topography of the knee joint, once confirmed intraoperatively, can be processed by the software and used to set an initial personalized plan for bony cuts. The surgeon is able to use functional positioning principles, in which a 3-dimensional (3D) CT is utilized to assess the individualized planned implant position and subsequently balance the knee prior to bone cuts to minimize the need for soft tissue releases. Not only does the robotic-arm assisted surgery help with preoperative implant size prediction and intraoperative planning, but it has also demonstrated superiority over manual techniques in Knee Society Outcome Scores and other patient-reported outcomes over a mean of one to three years.[1,3-12]

For example, Mahoney et al. compared 143 robotic-arm assisted versus 86 manual TKAs and found that CT-based robotic-arm assistance provided significantly greater accuracy for tibial component alignment, femoral component rotation, and tibial slope ($p<0.05$).[5] This system has also been noted to produce less iatrogenic soft-tissue damage,[13,14] which is likely due to the haptic feedback provided to the surgeon. Patient-reported outcomes have also been shown to be favorable in patients who have undergone robotic-arm assisted total knee arthroplasty.[1,3-12] Though the first generation of CT scan-based robotic technology in TKA has had substantial success, most, if not all, medical technology can always be enhanced to improve outcomes and/or the user's experience. Many of the robotic systems that are commonly utilized in orthopaedic operating rooms have developed several iterations and/or updates in order to accommodate the user experience and optimize intraoperative performance in the hope of leading to improved patient outcomes as well as improved surgeon usability. Furthermore, recent studies have demonstrated that the learning curve for robotic-arm assisted TKA was 10 to 20 cases for board-certified joint arthroplasty surgeons.[15-17]

Recently, the first-generation CT scan-based robotic system was enhanced with the next iteration of the software program. This software upgrade was designed to have a more user-friendly interface with enhanced ligamentous assessment and balancing features. A recent study of 20 surgeons found that 19 of them (95%) reported that their overall intraoperative confidence increased with the new software upgrade.[18] In addition, 100% of the surgeons reported that they were more confident when performing intraoperative implant adjustments with the new software upgrade when compared to manual TKA. In addition, it has recently been shown that the new software program leads to repeatable and reproducible methods of assessing soft-tissue balance.[19] Based on intraclass correlation coefficient values (greater than 0.75 are considered excellent), the surgeons had excellent repeatability for pre-resection assessments (≥ 0.98) and trialing assessments (≥0.93). When comparing each surgeon to themselves, they were repeatable within 1mm 97% of the time during pre-resection trialing (the mean variation within a surgeon was 0.34mm during pre-resection and 0.29mm during trialing).

The present study seeks to demonstrate the enhancement of the Mako Robotic-Arm Assisted Surgical System via its updated TKA 2.0 software, which is specific to the total knee arthroplasty application. The purpose of this article is to delineate the CT-based implant planning and balancing using the Mako System with the TKA 2.0 software, as well as to highlight the enhancements offered with version 2.0 of the total knee arthroplasty application.

SUMMARY OF NEW FEATURES AVAILABLE WITH THE MAKO TOTAL KNEE 2.0 SOFTWARE UPGRADE

The new TKA 2.0 software builds on the prior version (1.0) with many new features, including the following: These features are provided in order of where they would be impactful to a surgical case when using the Functional Knee Positioning technique.

1. During surgical preparation, there is now the ability to place pins intra-incisionally for the tibia, placing them in the metaphysis instead of the diaphysis. This is intended to make the case easier to perform. As with the prior version of the total knee arthroplasty application, there is still the ability to place the femur pins both intra- and extra-incisionally.
2. During pre- and intraoperative planning, the surgeon has the ability to utilize the patient's constitutional alignment as a reference throughout the procedure. The constitutional alignment is defined as the patient's non-diseased hip-knee-ankle angle and is calculated using the preoperative CT scan.
3. Surgeons are able to input and save their own preferences. They have the ability to customize the experience and guide it with their own parameters throughout the case. This was included to make the system more user-friendly, seamlessly integrating the surgeon's preferences that can be saved in the software. There is also a new feature that gives the surgeon intraoperative warnings when they have exceeded their surgeon-specific preferences. Examples of surgeons' preferences include: "Measured Resection" or "Ligament Balancing" workflow, "Distal/Tibial Cut First" or "Pre-Resection Balancing" performed first, "Perform RIO Setup and RIO Registration before Bone Preparation," representation of depth represented as "Bone Resection" or "Estimated Cartilage," "Display Total Combined Resection Depth" for each compartment in flexion and extension, and "TKA Cutting Sequence" to set the order of femur and tibia cuts.
4. After setting an initial plan, the surgeon then intraoperatively assesses the soft tissue laxity with the Digital Tensioner. The Digital Tensioner provides a repeatable and reproducible laxity assessment with no additional instrumentation or hardware. Medial and lateral compartment laxities in both flexion and extension can be captured independently and measured every 0.5mm. As the surgeon applies tension to the ligaments and opens each compartment, an audible and visible cue will be provided every 0.5mm. As the surgeon opens a compartment, they may reference the audible cues. Once the surgeon finds the end stop of the ligament, by referencing the plateau of the stress/strain curve, the audible and visual feedback will start to slow and eventually stop. That signifies capturing this point. The system will store the maximum laxity value that was assessed, and then it will be saved in the software, by either the surgeon using the foot pedal or the MPS. Once captured, the surgeon can move on to the next compartment.
5. Laxity assessments are limited to 0.5mm values, allowing the surgeon to make fine adjustments when planning their case.
6. There are updated extension and flexion pose capture windows. For extension, the window is based on the patient's native deformity, while the flexion range is a fixed 85° to 105° range.
7. After initial assessments are completed, the user can now finalize their implant plan and balance the knee. One feature to improve the balancing experience is the addition of multiple stops (F keys) to pivot points. The red spheres indicate these pivot points (F1 to F7), so the surgeon can move in any manner to adjust the virtual position. This was included to make it easier and more efficient to balance the knee with the new program.
8. There is a save plan feature, allowing the surgeon to have the ability to save, balance, and toggle between multiple plans for each patient. For example,

the surgeon can balance the knee in multiple different ways—independently of each other, assess the different plans, and then choose which they would like to execute—whether they want to evaluate different implant sizes or balancing methodologies. This feature also allows Mako TKA to be an excellent learning tool for residents and fellows, letting them evaluate various balancing plans.

9. In the CT view mode, the surgeon can move the implant and look at the bone from different vantage points. The surgeon can look through the virtual prosthesis to see the bone; for example, the surgeon might see that they are not cutting bone, but actually in the air. This CT view mode affords the ability to balance the knee through implant adjustments while visualizing the changes of the virtual implant on the bony anatomy and further allowing for the ability to make implant adjustments. Consistent with the prior total knee application, the user still has the ability to make 0.5mm implant adjustment increments.
10. An improved user interface was developed, which is intended to be more surgeon-friendly. This enhances user experience, and updates to the software (customizable and guided workflow, with more opportunities to capture datapoints) provide the surgeon with a clearer view and draw focus on what's most important on the screen during each step or page.
11. Once balancing is complete, the surgeon can move on to cutting the bone according to plan. To aid with making cutting more efficient, the Mako Park feature provides visual guidance so that the Mako Product Specialist (MPS) can position the system in the ideal spot for bone preparation, whether they need to adjust the knee closer or farther away from the Mako system before cutting and to check that the leg is not overly internally or externally rotated.
12. With the new program, one can use a narrow blade for all implant sizes, not just a few as in the previous iteration. The narrow blade also allows the surgeon to get deeper into the more difficult-to-access postero-lateral corner.
13. To make cutting easier and more efficient, the surgeon has the ability to advance the cutting sequence on their own.
14. The new software provides optimized Mako Case Information, which is the ability to capture surgical data throughout the case that is not captured through the software itself. The surgeon can see a "summary" page for each case.

Figure 1. A 67-year-old man who had (a) antero-posterior (AP), (b) lateral, and (c) merchant radiographs of the right knee demonstrating tricompartmental osteoarthritis.

The following case history will more specifically illustrate these and other enhanced features.

CASE EXAMPLE

A 67-year-old man who had a history of bilateral knee osteoarthritis and previously had a left total knee arthroplasty presented with worsening right knee osteoarthritis after failing six months of nonoperative treatment methods for his severe knee pain.

Preoperative weightbearing radiographs demonstrate tricompartmental osteoarthritis with joint space narrowing (medial greater than lateral), osteophyte formation, and varus alignment (Fig. 1).

The patient was sent for CT imaging using the Mako protocol, which was used to support the Mako Robotic-Arm Assisted surgery.

3D CT-BASED PLANNING

Once preoperative CT imaging was obtained, a model of the knee was created with patient-specific granularity, which is integral to the bony cuts and soft-tissue balancing. By obtaining this patient-specific model, the software allows the surgeon to correlate intraoperative landmark registration with the preoperative CT, achieving exact real-time feedback and registration accuracy.

The following will be a step-by-step instructional guide to performing a Mako Total Knee with the Mako Robotic-Arm Assisted Surgical System with TKA 2.0 for a standard varus-aligned, osteoarthritic primary knee.

OUTLINE

The following outline serves as a general workflow for surgeons as they prepare, execute, and complete a robotic-arm assisted TKA:

1) Preoperative CT-based planning (assess and adjust the default plan as necessary)
2) Operative setup, including retractors, pin placement, and checkpoints
3) Assessing intraoperative dynamic joint balancing
4) Making intraoperative adjustments to the surgical plan
5) Execution of the plan (bone cutting) and bony resections
6) Trialing, implantation, and final assessments

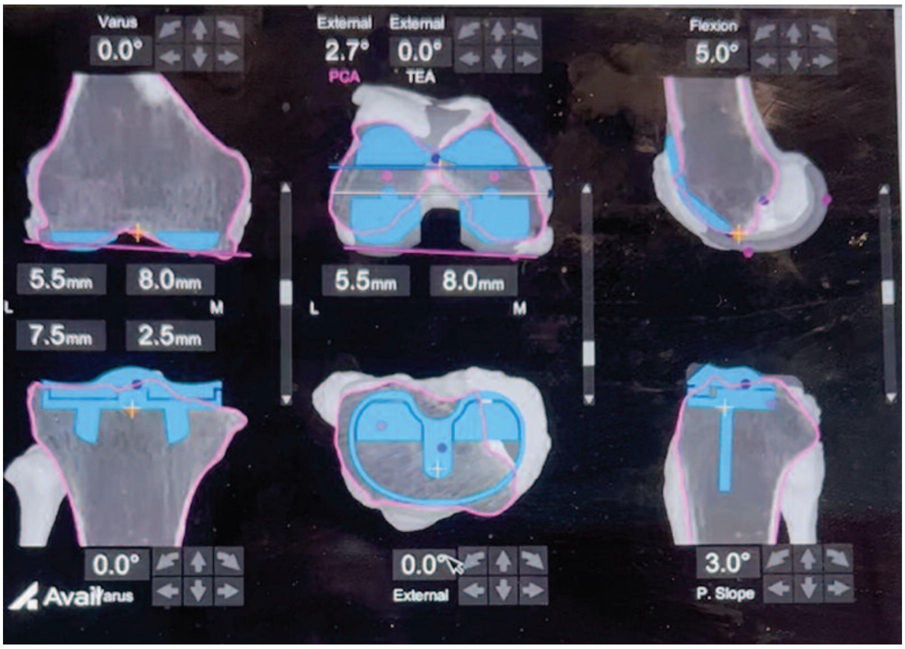


Figure 2. Preoperative screen demonstrating femoral and tibial component positions, rotations, and coronal/sagittal alignments based upon the preoperative computed tomography scan.

PREOPERATIVE CT-BASED PLANNING

The surgeon will be provided with an initial patient-specific CT-based plan, which the surgeon can evaluate, modify, and virtually assess and account for features such as the evaluation of osteophytes. The preoperative planning stage of the Mako Total Knee arthroplasty operation allows the surgeon to critically analyze femoral and tibial component size, position, and rotation, as well as the depth of bony resection.

This 3D CT-based planning allows the surgeon to plan the positioning of the Triathlon component in the coronal, transverse, and sagittal planes. Figure 2 shows the first screen that the surgeon will encounter from the software. Following a counterclockwise sequence on the planning screen, the surgeon is able to complete a functional knee positioning assessment. As the surgeon progresses through the plan, they will prioritize attributes of the knee that have the most impact on the function of the knee, known as the functional positioning guidelines. The top block of the screen demonstrates femoral component orientation and rotation. Following a counterclockwise approach, surgeons can assess the sagittal fit of the femoral component, followed by rotational, and then coronal. Moving to the bottom block of the screen, surgeons can then evaluate the orientation of the tibial component, including coronal alignment, rotation, and tibial slope of the intended component. When adjusting the implant plan, the surgeon has the ability to move anchor points. For example, if the surgeon is adding internal or external rotation to the femur, they may want to anchor the femoral component centrally, but if they are adding valgus to the femur, they may want to anchor on the medial aspect of the femur, so only the lateral compartment in extension is affected.

The values that are found on the patient-specific screen can be adjusted by the surgeon to fit their specifications for alignment and rotational goals for the patient. Recommended femoral and tibial component planning guidelines are provided in the Mako TKA Surgical Guide based on Triathlon design. These values can be saved, and the surgeon can perform balancing with these saved values. A new feature of the TKA 2.0 version is that the surgeon can also elect to develop a new plan preoperatively or intraoperatively with different values and toggle between various plans created for an individual patient.

The following will be a step-by-step comprehensive description of each tab of Figure 2, followed by six specific steps to better delineate how the surgeon can modify various factors of the femoral and tibial components in the preoperative planning stages of this operation according to functional knee positioning guidelines.

STEP 1: ENSURE MEDIAL CONCENTRICITY

Triathlon's single-radius design matches the curvature of the native femur[1-3] to help achieve concentricity and stability throughout the active flexion arc.[4-6] Ensure that the femoral component's medial condyle is concentric with the native condyle preoperatively and after making implant adjustments. The magenta line of native bone should match the blue of the implant.

STEP 2: ESTABLISH MID-TROCHLEA FLEXION

The unique 7° anterior flange design of Triathlon is designed to avoid the occurrence of notching. Scroll through the CT slices to ensure implant anterior runoff. The surgeon has the ability to anchor at the flexion radius center to flex the component and optimize femoral size while maintaining medial femoral concentricity. Evaluate femoral flexion and size in comparison to the tibia. Typically, the femur is the same size or one size smaller than the tibia. Use the anchor point to flex the component accordingly. Assess the volume of the anterior flange, proximal to the native trochlea, and anterior to the anterior cortex.

STEP 3: REPRODUCE THE NATIVE TROCHLEA POSITION

Triathlon's deepened trochlear groove is designed to help relax the extensor mechanism, enable deeper flexion, and reduce contact stresses exerted across the patella. Use a transverse CT slicer view to confirm the femoral component does not overstuff the patella-femoral compartment. Set the component to the desired size and center the component between the resected medial and lateral cortical edges so that there is no overhang. Position the component medial-lateral (ML) to reproduce the patient's native trochlea position, resulting in symmetrical ML trochlea resection. When making intraoperative adjustments, note the amount of external rotation that is added to the femoral component, as this can disrupt the medial concentricity.

STEP 4: ENSURE THE LATERAL COLUMN IS NOT OVERLENGTHENED

In the coronal view, ensure that the lateral side of the component is not adding excessive tension to the lateral side in extension and flexion. Greater laxity laterally in both extension and flexion may be desirable. To avoid over-lengthening the lateral column, the surgeon may modulate the femoral valgus and lateral laxity in extension. Modulate femoral IE rotation and lateral laxity in flexion by reducing resections laterally, which will likely add more tension to the lateral slide. Balance and position to respect the medial role of the medial collateral ligament (MCL) and the posterior cruciate ligament (PCL) and the lateral collateral ligament (LCL).

STEP 5: ADJUSTMENT OF THE TIBIAL VARUS

Confirm that the tibial resection landmarks are positioned 2/3 posterior and that the default lateral resection value is 7mm. Medial tightness is more predictable to change by adjusting the tibial varus with a lateral pivot point than by adjusting the tibial slope. With medial bony erosion, the medial resection may be less than 7mm. The surgeon can accommodate medial tibial bony erosion. As a starting point, pin the tibia laterally and drop the medial side into the varus to coronally orient the tibia to reflect the estimated pre-diseased joint orientation.

STEP 6: SETTING THE TIBIAL SLOPE

Triathlon CR tibial posterior slope is set between 0 and 3°, as Triathlon's shortened, flared posterior condyles are designed to facilitate the relaxation of the soft tissues and enable deep flexion without excessive slope.[10] The reduced slope guidance is designed to enhance rotary and AP stability when there is no ACL and no meniscus. Triathlon's short-flared condyles take tension out of the flexion space beyond 110° and allow for stability at 90° with minimal slope. Excessive slope may: result in PCL laxity in mid-flexion with the potential for inconsistent femoral translation; cause the femur to ride posteriorly; or block extension. Excessive rollback laterally is undesirable in TKA as the popliteus lateral meniscus mechanism is disrupted when the lateral meniscus is removed.

Lastly, the surgeon should scroll through the axial view to ensure that there is appropriate coverage and cortical contact.

Table I
Femoral component

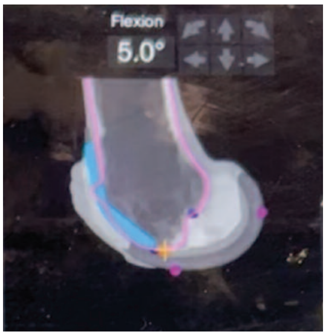
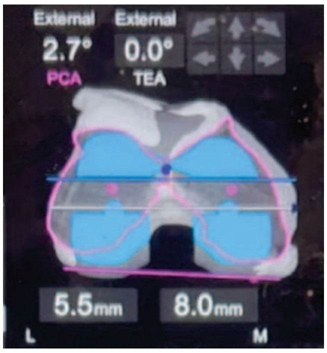
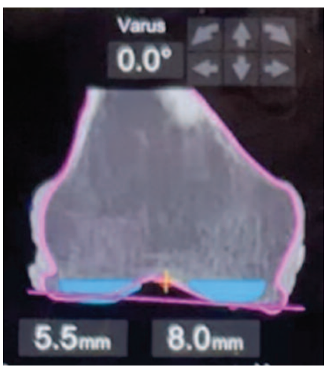
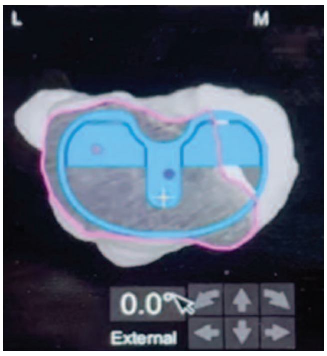
Top Right-Hand Screen:	
Figure 3. Sagittal plane 	Displays the femoral component position in the sagittal plane as well as the resection depth. Using the top left and right arrows, surgeons can adjust the flexion or extension of the component, while the up and bottom arrows can adjust the position of the component in the sagittal plane. Surgeons can calibrate the degree of notching and change the position of the component according to their specifications. In this case, the original plan has 5 degrees of femoral flexion. Additionally, the surgeon can use this view to ensure the femoral component's medial condyle is concentric with the native condyle. The surgeon should also consider mid-trochlea flexion by scrolling through the CT slides in this view to ensure implant anterior runoff.
Top Middle Screen:	
Figure 4. Transverse Plane 	Displays the component axial rotation by using the posterior condylar axis (PCA) and the trans-epicondylar axis (TEA), as well as posterior femoral resection depths. The top left and right numbers can be used to modify the rotation of the component into internal or external rotation, while the up and down arrows can be used to adjust the femoral component's position in the transverse plane. In a varus knee, the medial joint space is narrower than the lateral space, and therefore, in order to create equal gaps in the coronal plane, the default plan will resect more medial and posterior condylar bone than lateral bone. In this case, the default external rotation that the software set was 2.7 degrees based off of the PCA and 0 degrees from the TEA. The surgeon can use this view to check the trochlea groove. They can move through the CT slides to ensure the femoral component does not overstuff the patellofemoral compartment. Be sure after positioning the component that there is no ML overhang and the component's ML is positioned to reproduce the patient's native trochlea position.
Top Right-Hand Screen:	
Figure 5. Coronal plane 	Displays the varus-valgus alignment of the distal femur as well as the distal femoral bone resection depths. Using the upper arrows to the right of the varus-valgus degree, the surgeon can modify the varus-valgus alignment and the bottom arrows to modify the component position. These changes are reflected in real-time for the surgeon to determine at which point they can be saved or modified further. The default values set by the software are 0 degrees of varus-valgus with 6mm of resection of bone to account for 2mm of cartilage on the medial side and 2mm of bone on the lateral side. The surgeon can use this view to ensure that the lateral side of the component is not adding excessive tension to the lateral side in extension and flexion. To avoid overlengthening, the surgeon may modulate the femoral valgus and lateral laxity in extension, while they may modulate the femoral IE rotation and lateral laxity in flexion.

Table I (continued)
Femoral component

Tibial component	
Bottom Left Screen:	
Figure 6. Coronal plane  	Displays the tibial component varus-valgus rotation, position, and proximal tibial bone resection depths. As above, the top right and left arrows can be used to adjust the varus-valgus, and the up and down arrows can be used to finely adjust the component position. In this varus knee, the default plan will resect more lateral bone since the medial plateau is more diseased and therefore has less bone than the lateral plateau. Therefore, the default plan will usually resect more lateral (7.5mm) than the medial plateau (2.5mm), as shown in this case. The surgeon can use this view to confirm that the tibial resection landmarks are positioned 2/3 posterior and the default lateral resection value is 7mm. If there is medial bony erosion, the medial resection may be less than 7mm. To accommodate for medial erosion, pin the tibia lateral and drop the medial side into the varus to coronally orient the tibia to reflect the estimated pre-diseased joint orientation.
Bottom Center Screen:	
Figure 7. Transverse Plane  	Displays the tibial component rotation and position, as well as the antero-posterior (AP) tibial bone resection depth. The left and right arrows can be used to adjust the internal versus external rotation of the component. The surgeon can scroll axially through the component to ensure that there is appropriate cortical coverage of the component throughout. The program sets the rotation to 0 degrees as a default. The appropriate tibial component should be the largest possible without any overhang to maximize cortical contact.
Bottom Right Screen:	
Figure 8. Sagittal plane  	Displays the posterior tibial slope of the component as well as the sagittal resection depth. The left and right arrows can be used to adjust the tibial slope to be increased or decreased, while the top up and down arrows can be used to change the position of the component in the sagittal plane. The slope of the component is set to 3 degrees by default. In general, the slope is set between 0 and 3 degrees, and the surgeon should avoid excessive slope as this may result in PCL laxity in mid-flexion, cause the femur to ride posteriorly, or block extension.

Operative setup, intraoperative sequence

Incision and arthrotomy

Once proper aseptic draping and setup have been completed to the surgeon's liking, a standard median parapatellar approach is utilized. A conservative medial release is performed by excising medial osteophytes. The infrapatellar fat pad is excised, as is the synovium on the anterior aspect of the distal femur. The anterior cruciate ligament (ACL) is sharply excised with electrocautery or a knife, and the posterior cruciate ligament is retained if using standard cruciate-retaining implants. There are two sharp retractors applied to the medial and lateral sides of the knee to protect the superficial medial collateral ligament and the extensor mechanism, respectively (Fig. 9).

The arrays are then placed into the distal femur and proximal tibia, either by placing them within the incision created for surgical exposure or with a separate incision (Fig. 10). If placing them in a separate incision, please be sure to flex the knee prior to pin insertion to move the quadriceps muscle away from the intended pin entry point, as this can affect patellar tracking. It is also important to place femoral and tibial pins outside of the intended areas of resection, as well as ensure that the arrays are pointed directly to the Mako system's camera that will register the surgeon's manipulation of the knee throughout the operation.

The next step for the surgeon is to perform bony registration, registering the patient's bone anatomy to the patient-specific 3D CT-based bone model. Bony registration can be further subclassified into three main steps. The first is obtaining patient landmarks from the hip center. The hip center is obtained by mobilizing the ipsilateral hip in an expanding manner until the screen shows 100% (Fig. 11). Next, the medial and lateral malleoli are identified and registered by the surgeon with the probe (Fig. 12).

The femoral and tibial bony checkpoints are obtained after the malleoli are registered (Fig. 13). The femoral checkpoint should be at least 10mm away from the nearest resected bone. The tibial checkpoint should be similarly situated, at least 10mm away from the nearest resected bone.

Next, the Mako system's software will guide the user to select verification points on the distal and posterior femur, as well as the proximal tibia, to capture exact anatomic landmarks; this will help orient the robotic system to patient-specific anatomy and correlate intraoperative landmarks with those of the preoperative CT scan (Fig. 14). A total of 40 points are registered for the femur and tibia. Since the program is attempting to correlate with bony anatomy from the CT, it is imperative that the surgeon pierce through cartilage and engage cortical bone for each registration point. These points are registered by the software and correlated to patient-specific anatomy based on the CT scan.

Assessing dynamic joint balancing

Once this is complete, the surgeon is able to begin the ligament tensioning steps, which have been updated with the TKA 2.0 version software (Fig. 15).

Once registration is complete, the Mako system's software will display a digital tensioner screen (Fig. 15), which demonstrates the native alignment of the knee in both the coronal and sagittal planes based upon the intraoperative registration points and preoperative CT scan. This new option of version TKA 2.0 allows the surgeon to intraoperatively assess ligaments in both flexion and extension to the half millimeter (versus the prior 1mm) with audible and visual feedback. This allows for a more reproducible and quantifiable ligament assessment, as well as capture of the native alignment and alignment after any modifications are made to the plan by the surgeon (Fig. 16). The surgeon can capture the native coronal and sagittal alignment by pressing on the foot pedal at the intended varus-valgus and flexion-extension, respectively. The surgeon can see the degree of deformity captured in the bottom right-hand part of the screen.

The surgeon is also able to capture the correctable deformity by holding the leg by the heel and taking three fingers to gently toggle the degree to which the knee can be passively correctable in both the coronal and sagittal planes. It is based upon the surgeon's preference and assessment of how correctable the knee is in both planes. The correctable coronal and sagittal plane deformities can be obtained by moving the knee in their respective planes to the point to which the knee begins to feel tight, at which point the "Capture" button can be clicked at the right hand of the screen.

In addition, the features of the TKA 2.0 program allow an additional assessment of tightness by audible monitoring; beeps are heard as one stresses the knee until maximum stress is placed, at which time the beeps are not heard.

Once those measurements are captured, the Mako system's software will develop a soft-tissue laxity plan that can be manipulated by the surgeon. On this screen, there is a bar on the right part of the screen that has a blue range for showing the surgeon the degrees of motion that the leg is being held in different positions from 20° to 90°. Extension laxity is measured at the bottom of the blue bar at approximately 20° (Fig. 17). Flexion laxity is measured with the extremity held at the top of the blue bar at 90°. The circle represents the level of laxity that each compartment can tolerate both in extension and flexion. Once at an appropriate level of laxity deemed by the surgeon, the foot pedal can be pressed and this laxity level can be captured. Levels of laxity in millimeters will be shown in Table I.

A valgus force is applied by the surgeon while simultaneously holding the heel to capture the medial laxity (Fig. 18). A varus force is applied in the same manner to capture lateral laxity while in extension. Next, the surgeon should flex the knee and perform the same in order to capture medial and lateral laxities.

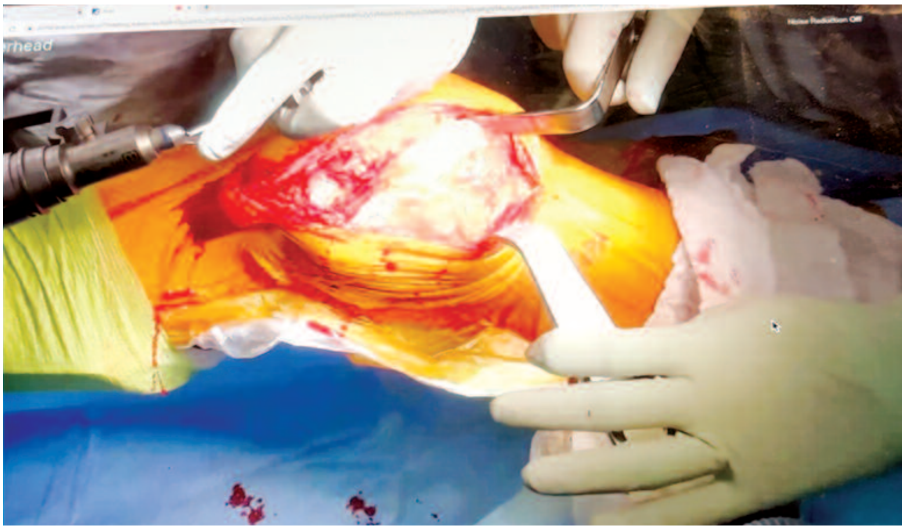


Figure 9. Excellent exposure of the knee joint with medial and lateral retractors in place.

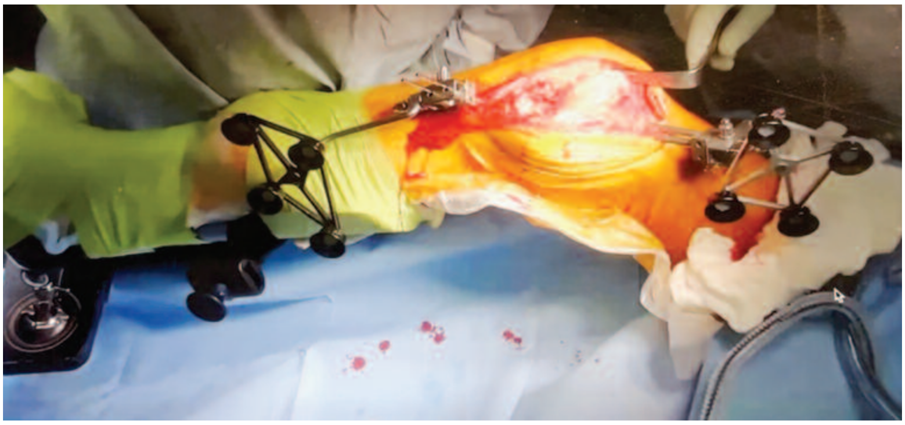


Figure 10. Demonstrates the intra-incisional placement of pins with arrays facing the Mako system's camera (not pictured).

Figure 11. Demonstration of the Mako system's software prompting the surgeon to circumduct the hip to find the hip center of rotation.

Figure 12. Demonstration of the Mako system's software prompting the surgeon to find the lateral malleoli with the probe.

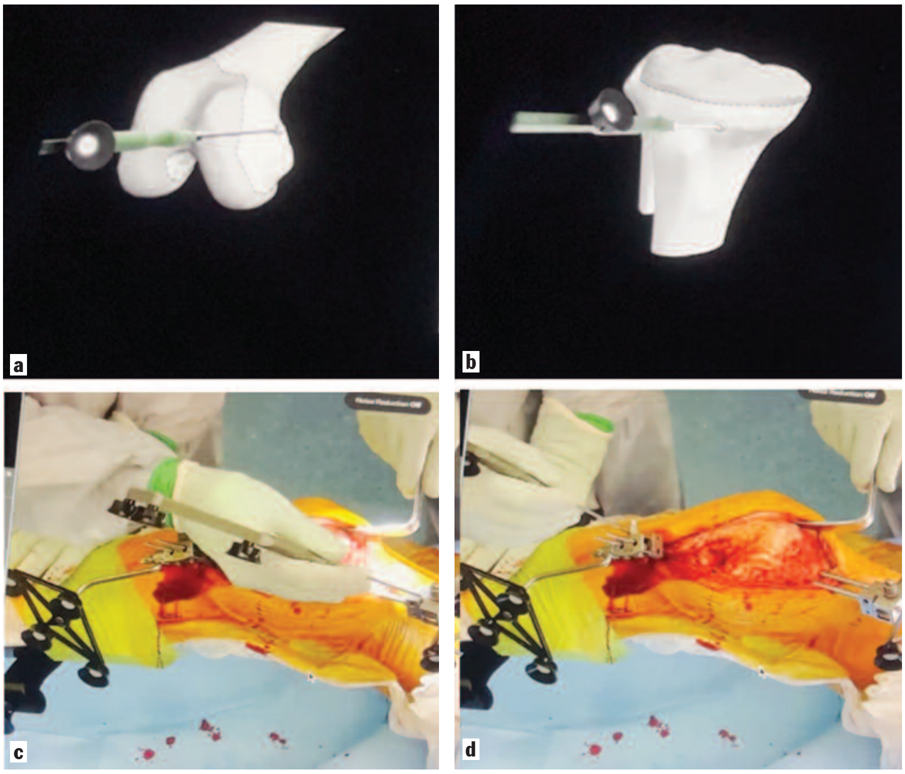


Figure 13a. Femoral and (b) tibial checkpoint registration with the (c and d) corresponding Mako system's software mapping images.

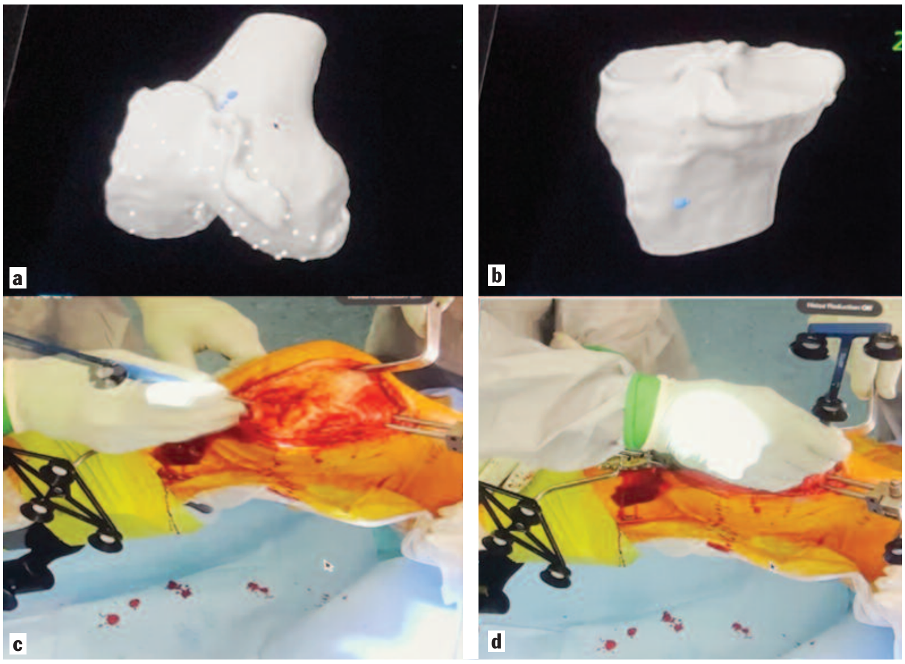


Figure 14. Bony landmark registration on the (a) femur and (b) tibia (40 points for each femur and tibia). (c and d) Intraoperative demonstration of a surgeon using a navigation probe to mark anatomic landmarks on the femur and tibia.

Intraoperative adjustments to the surgical plan

Once the laxities have been captured, the TKA 2.0 software will internalize this data and shift to the data screen, which is similar to the preoperative screen (Fig. 19). This screen provides the surgeon with everything they need to balance the knee, making it user-friendly for the surgeon and reducing mental demand as the surgeon plans the balancing of the knee.

This screen displays the flexion and extension gaps, and all components of this screen are modifiable by the surgeon to their specifications. The following will detail the specific steps that the surgeon should take to systematically balance the knee in flexion and extension, ensuring components are placed in the correct spot for each individual patient. The surgeon should apply Functional Knee Positioning guidelines that were detailed in the preoperative planning section.

1) Check the extension gap and correct it as necessary.
   a. Initially, the software developed expected gap depths at 3.5mm laterally and 3.0mm medially, based upon registration landmarks and preoperative balancing. The surgeon can modify the degree of varus and/or valgus and change resection depths in order to meet the appropriate targets of the extension gap (Fig. 20). The gaps were decreased to 1.5mm, and 0.5° of varus was added to the tibia to normalize extension gaps to 1.5mm medially and laterally.
   b. In general, the surgeon should aim for 0 to 1mm of an extension and flexion gap, as this correlates to the thickness of the implant and polyethylene. As in this case, if the patient has a preoperative flexion contracture, consideration can be given to increasing the extension gap further. The lead author (RM) suggests a 2mm increase in extension gaps for every 10° of flexion contracture.

2) Check the flexion gap and correct it as necessary.
   a. The goal for the surgeon should be to create the flexion gap into a trapezoid. For a standard varus knee, the lead author (RM) recommends aiming for 1mm more on the lateral side. In this case, the femur was externally rotated by 1.4° to achieve a trapezoidal flexion gap.

It is also important to judge the sagittal view of the femur to avoid any notching. Cuts can be modified, and the femoral component can be flexed and/or extended to avoid anterior notching.

The surgeon can then navigate to the bone resection cut on the right hand of the screen to visualize the bone resection depths, as shown in Figure 15.

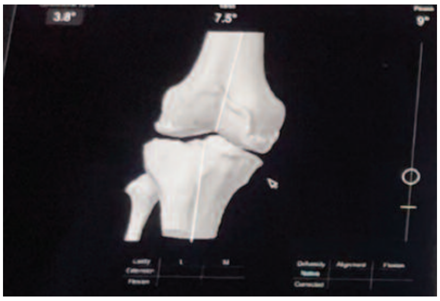


Figure 15. Digital tensioner, which confirms a 7.5-degree varus alignment with a 9-degree flexion contracture.

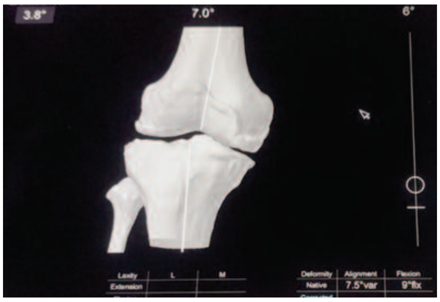


Figure 16. Demonstration of capturing the native deformity in the coronal and sagittal planes.

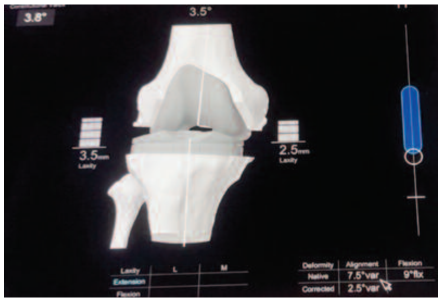


Figure 17. Demonstration of the surgeon determining medial and lateral laxity in extension.

The aforementioned adjustments are standards of practice in basic TKA balancing to achieve appropriate flexion and extension gaps to reliably produce stable knee kinematics. Below are several options that can be utilized by the surgeon to aid in an algorithmic approach to balancing flexion-extension gaps:

i. If both the flexion and extension gaps are unbalanced, the surgeon's focus should be on the tibia, as this affects both gaps. In a varus knee, the pivot point can be set to the lateral side, and one can apply progressively larger degrees of varus to achieve improved flexion and/or extension gaps.

ii. To correct the flexion gap, the external rotation of the femur should be adjusted. In a varus knee, the lateral side should be locked and external rotation should increase on the medial side.

iii. The extension gap can be balanced by changing the varus and/or valgus orientation of the femur.

iv. If the flexion gap is balanced, but still tight, the posterior tibial slope can be increased or the femoral component can be moved anteriorly, though it is important to recheck implant position and bony cuts as these maneuvers may also impact those parameters.

v. If the knee is balanced in extension but tight or loose, the surgeon can move the femoral component more distal or proximal.

vi. If tight or loose, but balanced in both extension and flexion, the surgeon can either resect more or less tibia bone.

Figure 18. Demonstration of the surgeon holding the leg to assess medial and lateral laxities in extension.

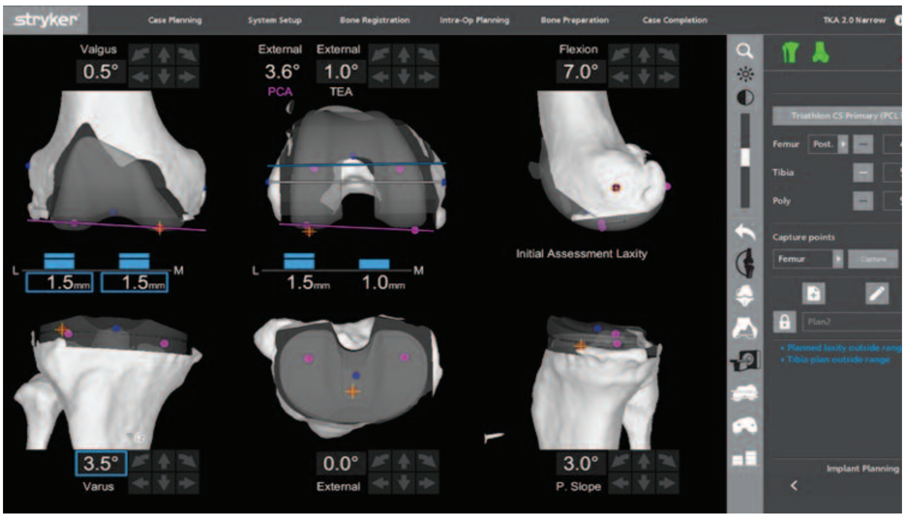


Figure 19. Computed tomography scan screen based upon alignment parameters and landmark registration obtained previously. Including laxity bars for visual and ease of balancing laxities. Also, there is the ability to toggle between implant and resection views.

Once satisfactory (Fig. 21), the surgeon can save the changes and navigate to the next step, which will consist of executing the plan and performing bony cuts.

Execution of the plan: bone resections

The surgeon uses the Mako system with a saw blade on the end of the robotic arm. Bone resections are performed

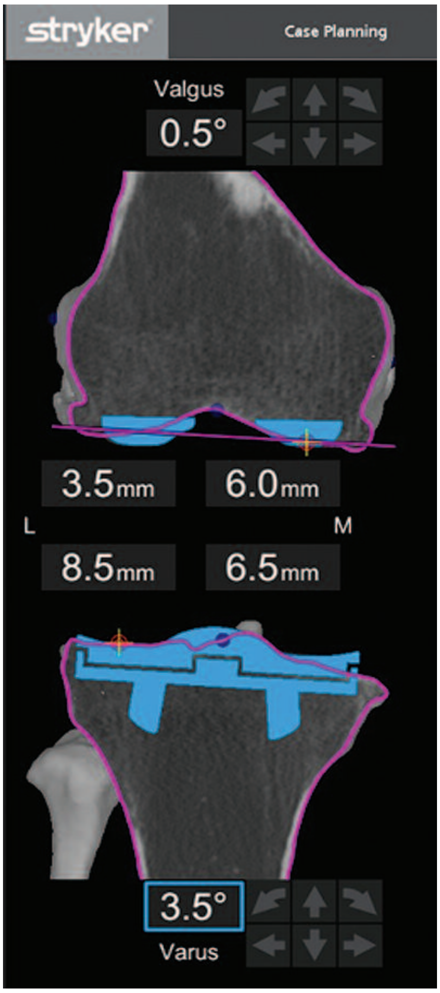


Figure 20. Demonstration of a balanced extension gap.

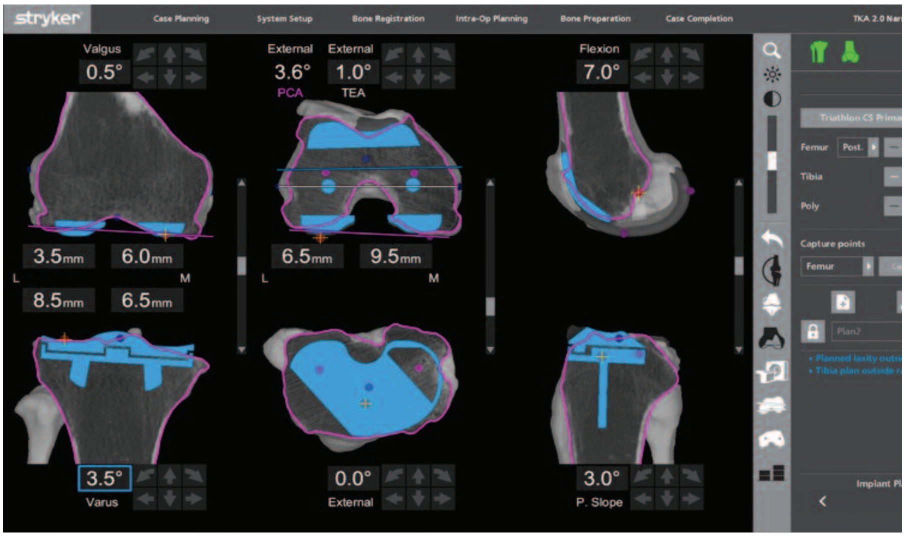


Figure 21. Demonstration of balanced flexion and extension gaps with resection depths.

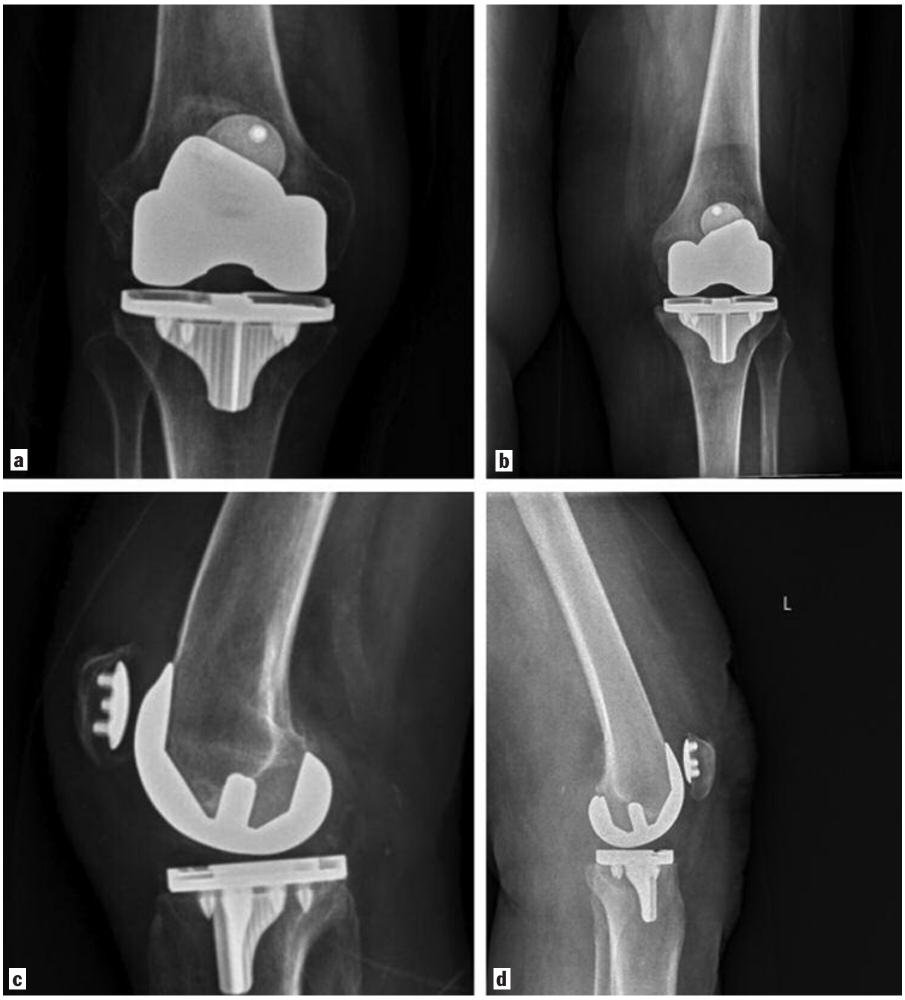


Figure 22a. Antero-posterior, (b) lateral radiographs, and sunrise views demonstrating (c) well-positioned and (d) well-aligned.

using the AccuStop™ haptic technology, which constrains the saw within a virtual boundary that is based on the patient's specific plan.

Proceed with robotic-arm resections based on surgeon preference. The lead authors' preferred steps for bony resection are as follows:

1) Tibia
2) Posterior femur
3) Anterior femur
4) Anterior chamfer
5) Posterior chamfer
6) Distal femur

The TKA 2.0 version allows for narrow saw blade usage on all implant sizes; whereas, previous versions of the platform only allowed for narrow saw blades on smaller sizes (1 and 2).

The TKA 2.0 version also creates a mid-resection tensioner page, which allows the surgeon to reassess and capture laxities in extension and flexion after making the initial bony cuts. This screen is similar to the one prior to any balancing being performed and prior to the bony cuts being utilized as a fail-safe mechanism for surgeons to iteratively check how their bony cuts are affecting the intended laxity.

Trialing, implantation, and final assessment scan

Once the laxity and tensioning are complete to the surgeon's satisfaction, trial implants can be placed, and the surgeon can assess and capture final laxities

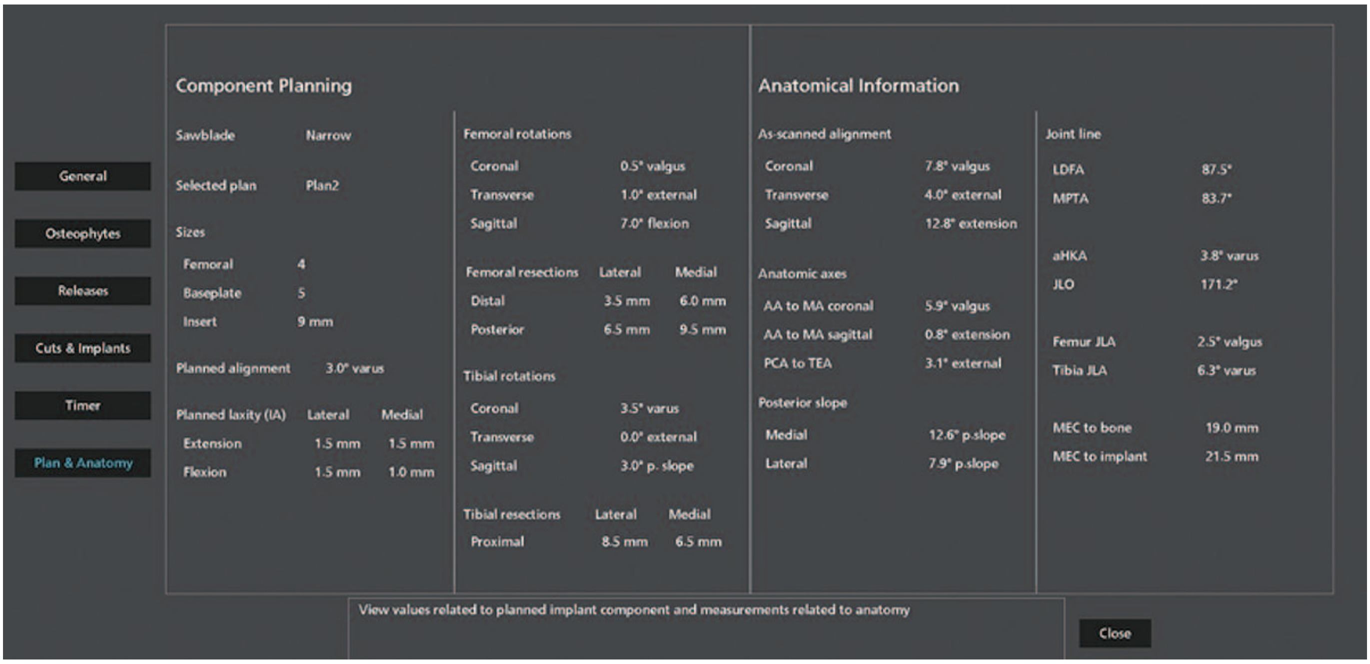


Figure 23. A robotic case summary developed at the conclusion of the case, detailing final alignment, rotation, and resection parameters, as well as other parameters not explicitly mentioned throughout the case.

in both flexion and extension. The surgeon will be able to visualize the limb, component position, and translations throughout the range of motion in different views.

The coronal and sagittal alignments can be checked once implants are in place, and the flexion and/or extension gaps can be manually checked as well. These values should be similar and/or identical to those planned prior to bony resection. If satisfactory, checkpoints can be removed at this time. If not satisfactory, the surgeon can further adjust soft-tissue balance through bony cuts or soft-tissue releases, repeating the above steps as necessary.

Trial components are removed, and the knee is prepared for final component implantation. Both cemented and cementless Triathlon (Stryker, Mahwah, New Jersey) can be used with the Mako TKA system. The final components are implanted, and the knee is closed in a layered fashion based on surgeon discretion. Radiographs are obtained postoperatively which, in the case of our patient, demonstrated excellent alignment with no hardware complications (Fig. 22). A robotic case summary is developed at the conclusion of the case, detailing final alignment, rotation, and resection parameters (Fig. 23).

DISCUSSION

This article demonstrates a straightforward, conventional surgical technique using the Mako Total Knee 2.0 system that is able to reliably produce balanced flexion and extension gaps in a varus osteoarthritic knee. The TKA 2.0 version of this system has several key upgrades from the previous version that help optimize surgical workflow. In general, the version comes with an improved user experience and several updates to the software. This allows the workflow to be more customizable, which makes it easier for the surgeon to remain focused on the procedure.

When surgeons initially evaluate the preoperative plan and modify it as necessary, they can save multiple plans and toggle between them to compare and contrast various component positions, rotations, and alignment permutations. The TKA 2.0 software version allows for the surgeon to evaluate ligament tensioning prior to any bony cuts once the preoperative CT has been balanced to the surgeon's satisfaction and bony landmarks have been registered with the probe. It also allows the surgeon to capture native alignment, corrected alignment, and flexion deformity. At this stage, the surgeon can also capture medial and lateral laxities in flexion and extension.

Once this is complete, the TKA 2.0 software version allows the surgeon to return to the CT scan viewing screen, at which point they can modify cuts, resection depths, alignments, and rotations while visualizing changes of the virtual implant on the bony anatomy. This new version allows the robotic arm to engage in the "Mako Park" feature—the robotic arm can be parked in the ideal spot for bony cuts and provide feedback to the surgeon to position the patient's leg in the appropriate space to optimize bony cuts. Narrow sawblades can be used for all implant sizes as well, with version TKA 2.0, not just for sizes 1 and 2 as in previous iterations. Furthermore, once the surgeon begins performing bony cuts, the software will prompt them to return to a mid-resection tensioning page, where one can reassess and capture medial and lateral laxities after initial bony cuts.

The surgeon now has control over cut sequences and advancements by pressing the foot pedal to advance further. Also, at the end of the case, the new software develops a case summary page, which details further surgical data that may not have been obvious throughout the case.

CONCLUSION

This surgical technique, using the Mako Total Knee 2.0 system, was able to reliably achieve balanced flexion and extension gaps in a varus osteoarthritic knee in an efficient manner. The clear and straightforward sequence, as outlined within this article, will help surgeons understand both the philosophy and technical aspects behind this robotic-arm assisted TKA. Furthermore, the upgrade of this system to the TKA 2.0 version allows for added convenience, accuracy, and a streamlined workflow for both the provider and operating room team. This demonstration should encourage providers to include CT-based robotic-arm assisted total knee arthroplasty in their surgical armamentarium. STI

AUTHORS' DISCLOSURES

Dr. Mont is a board or committee member for the American Association of Hip and Knee Surgeons, Hip Society, and Knee Society. He holds stock in CERAS Health, MirrorAR, and PeerWell. Dr. Mont receives research support from CyMedica Orthopedics and the National Institutes of Health (NIAMS & NICHD), and he is on the editorial board for Surgical Technology International, the Journal of Arthroplasty, the Journal of Knee Surgery, and Orthopedics. He is a paid consultant for Kolon TissueGene, Pacira, Smith & Nephew, and Stryker. Dr. Mont receives royalties and research support from Stryker, UpToDate, and Wolters Kluwer Health - Lippincott Williams & Wilkins.

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Dr. Scholl receives stock options from Stryker.

All other authors have no conflicts of interest to disclose.

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