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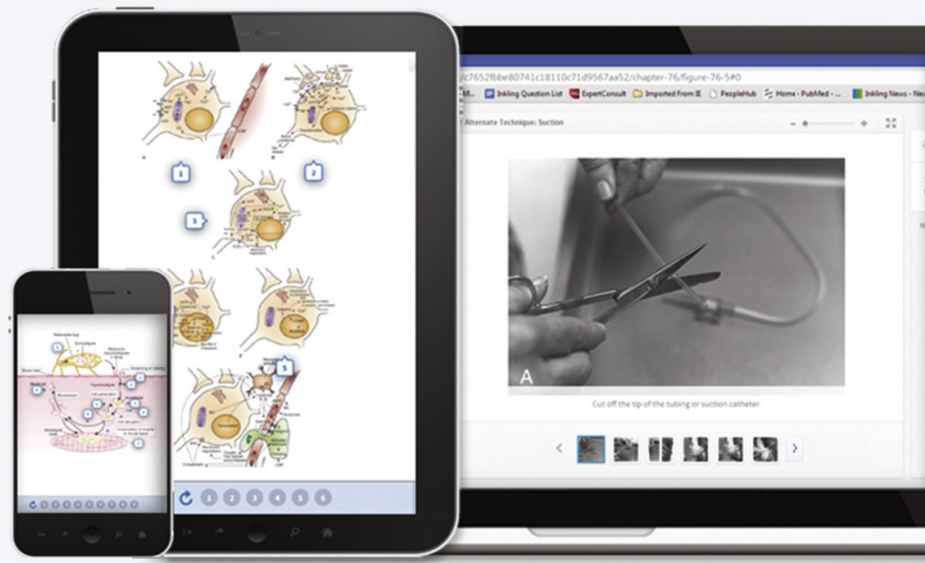
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Calipered Kinetically Aligned Total Knee Arthroplasty



Calipered Kinematically Aligned Total Knee Arthroplasty

THEORY, SURGICAL TECHNIQUES
AND PERSPECTIVES

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“Through the looking-glass” refers to the Lewis Carroll novel (i.e., the sequel to *Alice in Wonderland*) where Alice crosses over into a “bizarre universe” when she enters the flipped world on the other side of a mirror. The phrase implies unpredictable and strange happenings, a poignant metaphor for the mechanical alignment (MA) total knee arthroplasty (TKA) surgeon’s initial confrontation with kinematic alignment (KA)!

Interest in calipered KA TKA is justifiably growing because most randomized trials show clinical outcomes are better, and registry and case series analyses show implant survival is comparable or better than MA, with a negligible risk of varus tibial component failure and comparable risk of patellofemoral complications at 7 to 10 years. KA is “personalized” and three-dimensional; MA is “one approach fits all” in the coronal plane.

Calipered KA is defined as the setting of the femoral and tibial components to restore the patient’s prearthritic joint lines without the release of ligaments, including the posterior cruciate ligament. Resurfacing the knee closely coaligns the components’ axes with the three kinematic axes of the native (i.e., healthy) knee, thereby preserving the posterior cruciate, collateral, and retinacular ligaments’ resting lengths, which reduces the risk of kinematic conflict between the components and soft tissues.

The surgeon uses caliper measurements of bone resections to confirm that the varus-valgus and internal-external orientations and proximal-distal and anterior-posterior positions of the femoral component are coincident within ± 0.5 mm of the prearthritic joint lines. The fine-tuning of the varus-valgus and posterior slope of the tibial cut to match the patient’s prearthritic slope creates a tight rectangular space in extension and balances the knee. These steps restore the tibial compartment forces of the native knee without ligament release, a target that compartment force studies of mechanical, functional, and restricted kinematic alignment have not achieved, even after the release of healthy ligaments.

The MA surgeon learns to “see” the knee differently, operating in the “bizarre universe” of KA. No longer are components set to the MA targets of the femoral head and ankle, the trans-epicondylar axis and Whiteside’s line, and a fixed posterior slope. The need for releasing ligaments disappears. Contracted and stretched ligaments are strikingly rare, even in the most deformed knees. Correction of severe varus and valgus deformities becomes surprisingly straightforward, and flexion contractures readily resolve by releasing the posterior capsule.

The calipered KA surgeon incorporates the dentist’s technique of assessing surface relationships inside the mouth to three-dimensionally fit a crown on a worn tooth without referring to a preoperative image. Similarly, the surgeon opens the knee, assesses the cartilage wear on the distal femur, sets the femoral resections’ thickness compensating for cartilage loss at 0 and 90 degrees, cuts the tibia to restore a rectangular extension space, records the resection thicknesses in their operative note, and achieves a “personalized” approach. They do not consider the tibial component is set in “varus or valgus,” because restoring the patient’s prearthritic joint line is the target. The postoperative radiographic expectation is that component alignment matches the contralateral knee’s joint lines and limb alignment within 2 to 3 degrees when the paired femora and tibia are normal.

They gain confidence from those patients with a prior contralateral MA TKA that they treat with calipered KA. In studies of patients with bilateral TKA, the recovery of the KA TKA is more often less painful and faster, and the narcotic use is less. The Forgotten Joint Score is higher and comparable to a total hip replacement. Encouraging results and a surgery free of morbidity from ligament release enable the transition from an overnight hospital stay to same-day discharge. Patients realize that self-administering motion exercises and forgoing formal physical therapy result in a less painful and faster recovery.

MA surgeons always ask the range of the varus, valgus, and posterior slope angles after calipered KA cuts the femur and tibia. This question is irrelevant and distracting to the calipered KA surgeon because they set no components in varus, valgus, or to a fixed posterior slope as the patient’s prearthritic joint line is the target. Instead, imagine the MA surgeon switches things up and examines their bone resections through the KA looking-glass. They will realize that MA’s one-approach-fits-all cuts 85% of distal femurs in varus and 70% of proximal tibias in valgus relative to the patient’s prearthritic joint lines and reduces the Q-angle in 70% of patients. The higher frequency of a varus cut of the femur than a valgus cut of the tibia explains why varus knee and limb alignment are more frequent after MA than KA. The low risk of patellofemoral complications with both alignments is explained by KA restoring the prearthritic Q-angle and not decreasing it like MA, which apparently offsets KA’s internal rotation of the femoral component relative to MA.

Any TKA surgery can be like a well-planned wedding, intended to come off without a hitch yet with the unintended occurring. Whether the surgeon performs KA with manual, patient-specific, navigation, or robotic instrumentation, it is best to double-check the femoral component resurfaces the femur by measuring resections with a caliper. Intraoperative recognition of an unexpected resection deviation of 1 mm or more from the patient’s prearthritic joint lines provides an opportunity to correct component position and orientation before cementation and implantation.

Surgeons adopting KA go through a learning curve and starting with patients with simple varus deformities eases concerns. It is better to use MA than calipered KA when the surgeon is uncomfortable fully restoring the prearthritic joint lines. Restricting correction can result in instability, high tibial compartment forces, and a limb alignment unnatural to the patient.

In conclusion, several implant designs are US Food and Drug Administration (FDA) and European Union (CE) approved for use with calipered KA, fostering a spirited competition between the KA and MA techniques. Surgeons considering the transition from MA to calipered KA need to appreciate the unresolvable conflict between the two alignment philosophies. As F. Scott Fitzgerald wrote, “The test of first rate intelligence is the ability to hold two opposed ideas in the mind at the same time, and still retain the ability to function.” Those that blend the techniques experience frustration that compromises the patient’s result. It is best to follow all the principles and use the specific looking-glass for calipered KA to set and assess component positions.

It is with great pleasure that I write this introduction to a textbook focusing on a new approach to total knee arthroplasty (TKA). On the surface this would appear to be a technical monograph on a technique for primary TKA, but in reality it is far more significant than that. A widely quoted study by Kurtz et al.¹ indicates that close to a million TKAs are expected to be performed in the United States this year and that number is projected to grow almost exponentially to 2 to 3 million over the next decade or two. The other most widely quoted statistic in the TKA literature is that approximately 20% of TKA patients are dissatisfied with their knee,² often to the point that they are seeking revision or regret the decision to have a knee replacement. Similar results are not seen with total hip arthroplasty, and the reason for this disparity is the topic of intense research and debate. The potential contributing factors include patient selection, implant design, and surgical technique. Certainly, there is strong evidence that performing TKA for early arthritis as seen radiographically and with only mild to moderate symptoms is associated with a high rate of dissatisfaction. In a study published from our center, a group of about 50 painful TKAs presenting with normal X-rays and laboratory exams and normal range of motion were studied. When the initial preoperative radiographs were tracked down, about half had very early osteoarthritis (OA), most often Kellgren-Lawrence grade 2 or 3.³ A national multicenter study indicated that about one-third of primary TKAs were deemed to be “inappropriate” in terms of having early-grade OA and only mild-moderate symptoms.⁴ Early intervention seems to be a factor, therefore, in up to one-third of dissatisfied TKA patients.

The other possibility is suboptimal implant design. Numerous designs have been introduced in an attempt to improve patient satisfaction. In a national multicenter study coordinated by our center, we used an independent blinded medical interview service to survey almost 1000 TKA patients from leading total joint centers. We discovered that there was indeed a very high level of residual symptoms, with 30% to 50% of patients reporting symptoms with normal daily activity, especially stairs and kneeling, and less than half having participated in their most favored activity in the preceding month.⁵ Notably, none of the recent designs (mobile bearing, high flex, or gender) performed any better than an older cruciate-retaining TKA design.⁶ A recent study by Kahlenberg et al.⁷ came to the same conclusion.

The remaining potential factor to consider is implant alignment. Using standard manual instruments, surgeons are not able to consistently hit an alignment target with outliers of greater than 3 degrees from neutral mechanical alignment (MA) observed in 10% to 30% of cases and related to surgeon volume.⁸ The percentage of outliers can be reduced significantly with investment in advanced technologies such as computer navigation or custom cutting guides. Unfortunately, whereas

both of these options have dramatically improved the ability to achieve neutral MA and minimize outliers, this has not been associated with improvement in patient satisfaction, outcome, or revision rate.^{9–11} This has left knee arthroplasty surgeons at a frustrating impasse, with 20 to 30 years of techniques and technologies failing to improve TKA outcomes.

Into this challenging environment, Dr. Howell and his colleagues have pioneered a novel approach that questions the traditional gold standard of a neutral MA target for TKA. Although this initial approach was successful in introducing TKA decades ago and has been successful in millions of patients, we seem to have hit a plateau and must accept a high degree of residual symptoms and dissatisfaction unless a different approach is taken. Kinematic alignment (KA) is such a different approach. It incorporates the constitutional varus concept popularized by Bellmans et al.¹² that points out that many patients, particularly athletic males, frequently have anatomy that varies substantially from neutral MA. KA also expands on the landmark work of Eckhoff et al.¹³ who applied three-dimensional imaging and virtual reality to redefine the anatomy and kinematics of the knee. Applying these principles revealed that the bone cuts necessary to align a TKA in neutral MA substantially changed the axis of rotation and resulting soft tissue strains in most patients, which logically could result in pain, limited motion, and dissatisfaction.

Howell and his colleagues have devised a technique to recreate the joint line obliquity and axis of rotation close to the normal anatomic state. When this was achieved with custom cutting guides in years past, his group of patients achieved a higher degree of patients feeling their knee was normal than any of the dozen or so cohorts of TKA that have been surveyed with by blinded medical interviews.¹⁴ Promising results for improving outcomes and satisfaction have been reported in a randomized clinical trial,¹⁵ case cohort studies,¹⁶ and in meta-analysis of comparative studies.¹⁷ Although further studies must be done to more definitively confirm the benefits of KA, Howell and colleagues have done a great deal to advance the state of knowledge of the anatomy and kinematics of the knee before and after TKA. Finally, his approach shows great promise in making headway in one of the greatest current challenges in orthopedics: the dissatisfied total knee patient.

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ACKNOWLEDGMENTS

In 2013, I visited with Dr. Stephen Howell to watch a kinematically aligned (KA) total knee replacement. I left relatively confused. I went back two more times to get some clarity on the concept. It was so very different from what I had been taught and was actively teaching. It took some getting used to. That “getting used to” bit took 6 months. I performed my first calipered kinematically aligned (KA) total knee arthroplasty (TKA) in the opposite knee of a patient with a perfectly performed, mechanically aligned TKA that was painful and stiff. The result was a painless KA knee with excellent range of movement and a happy patient. I never turned back: aligning implants to recreate the prearthritic geometry simply made too much sense. My physical therapists noticed, my assistants noticed, and patients coming back for contralateral surgery noticed. As with published papers, there were no stiff knees, and there was less pain, quicker recovery, and no hint of midflexion instability. I started speaking about KA at various meetings and was often greeted with skepticism. The “system” is truly allergic to any challenges to the dogma on which it is built. And yet, slowly, open-minded surgeons started to come around, some companies embraced versions of KA, and the US Food and Drug Administration (FDA) began to allow it. When, 2 years ago, we decided it was time for a textbook, we chose to take advantage of the combined perspective of an international group of experts to explain KA from as many perspectives as possible.

As for all authors and editors from time immemorial, I found the process of writing a book more challenging and time-consuming than I imagined at the outset. And, as many before me, I also found the process rewarding and educational. I have learned an incredible amount along the way. I therefore want to thank my amazing coeditors who have made the work enjoyable, the contributors that have taught me so much, and our editorial team. Above all, however, I wish to thank and acknowledge Stephen Howell, MD, for having the courage, fortitude, and stamina to challenge the status quo; for optimizing, testing, and proving every assumption both in the lab and in the clinic; and for promoting the adoption and dissemination of a new thinking about knee arthroplasty: we are all grateful for your efforts.

Stefano A. Bini, MD

Despite an army of detractors, Dr. Stephen Howell dedicated his life and career to shifting the paradigm of how knee surgeons around the world approach a total knee replacement. This manuscript will cement his contribution to the advancement of the KA technique he pioneered. The international collection of world-renowned authors is a further tribute to the breadth and depth of this topic. I, like many of the other contributors, learned the KA technique directly from Dr. Howell and witnessed more universal acceptance over the years. This project will serve as a turning point to educate the knee arthroplasty community on a scale never imagined.

I am certain that this book will most certainly draw the ire of many, but I believe it can also pique the interest of those curious surgeons, as well as the younger generation. I look forward to the scrutiny, further research, and continued evolution in KA technique that Dr. Howell's original vision, embodied by this project, will develop from this book.

G. Daxton Steele, MD

Louis Pasteur, renowned for his discoveries of the principles of vaccination so prescient in this COVID era, stated that “in the field of observation, chance favors only the prepared mind.” As I look back over my 40-year career in orthopedics, my observation that knee arthroplasty patients needed a more “kinematic” alignment was only possible because of those colleagues, authors, and graduate students whose eye-opening instruction prepared my mind.

Distinguished Professor of Mechanical and Biomedical Engineering and my friend, Maury Hull, PhD, taught me how to see the knee from a biomedical engineer's perspective. Based on 27 years of cadaveric knee studies at the University of California, Davis, we learned from our 6-degree-of-freedom knee-testing machine that the native knee has three rotational axes the orientations of which are either parallel or perpendicular to the joint lines and are unrelated to a line drawn from the center of the femoral head to the center of the ankle. The publications by Hollister (1993), Coughlin (2003), Freeman (2005), and Eckhoff (2005) revealed the unexpected limitation that mechanical alignment changes the joint lines and misaligns the components to the kinematic axes in nearly all knees, and that accurately setting components to resurface the knee overcomes this shortcoming.

In December 2005, Charlie Chi and Ben Ilwan Park, with PhDs in robotics and automated manufacturing, shared the concept of using a patient-specific guide for TKA with Professor Hull and me. From that seminal moment, we launched the company called OtisMed, based on the concept of placing the implants to restore the native joint lines, ignoring the dogmatic mechanical alignment targets of the centers of the femoral head and ankle. Brook Byers, my friend from Kleiner Perkins Caufield and Byers, a premier venture capital firm in the Silicon Valley, provided funding for our fledgling company, and we were off and running.

The excitement around the KA concept and its ramifications for improving patient outcomes were palpable. Accordingly, Professor Hull and I quickly changed the lab's research orientation from anterior cruciate ligament reconstruction to TKA. My medical school friend, Gene Dossett, who performed the first randomized trial in 2007 at the Veterans Administration Hospital in Phoenix, Arizona, showed, early on, the clinical outcome superiority of KA relative to mechanical alignment.

In September 2009, the KA concept was nearly killed by the US Food and Drug Administration (FDA) when they stated that KA was substantially different from mechanical alignment and prohibited using it with patient-specific guides. As the FDA slammed one door shut, Dr. Norman Scott opened another when he asked and gave me 6 weeks to write a chapter for the Insall Scott Kelly textbook in November 2009. I first introduced calipered KA with manual instruments as an open-source concept in his authoritative text on knee surgery. The writing crystallized the need for the caliper's use to measure and adjust the bone resections within ± 0.5 mm of the target, to accurately position components coincident to the patient's prearthritic joint lines. This enduring principle of knee arthroplasty is the focus of the present textbook.

Between 2010 and 2017, Roman Gierts, the founder of VuMedi, provided the platform for disseminating the technique of calipered kinematic alignment with manual instruments! His “YouTube” of orthopedics provided free 24-hour, 365-days-

a-year worldwide surgeon access to instructional videos. The open-source concept and ever-accessible VuMedi surgical techniques enabled calipered KA to gain traction among surgeons and researchers in North America, Europe, Asia, and the Middle East.

Randomized trials and registry studies from England, Germany, Japan, Australia, Canada, and New Zealand comparing KA and mechanical alignment TKA collectively showed better clinical outcomes and soft tissue balance with fewer ligament releases and no increased risk of complications or implant failure at 7 years. The arthroplasty community and I are indebted to the clinicians and researchers who pioneered this work, culminating with the FDA approving the use of caliper KA for two implant companies in 2017. A welcome and complete turnaround from the 2009 decision!

I am grateful to the many US and worldwide surgeons who spread the word after learning calipered KA from a visit to my operating room and clinic beginning in 2006 (you know who you are—thank you!). They showed great courage by taking up the concept against the overwhelming disapproval of the mechanical alignment thought leaders in the United States.

I am incredibly grateful for my coeditors, Stefano Bini and Dax Steele, two high-volume and exceptional fellowship-trained arthroplasty surgeons, who are actively involved in the American Association of Hip and Knee Surgeons (AAHKS) and the Personalized Arthroplasty Society (PAS). They were the catalysts for kicking me in the pants to help them write this textbook.

So why this textbook? Drs. Bini and Steele and I hope that the open-minded and curious surgeons will read the chapters and watch the videos carefully crafted by our highly experienced international group of coauthors and, like Louis Pasteur, take the time to prepare their minds to accurately perform and see for themselves the many benefits of calipered kinematic knee alignment.

We are hopeful that those who adopt the principles, gain experience, and observe their patients will add to the understanding and further the usefulness of calipered KA. Following the tenacity of Teddy Roosevelt, as I have, they may take satisfaction that “far and away the best prize that life has to offer is the chance to work hard at work worth doing.”

Stephen M. Howell, MD

This book is a culmination of many years of work and research. I wish to dedicate its publication to the following angels: my wife and kids, who had to put up with countless hours of my being glued to the computer; my father, for teaching me to question what is possible or true; my mother, for showing the value of perseverance and hard work; and my brother, for his unwavering dedication to a mission greater than himself. I also wish to dedicate this to my partners, residents, and fellows, for their thoughtful comments along the way; your questions helped clarify my thinking.

SAB

I would personally like to dedicate this publication to my fellow editors and authors, who spent countless hours bringing this project together. To my family, who have supported me through every step in this journey. To my staff and colleagues, who never receive the credit they deserve despite being indispensable in providing patient care. And, finally, to every patient who entrusted me to improve their well-being, we cannot forget the reason we started all this in the first place.

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Mechanical Alignment Total Knee Arthroplasty: A Thoughtful Beginning With Unanticipated Limitations

RICHARD F. SANTORE, MD

The evolution of total knee replacement (TKR) from a novel and unreliable procedure to a highly reliable one is one of the major achievements of modern surgery over the past 50 years. Improvements in alignment theory, implant and instrument design, and surgical techniques have cumulatively contributed to this. That being said, serious surgeons all over the world can never accept what we do “now” as the ultimate solution. Every aspect of total knee surgery must be continuously subject to scrutiny for both incremental and disruptive change. The pursuit of perfection demands nothing less than acceptance of constant change. Although the focus of this book is on the role of kinematic alignment principles, it is important to put this in historical perspective and to acknowledge the roles played by perioperative patient management and implant and instrument design.

How did we get to where we are today, in 2021? The early phase of the modern era of artificial knee replacement began with the hinge prostheses in Europe by Börje Walldius of the Karolinska Institute in Stockholm, Sweden, and the interposition arthroplasty in the United States. The original Walldius prosthesis in 1951 was a hinge made of acrylic inserted without cement. The material was soon changed to the cobalt chrome alloy. His report of the technique and results in 1960 included an interesting reference to instrumentation: “No special instrument is required...”¹ Although the early results were encouraging, fixed hinge designs of various types, including the Guepar, fell out of favor because of high failure rates. Aware of the work by Venable and Stuck on the use of Vitallium alloy in fracture surgery in the late 1930s, Marius Smith-Petersen, a Norwegian-born surgeon working at the Massachusetts General Hospital in Boston, used this material for his famous cup arthroplasty of the hip and experimented with an analogous cobalt-chrome resurfacing of the distal femur with a stem into the distal femur. In that same time frame, MacIntosh and Duncan McKeever developed interpositional metal hemiarthroplasties.²⁻⁴ These were inserted without cement with a keel in the surface of the tibia for fixation and direct articulation against the bone of the femur. I was the assistant surgeon for several of these cases still being done occasionally by Richard (Dick) Scott in Boston in the late 1970s.⁵

In the United Kingdom in 1962, Mr. John Charnley introduced the total hip with acrylic cement fixation. There were many materials tried on the acetabular side until the introduction of polyethylene after failures with other materials such as Teflon. The combination of polymethylmethacrylate acrylic cement and polyethylene as a bearing surface by Charnley for the hip was a game changer and ushered in the true modern era of total joint replacement.⁶ In the late 1960s, Gunston, a Canadian who had worked in Charnley’s lab, developed a bicompartamental knee

arthroplasty with cemented poly on the tibia and round metal femoral components on the condyles.⁷ Charnley experimented with a hemiarthroplasty that had a poly component on the femoral side and metal on the tibial side (Load Angle Inlay, Thackeray).⁸ The success of this was short lived. I revised one of these knees 20 years ago in a rheumatoid patient with a combined varus supracondylar osteotomy and revision arthroplasty (see Fig. 1.1).

The further development of unicompartmental arthroplasty by Marmor,⁹ Murray, Goodfellow and O’Connor of the Oxford group,¹⁰ Scott and the Brigham Group in Boston,¹¹ and many others is not a focus of this book and will not be covered further in this introduction; suffice to say that a uni is an example of an anatomic versus mechanical alignment-based procedure. Intact anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) are prerequisites, and overcorrection is to be avoided. In some high-volume knee arthroplasty practices at this time (i.e., 2021), up to 60% of cases of primary knee osteoarthritis are being done with unis rather than full TKR.

In the late 1960s, also in England, Michael Freeman, surgeon, and SAV Swanson, engineer, developed a single radius of curvature, nonlinked prosthesis with a flat anterior femoral design.¹² It was a “roller in trough” design—a virtual modular equivalent of the hinge prosthesis. Both cruciate ligaments were sacrificed. More important than the prosthesis, however, were Freeman’s important contributions to the history of surgical technique and instrumentation. It was Freeman who introduced parallel cuts of the two major bones that were perpendicular to the mechanical axis. Furthermore, he introduced intramedullary instrumentation to facilitate reproducibility of the cuts. Many of the knees in that era were associated with severe deformities from inflammatory arthropathies, particularly rheumatoid arthritis. He prioritized achievement of reproducible mechanical axis, rather than anatomic alignment.

A major leap forward was the development of the total condylar prosthesis by the English surgeon John Insall, working at the Hospital for Special Surgery in New York City in collaboration with the engineer Peter Walker and Drs. Ranawat and Ingless.¹³ Both cruciate ligaments were sacrificed. Further refinements by the engineer Burstein led to the Insall-Burstein total condylar prosthesis with an all-poly tibia with a post.¹⁴ This laid the foundation for all modern posterior cruciate-sacrificing knee replacements. Parallel with this major achievement was work in Boston by Sledge et al. on designs that preserved the posterior cruciate.¹⁵ These early generation knees had drawbacks of all-poly tibial components, which resulted in high stresses on the cement, particularly in larger sizes, and poor patellar tracking. The metal-backed modular tibia solved that problem, and posterior cruciate-retaining philosophy was established as a highly reliable alternative to the New York school,

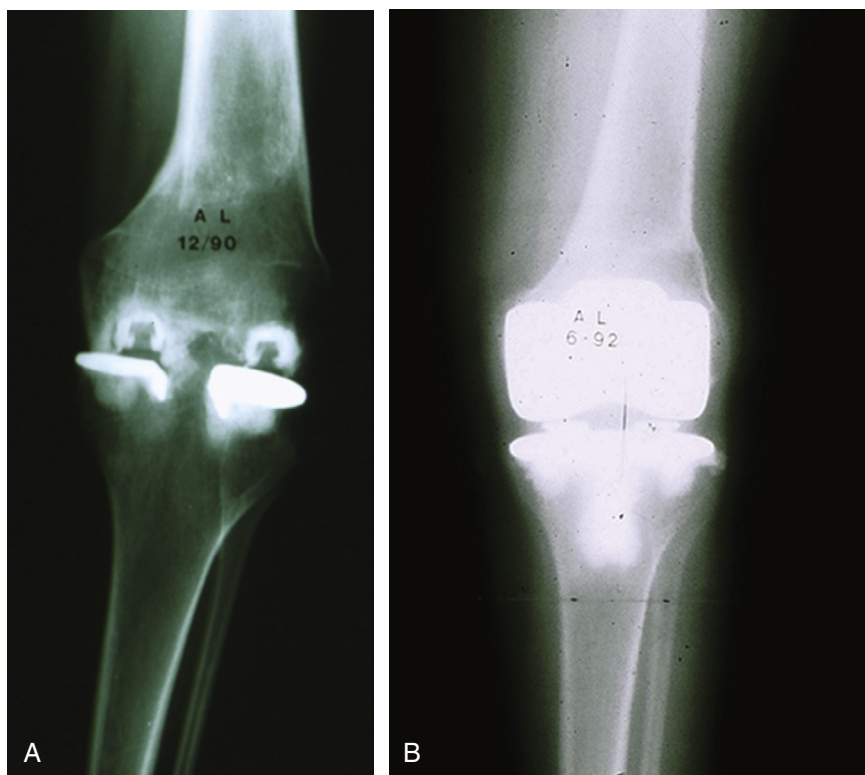


Figure 1.1 The Charnley knee arthroplasty (A) was a biocompartmental hemiarthroplasty with polyethylene femoral component and Vitallium tibial component. I revised one of these in a rheumatoid patient who also had undergone a varus supracondylar osteotomy years before the arthroplasty. The revision was done with posterior cruciate ligament sparing primary implants and a supracondylar valgus femoral osteotomy. This postop image (B) was taken after the osteotomy implant had been removed. The revision total knee replacement was done at the same time as a primary total knee replacement on the opposite knee so that the resected bone from the primary could be used as bone graft for the revision of the left side.

which requires posterior cruciate sacrifice in all cases with much greater femoral bone stock loss. Patellofemoral issues were serious problems with both the cruciate-sacrificing designs of the New York school and the posterior cruciate-retaining designs of the Boston school. Implant design improvements with a central trough in the femoral component and high profile of the anterior lateral femoral flange helped greatly to improve patellofemoral mechanics.

Some confusion exists in historic terminology. The Boston surgeons at the Brigham and engineer Peter Walker designed the posterior cruciate-retaining “Kinematic Knee Prosthesis,” manufactured by Howmedica and subsequently acquired by Stryker years later. The Kinematic prosthesis was inserted using mechanical alignment instrumentation and principles. Over time, the term “kinematic alignment” has come to mean principles of insertion that respect and reproduce to varying degrees the anatomic variations of individual knees.

No two knees are identical, even in the same individual. Think of the analogy to the human face. We all have faces, yet no two faces are the same. Imagine a facial plastic surgeon dealing with posttraumatic facial deformities or elective facial reconstruction. Is the goal to make every face look the same? Is it not important to respect individual variations that make each face unique? So, too, with the knee. It is clearly understood that the human knee has a few degrees of physiologic varus in the coronal plane, yet the mechanical axis principles require a perpendicular cut of the tibia with the goal of making “every knee the same.” The groundbreaking instrumentation of Freeman was adopted and improved by others. An alternative approach was introduced by Hungerford and Krakow, a more physiologic “kinematic alignment” that respected variations in anatomy of the knee. This was paired with the first U.S. Food and Drug Administration-(FDA)-approved cementless TKR in the United States in 1984, the porous-coated bead Porous Coated Anatomic (PCA).^{16,17} That

device went on to a much higher failure rate than expected, and porous bead technology is no longer used. This impact on alignment philosophy has lived on, however. It is important to recognize the contribution from Japan by Yamamoto, who reported on a cementless design with superior results to the cemented version in the late 1970s.¹⁸ This book explores the evolution and current status of kinematic alignment.

There is a major difference between the mindset of a surgeon and a bench scientist. A scientist postulates many ideas and seeks then to prove that the hypothesis is either wrong or right, without bias. A surgeon works with the burden and expectation of perfection in every operation. Acceptance of an error in planning or technique in any case is difficult for a surgeon to deal with. Accordingly, discarding a traditional and customary technique is difficult, even when data from a well-done study dictate that change is warranted. Consider how many years it took for the majority of surgeons to abandon the use of drains for knee replacements, even when published studies as early as 1998 showed no harm as well as benefits to doing so.¹⁹

So how does adoption of kinematic alignment fit in? Mechanical alignment has served as a straightforward and easy-to-teach technique. Why change now? The real issue is that 6% to 14% of total knee patients are unhappy with their outcomes in the peer-reviewed literature.²⁰ It is reported much higher, up to 30%, in the lay press.²¹ Can adoption of kinematic alignment lead to a significant improvement in patient satisfaction? The hypothesis that it will be superior is based on studies that show that the imposition of a rigid, “one size fits all” mechanical alignment approach actually reproduces the native anatomy for less than 5% of individual knees. Hungerford made an even stronger assertion in his chapter on alignment in a TKA book in 2005, when he wrote, “In single-leg stance the ankle must be brought directly under the center of gravity. This means that



Figure 1.2 Long standing X-ray with normal alignment. With the ankles together, single-leg stance is stimulated. The mechanical axis is 87 degrees to the joint line, which is horizontal in the stance position. (From Hungerford DS, Hungerford MW. Alignment of the human knee: relationship to total knee replacement. In: Bellemans J, Ries M, Victor J, eds. *Total Knee Arthroplasty: A Guide to Better Performance*. Heidelberg, Germany: Springer-Verlag; 2005:25–32.)

the lower leg and the mechanical axis are inclined toward the midline by 3 degrees. This can vary by as much as ± 1.5 degrees depending on the breadth of the pelvis and the length of the femur..." In our experience of measuring this relationship in thousands of patients, we have seen only one patient in whom the joint line was actually perpendicular to the mechanical axis. The tibial shaft is normally parallel to the mechanical axis and is therefore 87 degrees to the joint line and not perpendicular to the joint line (see Fig. 1.2).²² Furthermore, in the peer-reviewed, Ranawat Award-winning paper by Bellemans et al. in 2012, it was reported that up to 32% of men and 17% of women have a native mechanical axis of 3 degrees or more.²³ The kinematic alignment philosophy that recognizes and respects the bell curve distribution of "normal" for each individual has intuitive attractiveness. This is not a new concept, but enthusiasm for change has accelerated. However, it is important to include in the introduction that one prospective, randomized study by Young et al., also a Ranawat Award winner of the Knee Society, found no difference between kinematic technique with custom jigs and mechanical axis technique with computer-assisted technique.²⁴ This must be taken into account in the overall equation of what really matters in the quest to make total knee patients as happy as those who get total hips. Is it possible that the way in which the kinematic alignment was performed in that study was significantly different from that proposed in this book? Regardless, the key to widespread acceptance of the principles and adoption of the kinematic technique by the majority of surgeons will hinge on successful results reported by independent surgeons

performing similar studies. One study alone cannot be accepted as definitive, but it must be acknowledged and respected for its impact on the discussion. Other studies have shown improved flexion and improved patient-reported outcomes in kinematically aligned knees, including the prospective study by Dossett et al.²⁵ This is a dynamic and evolving area of clinical practice and research.

When I was a Harvard resident in Boston at the Robert Brigham specialty Rheumatoid and Total Joint Hospital in the late 1970s, total knee patients were admitted 2 days before surgery for "workup" and kept in the hospital for 2 weeks. After the surgery, a bulky Jones dressing was kept on for 5 days with elevation before initiation of partial weight-bearing ambulation and gentle range-of-motion exercises. As an aside, it is no wonder that the incidence of postoperative deep venous thrombosis was so high in that era. I vividly recall the excitement when Dr. Sledge and I got a patient home on day 7 after his total knee in 1979. Now, in 2020, almost all my total knee patients go home without pain on the day of their surgery and take no narcotic medications during their postop recovery period. This is commonplace in many centers in the United States. Within the large Kaiser system in California, over 80% of total knee patients go home on the day of surgery.

In Japan, patients stayed in the hospital for 6 weeks, not because of any inferior surgical techniques, but for cultural and tradition reasons. In fact, Japanese orthopedic surgeons are among the best in the world and surgical standards are very high.

The real issue is that a significant number of patients with a TKR have undesirable residual symptoms or are not satisfied with their surgical outcome. Focus on improvements in alignment are part of the quest for a marked reduction in this very disappointing situation. It is clear to any experienced surgeon who does both hip and knee replacements that the "I forget that I ever had surgery" comment, codified in the "Forgotten Joint Score-12," is much more common after hip replacements than after knee replacements.²⁶ Many approaches have been taken to address the outcome disparity with the knees. Psychological factors such as high preoperative scores on anxiety or anxiety/depression screening tools (K10, PHQ-9, STAI, etc.) have been studied. Reactive depression postoperatively that can rise to the level of diagnosable posttraumatic stress disorder (PTSD) has been described. Surgical technique factors such as excessively large components; tibial components that overhang the bony margins; tibial components that have reverse slope in the sagittal plane, that is, slope upward from anterior to posterior; malrotated femoral or tibial components, or both; elevation of the joint line; damage to or avulsion of the infrapatellar tendon; chronic, unrecognized, low-grade infection; arthrofibrosis; annoying "clicking and clunking" sounds; excessive laxity in extension only, or in flexion only, or both; patellar dislocation; excessively thick patella because of insufficient bone resection; or neuroma of the infrapatellar branch of the saphenous nerve are just some of the factors that can be associated with patient dissatisfaction after a "routine" TKR. To this day surgeons remain frustrated by the lack of guidance from computer-based surgical planning tools or intraoperative computer-assisted or robotic technology to guide rotation of the tibia component, which remains largely a "judgment call" at the time of surgery.

A new approach to alignment is a potentially important part of the solution to making patients much happier after their total

knees. The intuitive appeal of a kinematic approach to alignment is that it respects the unique differences of each knee. Just as in the example of the human face, no two knees are completely identical even in the same individual. The patient with the wind-swept knee appearance is the perfect example, with one knee in varus and the other in valgus. One interesting piece of history with regard to alignment in unis is that Hernigou reported on long-term follow-up of medial compartment unis of the Guepar group (Mark 1, Howmedica). The best 10-year outcomes were in the knees with mild varus alignment postoperatively.²⁷

The mechanical axis approach had the advantage of simple instrumentation for a perpendicular cut of the tibia with matching rectangular cuts of the femur. It was easy to teach and has given satisfactory overall results. However, there are some readily identifiable theoretical shortcomings. First, the upper tibia in humans is not biologically designed perpendicular to the long axis of the leg in either the coronal or the sagittal plane. If it were, you would not be reading this book. Second, the imposition of perpendicularity in the coronal plane causes tightness medially that leads to the need for medial releases and surgical weakening of the important medial collateral ligament. It is particularly problematic in knees that have outlier amounts of native varus. Next, the knee becomes too tight in flexion on the medial side, hence the rationale of the “standard 3 degrees of external rotation” of the femoral component. Resection of more bone from the posterior aspect of the medial femoral condyle gives more room for the artificially elevated medial aspect of the tibia in flexion. This is a modification based on an arbitrary commitment to a nonphysiologic perpendicular cut of the tibia.

Every surgeon has a favorite surgical approach, a favorite implant, a preferred alignment philosophy, and a preferred approach to rehabilitation. What matters? There is a big difference between passion for a certain aspect of surgical strategy by surgeon innovators and demonstration of a significant impact on outcomes of that strategy that would compel sceptics and the broad community of knee arthroplasty surgeons to change their own practices to adopt that strategy and abandon their own prior preferred surgical strategy. One example of a strategy that compels widespread adoption is the use of tranexamic acid (TXA) to reduce operative blood loss. Because of this, blood transfusions after knee arthroplasty are now very

uncommon. Twenty-five years ago, it was common for patients to drop hemoglobin level four or more points after surgery and require two or more units of allogenic blood transfusions. Use of TXA is now a “standard of care” for all arthroplasty surgeons. To propose a randomized prospective trial of TXA versus no TXA for TKA would now not be ethically justifiable. This is not the case with matters such as PCL-sacrificing versus PCL-preserving approach, rotating versus fixed platform tibial components, use of patient-specific versus standard instrumentation, use of computer-assisted versus conventional technique, and so on. Surgeons have their own reasons for selecting one of these options for their cases, but there is no consensus comparable to that on the use of TXA. We do not really know the causes of the high dissatisfaction rate after knee replacement surgery or how alignment contributes to the mix. It is exciting to see serious efforts to pursue the potential benefit of kinematic alignment with novel instruments designed to help achieve the intended outcome reliably. Validation of meaningful, game-changing improvement in patient satisfaction because of adoption of kinematic alignment will require confirmation and validation from independent surgeon researchers who perform well-controlled prospective studies with excellent technique for both mechanical alignment and kinematic alignment approaches. The data need to be so impressive that proponents of mechanical alignment feel convinced to switch over to kinematic alignment. Availability of reliable, easy-to-use, and easy-to-teach instruments is a necessity.

Hopefully, the chapters of this book will stimulate interest in exploring the potential of kinematic alignment to improve patient satisfaction in a way that can isolate this variable from all the other incremental changes in surgical technique, implant design, and rehabilitation that are simultaneously taking place, and validate its independent contribution. The goal of incremental and disruptive change in knee reconstruction is to fundamentally improve the patient satisfaction after TKR to more than 95%. Those who are filled with a passion for change, including Howell and Bini, will lead the way. Those who are unbiased and inquisitive will prove or disprove the hypothesis that kinematic alignment is superior to mechanical axis alignment with carefully constructed, prospective, and randomized clinical research studies.

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Phenotypes of the Knee and Limb: Rationale for Transitioning Toward Personalized Alignment in Total Knee Arthroplasty

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CHAPTER OUTLINE

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Variability of the Native Knee Alignment

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Impact of Alignment Concepts on Knee Alignment

Mechanical Alignment Concept

Anatomical Alignment Concept

Kinematic Alignment Concept

Overview

For a long time, the alignment goal for total knee arthroplasty (TKA) was a neutrally aligned limb with orthogonal joint lines to the mechanical axes (mechanical alignment [MA]). This had mainly to do with the belief of a better long-term durability because of more equal load distribution in mechanically aligned TKA. Recognizing the variability in individual knee alignment and compromised functional outcomes in TKA, there is an increasing interest among knee surgeons for more personalized, more anatomical alignment (AA) methods.¹ Among those newer alignment concepts, the kinematic alignment (KA) method is the most promising one.^{2,3} The goal of the KA concept is to restore the prearthritic alignment of a patient.⁴ To achieve this goal, surgeons need to have a profound knowledge of the individual native anatomy of the knee and its variability.

This chapter provides a basis for all alignment methods and a detailed overview of the current knowledge regarding the variability of lower limb alignment. First, a review of the literature will be presented. Following the discussion of the literature, the functional knee phenotype concept is introduced. Based on these phenotypes, the difference between three alignment goals of the most common alignment concepts (mechanical, anatomical, and restricted kinematic) and the native alignment will be presented and thoroughly discussed.

Variability of the Native Knee Alignment

When performing TKA, a knee surgeon should consider the native knee alignment of the patient. Only with an extended knowledge of native knee alignment in all planes (coronal, sagittal, and axial) is the surgeon able to achieve the optimum

outcome for the individual patient. The basic principle in knee surgery is to be as anatomical as possible. This principle has been neglected in TKA in terms of alignment for decades and all knees were forced into an alignment not because of better function and anatomy but because of other considerations such as implant durability and implant design, as well as easier and more reliable instrumentation. However, the only constant in anatomy is its variability, as one of the godfathers in knee surgery, Werner Müller, once stated.⁵

WHAT DO WE KNOW SO FAR?

Numerous studies have investigated the native coronal knee alignment.⁶⁻⁹ The reported overall knee alignment, usually represented as the hip-knee-ankle angle (HKA), averaged around 180 degrees. However, several studies have found that the individual coronal alignment is highly variable, and a significant number of patients appears to have either a varus or valgus alignment. Bellemans et al. investigated the incidence of constitutional varus (HKA <177 degrees) in 250 patients (male:female 125:125), aged between 20 and 27 years, on long leg radiographs (LLRs) in a Belgian population.⁶ They found that 32.0% of the males and 17.2% of the females had a constitutional varus. Most of the patients (66% of the males and 80% of the females) had a neutral aligned lower limb (177 degrees – HKA – 183 degrees). Only 2% of males and 2.8% of the females had a so-called “constitutional valgus.” Although the ethnicity of the participants has not been described, most of them can be regarded as Caucasians. Shetty et al. investigated the distribution of HKA based on the same criteria as Bellemans et al. in an Asian population and found more knees in varus (34% Indian, 35% Korean).⁹ The authors suggested that femoral bowing of the Asian population might be one reason for this shift. Interestingly, Song et al. found contradictory results investigating only Korean females. More patients had a valgus than varus (25% vs. 20%) alignment.⁷ Clearly, to date, the influence of ethnicity and its potential interaction with sex on HKA remains unclear.

Even though there is a great interest in the coronal alignment, most previous studies only used conventional radiographs for their measurements and few used two-dimensional magnetic resonance images (MRI) or EOS images.¹⁰ More importantly, a recent systematic review by Moser et al. identified a number of limitations of the existing literature on native coronal alignment.¹⁰ For example, the systematic review found only four studies investigating the orientation of the femoral joint line (usually measured as femoral mechanical angle [FMA]) and

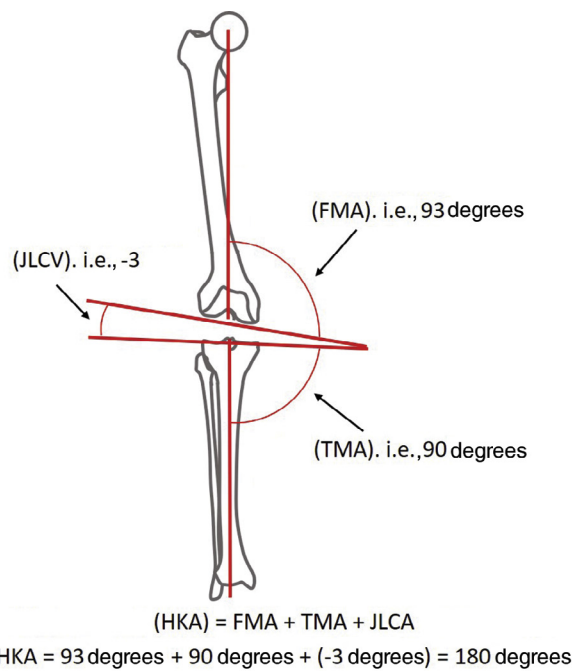


Figure 2.1 Measurement of coronal alignment and alignment equation. The hip-knee-ankle angle (HKA) is defined as the medial angle between the femoral mechanical axis and the tibial mechanical axis. The femoral mechanical angle (FMA) is defined as the medial angle between the femoral mechanical axis and a tangent to the distal femoral condyles. The tibial mechanical angle (TMA) is defined as the medial angle between the tibial mechanical axis and a tangent to the proximal tibial joint surface (tibial plateau). The joint line convergence angle (JLCA) is defined as the medial angle between the two joint lines. The JLCA thus takes negative values if the angle opens up laterally. The HKA equals the sum of FMA, TMA and JLCA ($HKA = FMA + TMA + JLCA$).

all studies only used LLRs. The reported mean values varied considerably (92.1 ± 1.9 degrees to 97.2 ± 2.7 degrees), and no study reported any ranges. The orientation of the tibial joint line (usually measured as tibial mechanical angle [TMA]) has been investigated by 10 studies, but sample sizes, reported mean values, and ranges varied widely (mean values ranged from 84.6 ± 2.5 degrees to 89.6 degrees). Additionally, many of these studies did not distinguish between male and female patients, although sex-related differences are well known. Therefore it seems that in the past, the research was focused on the overall alignment, whereas details about the orientation of the joint lines have been only superficially covered. As in many fields of knee surgery, for the sake of simplicity and reproducibility, more complexity was

avoided. However, in the context of TKA, the alignment of the joint lines is very important because they are not only directly accessible during surgery but also define the overall alignment. As shown by Cooke et al., the overall alignment defined by the HKA equals the sum of the FMA, TMA, and the joint line convergence angle (angle between joint surfaces [JLCA]).⁸ Fig. 2.1 shows a detailed description of these angles and the equation.

As a consequence of this lack of knowledge, the authors of the present chapter investigated the coronal alignment parameters of a young, nonosteoarthritic population using three-dimensional reconstructed computed tomography images.^{11–13} Their reported mean values support the findings of previous studies, but the reported ranges also demonstrate that the variability of the native anatomy had been underestimated. Mean values and ranges for HKA, FMA, and TMA are shown in Table 2.1. Based on these findings, it seems clear that a systematic MA or AA method will not fit all knees. In some knees the use of these systematic approaches will result in a major change of the alignment, which cannot be balanced by bone cuts only—extensive ligament balancing techniques need to be executed.

Looking at this huge mass of data on coronal knee alignment, one has to recognize that the conventional mindset of knee surgeons, which simply differentiates knees in varus, valgus, or neutral alignment, is too short-sighted. However, this myopic approach focusing on coronal limb alignment based on HKA is still the mainstay in TKA. Starting a more differentiated perspective by making subgroups of varus and valgus knees and including the joint lines draws a different picture, as our data show. There is a myriad of different combinations of the FMA and TMA, and the HKA is only a subordinate parameter of the FMA, TMA, and JLCA. It is therefore not sufficient to only consider HKA, and it is a prerequisite to include joint line orientation of the distal femur and proximal tibia, as well as JLCA, accordingly. An overall neutral, varus, or valgus HKA could have the theoretical combinations of the FMA and TMA shown in Table 2.2.

In fact, this might be one reason for conflicting findings in scientific articles. Some papers did not find any difference for mechanically aligned knees versus nonmechanically aligned knees, whereas others did. Clearly, the problem is that when looking at the overall coronal alignments, one fails to find any difference in outcomes with regards to alignment because patients with a distinctly different alignment are grouped together. The mass of data is in or around the mean and conceals the truth in a big foggy data cloud. We are just not able to see it yet.

TABLE 2.1 Mean values and ranges of hip-knee-ankle angle, femoral mechanical angle, and tibial mechanical angle for both sexes

	MALE		FEMALE	
	Mean $\pm$ SD (in degrees)	Range (in degrees, varus – valgus)	Mean $\pm$ SD (in degrees)	Range (in degrees, varus – valgus)
Hip-knee-ankle angle (HKA)	179.2 ± 2.8	172.6–184.9	180.5 ± 2.8	172.9–187.1
Femoral mechanical angle (FMA)	93.1 ± 2.1	87.9–100.0	93.8 ± 1.8	90.1–98.1
Tibial mechanical angle (TMA)	86.7 ± 2.3	81.3–94.6	88.0 ± 2.4	82.3–94.0

SD, Standard deviation.

TABLE 2.2 Definitions for all coronal phenotypes

Category	Deviation	Name	Mean Value (degrees)	Range (degrees)
Lim phenotypes (Hip-knee-ankle angle; HKA)	VAR _{HKA}	VAR _{HKA} 9 degrees	171	169.5<HKA<172.5
		VAR _{HKA} 6 degrees	174	172.5<HKA<175.5
		VAR _{HKA} 3 degrees	177	175.5<HKA<178.5
	NEU _{HKA}	NEU _{HKA} 0 degrees	180	178.5<HKA<181.5
		VAL _{HKA} 3 degrees	183	181.5<HKA<184.5
		VAL _{HKA} 6 degrees	186	184.5<HKA<187.5
		VAL _{HKA} 9 degrees	189	187.5<HKA<190.5
Femur phenotypes (Femoral mechanical angle; FMA)	VAR _{FMA}	VAR _{FMA} 6 degrees	87	85.5<FMA<88.5
		VAR _{FMA} 3 degrees	90	88.5<FMA<91.5
	NEU _{FMA}	NEU _{FMA} 0 degrees	93	91.5<FMA<94.5
		VAL _{FMA} 3 degrees	96	94.5<FMA<97.5
		VAL _{FMA} 6 degrees	99	97.5<FMA<100.5
Tibia phenotypes (Tibial mechanical angle; TMA)	VAR _{TMA}	VAR _{TMA} 6 degrees	81	79.5<TMA<82.5
		VAR _{TMA} 3 degrees	84	82.5<TMA<85.5
	NEU _{TMA}	NEU _{TMA} 0 degrees	87	85.5<TMA<88.5
		VAL _{TMA} 3 degrees	90	88.5<TMA<91.5
		VAL _{TMA} 6 degrees	93	91.5<TMA<94.5

Based on the aforementioned, it is clear that there is need for a more detailed analysis of coronal alignment. Consequently, we have developed a new classification system for knee alignment based on a native healthy population and have named it the “knee phenotype system.” This system aims first to allow a better understanding of variability in knee alignment and second, in a later stage, to give guidance for an optimal alignment in TKA for each individual knee.

THE KNEE PHENOTYPE SYSTEM

For all alignment parameters (HKA, FMA, TMA), groups with a range of 3 degrees, so-called phenotypes, were defined.^{11–13} The HKA groups were called “limb phenotypes,” the FMA groups “femoral phenotypes,” and the TMA “tibial phenotypes.”

The family of FMA, TMA, and HKA phenotypes are defined by the deviation from the mean value of a random sampling of a population of subjects with nonosteoarthritic knees and covers a range of ± 1.5 degrees from this mean (e.g., 180 ± 1.5 degrees). To state it another way, the phenotypes represent 3-degree increments of the angle starting from the rounded overall mean angle (HKA: 180 degrees; FMA: 93 degrees; TMA: 87 degrees). [Table 2.1](#) shows the definition of all these phenotypes.

The nomenclature of the phenotypes is organized as follows: The first part (NEU, VAR, VAL) defines the direction of alignment. The second subscripted part (HKA, FMA, and TMA) states the phenotype group. The last part (0, 3, and 6 degrees) shows the angular deviation from the mean value.

Until now, the different aspects of the coronal alignment have been investigated separately from each other. However, the coronal alignment is defined by the myriad of combinations of all these angles and, to see the bigger picture, it therefore seems important to assess the combination of the different parameters.

Thus, in the next step, the authors defined combinations of the three phenotypes, so-called “knee phenotypes” (combination of femoral and tibial phenotype) and functional knee phenotypes (combination of all three).

The alignment of the young, nonosteoarthritic population was phenotyped according to this new system. A total of 18 knee phenotypes were found out of the theoretically possible 25 knee phenotypes (by combining 5 femoral and 5 tibial phenotypes). Some 17 different knee phenotypes were found in the male population, whereas 12 different ones were found in the female population, including 11 mutual phenotypes. [Table 2.3](#) shows the found knee phenotypes and the percentage of patients they represent.

More importantly, it was observed that there were not only 17 different knee phenotypes (e.g., combinations of femoral and tibial joint line) but that the joint line orientations varied strongly in the varus, valgus, and neutral groups. Nine different combinations of femoral and tibial phenotypes (=knee phenotypes) could be found in the varus subgroup, eight in the neutral group, and eight in the valgus group.¹³

To give an example, a varus knee of 3 degrees HKA could have a distal femoral angle of 3 degrees varus and a proximal tibial angle of 6 degrees varus, whereas it could also have a distal femoral angle of 3 degrees valgus and 3 degrees varus. In TKA surgery, this is hardly the same knee. [Fig. 2.2](#) shows the three most common knee phenotypes in the VAR_{HKA} 3 degrees group and [Fig. 2.3](#) shows two neutrally aligned patients but different joint line orientations and the clinical impact of this.

Finally, 43 different functional knee phenotypes were found in this nonosteoarthritic population. Their distribution differed significantly between males and females. Separated by sex, there were 35 male and 26 female phenotypes, and a total of 18 mutual phenotypes. The most common eight functional phenotypes

TABLE
2.3

Knee phenotypes found in the total population and number and percentage of patients they represent

FEMORAL PHENOTYPES (FMA)					
	VAR 6	VAR 3	NEU	VAL 3	VAL 6
	87 ± 1.5 degrees	90 ± 1.5 degrees	93 ± 1.5 degrees	96 ± 1.5 degrees	99 ± 1.5 degrees
Tibial phenotypes (TMA)	VAR 6	81 ± 1.5 degrees	1	7	3
	VAR 3	84 ± 1.5 degrees	14	31	4
	NEU	87 ± 1.5 degrees	22	76	4
	VAL 3	90 ± 1.5 degrees	10	58	23
	VAL 6	93 ± 1.5 degrees	1	5	2
FEMORAL PHENOTYPES (FMA)					
	VAR 6	VAR 3	NEU	VAL 3	VAL 6
	87 ± 1.5 degrees	90 ± 1.5 degrees	93 ± 1.5 degrees	96 ± 1.5 degrees	99 ± 1.5 degrees
Tibial phenotypes (TMA)	VAR 6	81 ± 1.5 degrees	0.3%	2.3%	1.0%
	VAR 3	84 ± 1.5 degrees	4.5%	10.1%	1.3%
	NEU	87 ± 1.5 degrees	7.1%	24.7%	10.7%
	VAL 3	90 ± 1.5 degrees	3.2%	18.8%	7.5%
	VAL 6	93 ± 1.5 degrees	0.3%	1.6%	0.6%

for males and females are shown in Table 2.4.¹² In conclusion, it is obvious that the description of coronal knee alignment as “varus,” “neutral,” or “valgus” is outdated and should be replaced by the knee phenotype system.

Impact of Alignment Concepts on Knee Alignment

Different alignment concepts have been promoted since the initial development of TKA, and there is ongoing debate regarding the optimal alignment method and goal.^{12,14} Several recent studies found better clinical outcomes after TKA, when the postoperative alignment more closely resembled the native or prearthritic alignment of the patients.^{3,15} However, most of the promoted alignment concepts do not aim for the native alignment of the patients.¹² Surgeons need to understand both the technical

differences between the different alignment concepts and their impact on patients’ individual alignment. Many questions come into the mind of knee surgeons when thinking about coronal alignment in TKA. What is the rationale behind the use of each alignment system? What are the limitations? What are the pros and cons in terms of personalization? Most of these questions will be answered in this book; the latter one can be answered applying the knee phenotype system. When we aim for the least change from prearthritic native knee alignment, one can calculate the percentage of the population with an alignment (e.g., functional knee phenotype), within the target zones of the different alignment methods (mechanical, anatomical, kinematic). Clearly, the functional knee phenotype concept facilitates a more detailed discussion, as it incorporates all important coronal alignment parameters. The higher the percentage of the population covered by the chosen alignment method, the more likely it is that the native alignment of a patient is restored.

MECHANICAL ALIGNMENT CONCEPT

The alignment goal of the mechanical TKA alignment concept is a neutral limb alignment (HKA of 180 degrees) with femoral and tibial joint lines perpendicular to their mechanical axes (FMA and TMA of 90 degrees).¹⁶ Hence, the MA concept aims to purely create the following functional knee phenotype: $NEU_{HKA} 0 \text{ degrees} + VAR_{FMA} 3 \text{ degrees} + VAL_{TMA} 3 \text{ degrees}$. This functional knee phenotype was found in 2.05% of the males and 1.77% of the females. These values are comparable to values reported by Almaawi et al., who assessed the impact of the MA and the restricted KA (rKA) on the alignment of a knee OA population.¹⁴ These very low numbers are not surprising, as the classic MA concept aims to maximize the durability of the implants rather than restore the native alignment or optimal knee function.

Indeed, TKAs implanted according to this technique showed excellent survival rates in several registries. A pooled analysis in a systematic review found an all-cause survivorship of 96.3% (95% confidence interval [CI] 95.7%–96.9%) at 15 years and

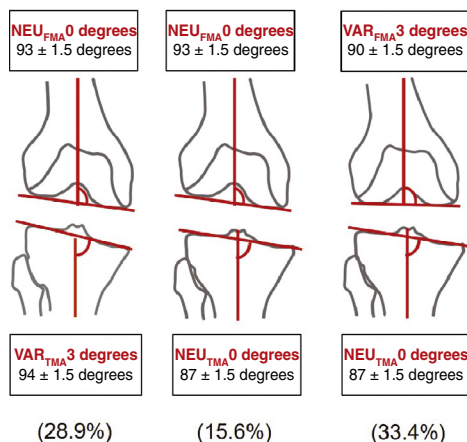


Figure 2.2 The three most common phenotypes in the $VAR_{HKA} 3$ degrees group (patients with a slight varus overall alignment (HKA 180 ± 1.5 degrees) and the percentage of the population they represent).

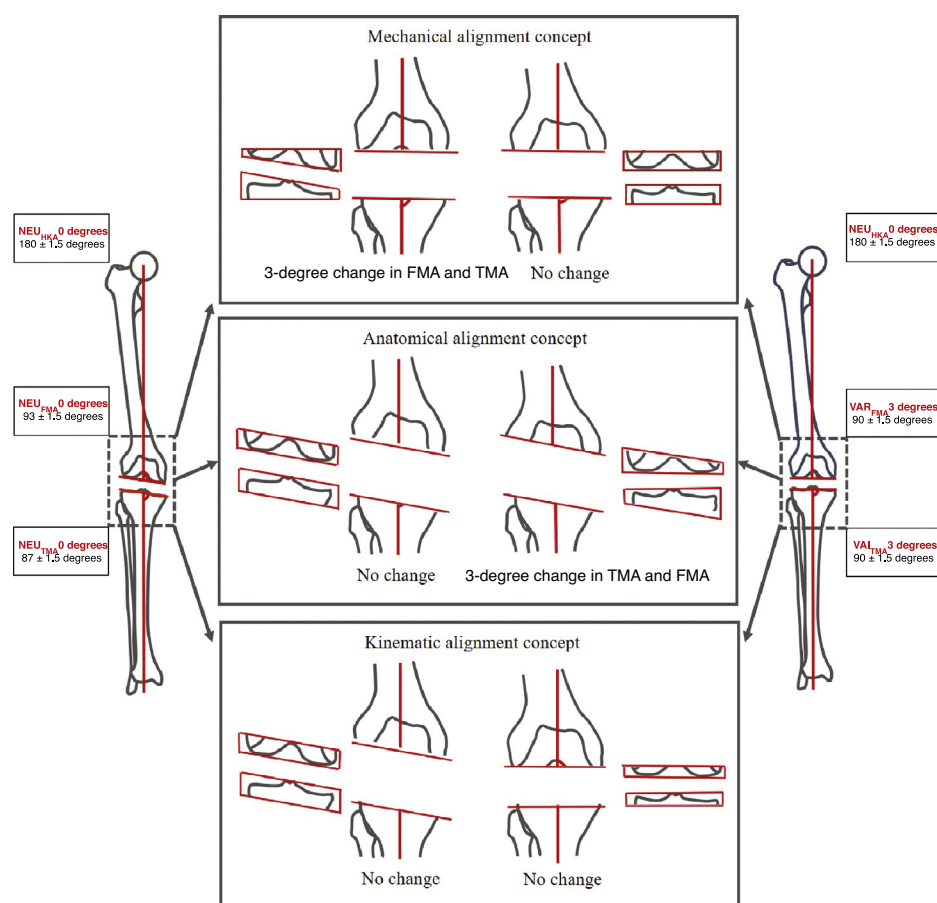


Figure 2.3 The schematic shows two patients with prearthritic neutral limb alignment with different femoral and tibial phenotypes and joint line orientation. Application of mechanical (top) and anatomic (middle) alignment changes the patient's prearthritic joint line orientation. Only kinematic alignment (lower) does not change the patient's prearthritic distal femoral and proximal tibial joint lines. FMA, Femoral mechanical angle; TMA, tibial mechanical angle.

94.8% (92.5%–97.1%) at 20 years.¹⁷ Furthermore, in the majority of patients a significant pain relief and improvement in function was seen.¹⁸ However, the question of why about 20% to 30% of all patients are not satisfied after TKA remains.^{19,20}

ANATOMICAL ALIGNMENT CONCEPT

The aim of the anatomical TKA alignment concept is to neutrally align the lower limb ($HKA = 180 \pm 1.5$ degrees) and to anatomically restore the native femoral and tibial alignment (FMA of

93 degrees and TMA of 87 degrees).²¹ Two biomechanical studies found better load distribution on the tibial component, better patellar kinematics, and reduced risk for lateral ligament stretching with this resulting joint line obliquity.^{22,23} Thus, the AA concept aims to purely restore the following functional knee phenotype: $NEU_{HKA} 0$ degrees + $NEU_{FMA} 0$ degrees + $NEU_{TMA} 0$ degrees. This functional knee phenotype was found in 18.97% of males and 17.70% of females. Hence, in comparison with MA, only a small adaption in the target zones for the tibial and femoral joint line orientation leads to an enormous increase in

TABLE 2.4 The most common eight functional knee phenotypes for males and females demonstrate a huge variability in coronal alignment

Functional Knee Phenotype	Male (%)	Female (%)
$NEU_{HKA} 0$ degrees $NEU_{FMA} 0$ degrees $NEU_{TMA} 0$ degrees	19.0	17.7
$NEU_{HKA} 0$ degrees $NEU_{FMA} 0$ degrees $VAL_{TMA} 3$ degrees	8.2	4.4
$VAL_{HKA} 3$ degrees $NEU_{FMA} 0$ degrees $VAL_{TMA} 3$ degrees	7.7	8.8
$VAR_{HKA} 3$ degrees $NEU_{FMA} 0$ degrees $VAR_{TMA} 3$ degrees	7.7	2.7
$NEU_{HKA} 0$ degrees $VAL_{FMA} 3$ degrees $NEU_{TMA} 0$ degrees	5.1	7.1
$VAL_{HKA} 3$ degrees $VAL_{FMA} 3$ degrees $VAL_{TMA} 3$ degrees	6.2	3.5
$VAR_{HKA} 3$ degrees $VAR_{FMA} 3$ degrees $NEU_{TMA} 0$ degrees	5.6	6.2
$VAR_{HKA} 3$ degrees $NEU_{FMA} 0$ degrees $NEU_{TMA} 0$ degrees	5.1	16.8

the covered population (compared with the MA). Interestingly, there is only one randomized controlled trial comparing the outcome of patients with an anatomical aligned TKA with the outcome of patients with a mechanical aligned TKA.²⁴ Yim et al. followed the patients for a minimum of 2 years and found no significant differences in any of the clinical or radiological outcome parameters. A major problem of this approach was and still is the difficulty in achieving a 3-degree cut at the tibia with conventional TKA instruments. Together with the risk of early poly-wear, these technical challenges limit acceptance among orthopedic surgeons. However, nowadays, owing to improvement in polyethylene quality, better and novel instrumentation, and aids such as patient-specific cutting blocks, navigation, or robotics, this alignment method has gained interest again.

KINEMATIC ALIGNMENT CONCEPT

The aim of the KA concept is to restore the native alignment of a patient.⁴ It can be performed as pure KA without any restrictions in terms of acceptable alignment and as rKA form, which restricts the alignment to certain safe zones (HKA 180 ± 3 degrees, FMA 90 ± 5 degrees, TMA 90 ± 5 degrees), to ensure durability and prevent severe alignment deviations.

The pure KA concept is represented by 100% of all knee phenotypes. It therefore represents the purest form of knee phenotype alignment. The question still is to find a safe balance between the aimed improvement in knee function and implant durability. Even if someone argues that owing to improvement in polyethylene liner quality, less equal load is tolerated, the stress distribution within the bone and within the prosthesis–cement–bone or prosthesis–bone interface is still under investigation under in-vivo conditions.²⁵

The targets of the rKA cannot be represented by the phenotype system, as there are different cut-off values or safe zones reported (phenotype concept HKA 180 ± 1.5 degrees versus rKA of HKA 180 ± 3 degrees). However, with a small adaption of the safe zones (HKA 180 ± 1.5 degrees instead of HKA 180 ± 3 degrees, FMA and TMA ± 4.5 degrees instead of 5 degrees) the rKA can be related to nine different phenotypes. To compare for this adaption, it was additionally calculated how many patients had an alignment within range of the safe zone. Four of these nine phenotypes were found in this population (three male, four female, three mutual). They represented 28.48% of all males and 39.13% of all females. They revealed that 53.10% of the females and 52.31% of the males had an alignment within the safe zones of the rKA concept. These values are nearly identical to the values reported by the aforementioned study by Almaawi et al., who also investigated whether the rKA concept would result in less correction than the MA concept and found a significant difference.¹⁴ Mean correction in FMA and TMA with the MA concept would have been 3.3 degrees (SD 2.1 degrees;

0–19 degrees) and 3.2 degrees (SD 2.1 degrees; 0–15.5 degrees), respectively, whereas with the rKA concepts, correction of 0.5 degrees (SD 1.1 degrees; range, 0–14 degrees) in the FMA and 0.3 degrees (SD 0.8 degrees; 0–10.5 degrees) and in TMA would have been necessary.

From a knee phenotype perspective, the greatest change of KA over MA or AA is the change of mindset of knee surgeons, moving away from a systematic identical alignment target toward personalization of TKA. To understand the greatest consequences and differences between these alignment concepts, one has to question which concept is able to restore native knee offsets best.

However, even with KA, the personalization of TKA has just begun. All current off-the-shelf TKA designs were designed to fit MA methodology. The shape and path of the trochlear in particular are currently not fitting KA. This discrepancy has partially to do with coronal and rotational orientation and design of the femoral component. Clearly, conventional TKA design was not born in the area of different alignment method to MA or AA. As a consequence of this misfit, there is an opportunity to modify or customize current femoral designs for use specifically with KA, to more closely restore the patient's prearthritic trochlear geometry. Only then will personalized TKA be achieved in both alignment and implant design.

Summary

Surgeons need to be aware that the anatomy of knees is highly variable and that the orientations of the femoral and tibial joint lines vary within a group of patients with a similar overall alignment. It is therefore insufficient to categorize knees as varus, valgus, or neutral. Furthermore, as a consequence of this enormous variability, a considerable number of patients end up with a postoperative alignment that differs significantly from their native alignment, if a systematic one target approach is used. More individualized alignment concepts are needed to achieve the goal of restoring the native alignment. Clearly, the KA represents 100% of all knee phenotypes and might be considered a true phenotype alignment. However, we need to investigate the survival and functional outcomes, as well loosening rates, in larger-scaled long-term studies. The functional knee phenotype system is a helpful tool to define the optimal alignment for each patient and to better discriminate the patients investigated in TKA studies. Otherwise we will go on comparing apples and oranges and the evidence will remain conflicting.

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It Is Time to Consider a Philosophical Change From Mechanical to Kinematic Alignment

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CHAPTER OUTLINE

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Overview

This chapter discusses the research that is driving the change in philosophy from mechanical alignment (MA) to kinematic alignment (KA) in total knee arthroplasty (TKA). The first section discusses the association between MA and patient dissatisfaction after TKA, and how improving satisfaction requires a change in alignment philosophy to one that does not require ligament release. The second section describes the recent discovery of three axes in the knee that determine kinematics and how resurfacing the knee is the only method for coaligning the three axes of the femoral and tibial components to those of the patient's prearthritic knee. KA can

be performed with manual, patient-specific, navigational, and robotic instrumentation; however, intraoperative caliper measurements of bone resections are required to verify the components are set coincident to the prearthritic joint lines. The third section shows that MA TKA does not restore knee kinematics, because the targets of alignment do not coalign the axes of the components to those of the patient's prearthritic knee. The fourth section uses evidentiary research to show that calipered KA TKA optimizes implant survival, medial compartment loading, and patellofemoral kinematics, when compared with MA TKA. The educational objective is to encourage surgeons to examine their experience with MA TKA and learn about the three kinematic axes that determine knee function. For those interested in improving clinical outcomes, consider performing calipered KA and intraoperatively verifying that the femoral component resurfaces the patient's prearthritic femur, with their preferred method of instrumentation.

Time for a Change in Alignment Philosophy

The recent identification of three axes in the knee that determine motion and kinematics encouraged a fresh examination of the limitations of MA and implant design (Fig. 3.1).¹⁻⁵ It is well established that MA does not consider the orientation and position of the three kinematic axes when setting components with manual, patient-specific, navigational, and robotic instrumentation, and that not doing so requires an undesirable use of ligament releases.^{3,6} Although the combination of MA philosophy and modern implants is very successful in improving the lives of patients, regrettably, most studies show that nearly 20% report some level of dissatisfaction.^{7,8}

Three observations suggest it is time for a change from MA philosophy with the intent of improving the rate of patient satisfaction. First, sophisticated computer navigational and robotic MA instrumentation that increased the reproducibility of achieving a 0-degree hip-knee-ankle (HKA) angle has not improved the incidence of patient satisfaction, which indicates that MA has a ceiling effect.⁹⁻¹¹ Second, an alternative alignment philosophy that balances the TKA, leaving healthy ligaments untouched, would mitigate pain, retain proprioception, and provide a more normal-feeling knee.¹² Third, as some patients complain of discomfort and others are relieved, perhaps a philosophy that individualizes component placement to the patient's prearthritic phenotype of the knee should be investigated (see Chapter 2 by Hirschmann).^{13,14}

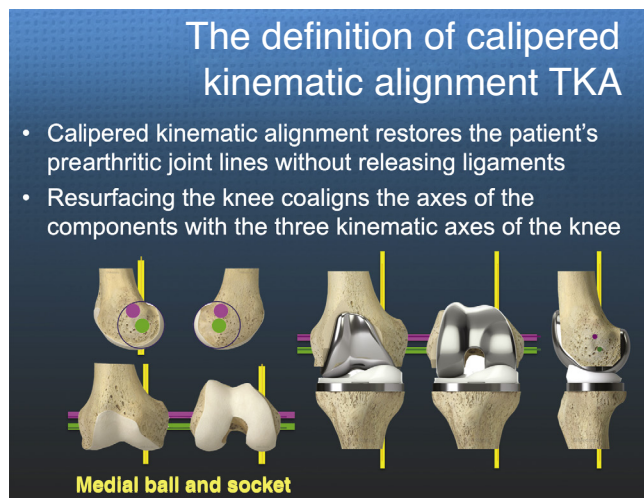


Figure 3.1 Schematics show the position, orientation, and interrelationship between the three kinematic axes (green, magenta, yellow lines) in the prearthritic right knee (left) and after calipered kinematically aligned total knee replacement (right). The green line is the flexion-extension (F-E) or cylindrical axis about which the tibia moves, which is parallel to the distal and posterior femoral joint lines. The magenta line is the F-E axis about which the patella moves, which is proximal and anterior and parallel to the first axis. The yellow line is the internal-external (I-E) rotation axis of the tibia that is perpendicular to the first two axes. Under joint compression the position of the I-E axis is fixed a few millimeters posterior to the center of the medial compartment, which functions like a ball and socket. When gravity distracts the knee and during some activities, the anterior-posterior and medial-lateral position of the I-E axis can vary. TKA, Total knee arthroplasty.

Three Axes of the Knee Make the Case for Changing to Kinematic Alignment

KA TKA strives to provide high patient satisfaction and function and long-term implant survival. The transition to KA follows naturally from biomechanical studies by Hollister, Coughlin, Freeman, Eckhoff, and Iranpour. They described the three “kinematic” axes in the knee that holistically define the patterns of movement between the femur, tibia, and patella (Fig. 3.1)¹⁻⁵:

- Axis 1: the tibia flexes and extends (F-E) around an axis centered in a cylinder best fit to the articular surface of the posterior femoral condyles.^{1,3}
- Axis 2: the patella F-E around an axis that is parallel and around 10 mm anterior and proximal to the F-E axis about which the tibia moves.^{2,4}
- Axis 3: the tibia internally-externally (I-E) rotates around an axis perpendicular to the F-E axes about which the tibia and patella move.^{1,5}

The three axes maintain an orthogonal interrelationship throughout flexion and extension. The transverse F-E axes of the tibia and patella are anatomically fixed in the femur and defined in orientation and position by the shape of the posterior condyles and trochlea, respectively. Both transverse axes are parallel to each other and parallel to the distal and posterior prearthritic joint lines. The orientation of the I-E axis of the tibia is perpendicular to the transverse F-E axes and the prearthritic tibial joint line.^{1-4,15} The orientation of the I-E axis is fixed; however, the anterior-posterior (A-P) and medial-lateral (M-L) positions may

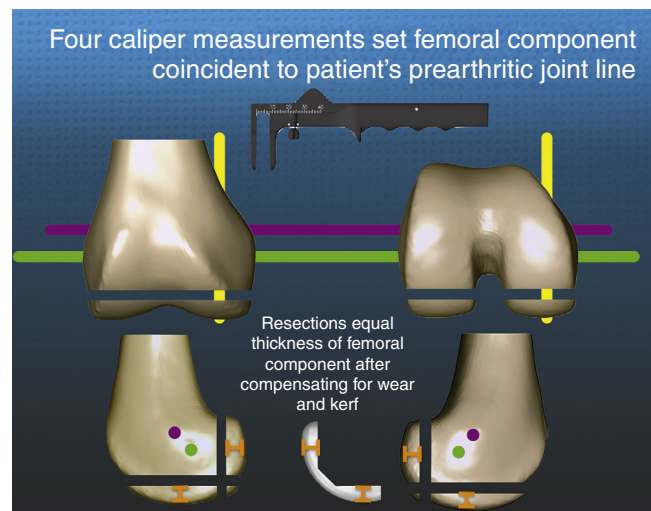


Figure 3.2 The schematic shows the three kinematic axes superimposed on four orthogonal projections of a right prearthritic femur with the distal and posterior bone resections separated. The thickness of the bone resections (orange line) is set to equal the target, which is the thickness of the distal and posterior condyles of the femoral component (silver) after compensating for cartilage wear and the kerf of the saw blade. The thickness of each resection is measured with a caliper and, when necessary, adjusted to within 0 ± 0.5 mm of the target. The caliper verifies that the femoral component is kinematically aligned, and that the prearthritic joint lines of the distal femur are resurfaced.

translate within the tibia, depending on how the knee is loaded. During weight-bearing activities, the ball-in-socket conformity of the medial femoral condyle, meniscus, and articular cartilage fix the position of the I-E axis of the tibia just posterior to the center of the medial compartment.¹⁶ Similarly, this kinematic pattern is closely reproduced by the medial ball-in-socket knee prosthesis design.¹⁷ However, without compression force and with gravity distraction, the A-P and M-L position of the I-E axis of the tibia varies within the tibia. Continuous X-ray imaging showed differences in knee kinematics and the position of the tibial axis between open-chain and closed-chain activities.^{16,18}

The three goals of calipered KA TKA are:

Goal 1: Restore the patient's prearthritic tibiofemoral articular surface (Fig. 3.2)

The first goal of KA is to set the A-P, proximal-distal (P-D), and M-L translation and F-E, varus-valgus (V-V), I-E rotation (6 degrees of freedom) of the femoral and tibial components, to restore the patient's prearthritic tibial-femoral articular surface of the knee. This principle automatically coaligns the axes in the femoral and tibial components with those of the patient's prearthritic knee and closely restores native patellofemoral kinematics.^{19,20}

Goal 2: Restore the patient's prearthritic joint line and limb alignment

The second goal is to restore the patient's prearthritic joint line and limb alignments. Any osteoarthritic knee will present with loss of cartilage on the femur and cartilage and bone on the tibia.²¹ The technique of KA uses strategies and methods to compensate for destruction at the time of knee arthroplasty, which automatically restores the patient's prearthritic joint line and limb alignment.²²⁻²⁴

Goal 3: Restore the patient's prearthritic tibial compartment forces and laxities

The third goal of kinematically aligned TKA is to restore the medial and lateral tibial compartment forces and laxities to those of the native knee, without ligament release. Native tibial compartment forces and ligaments are higher and tighter at 0 degrees than at 45 degrees and 90 degrees of flexion.²⁵ The calipered KA technique restores a tight rectangular extension space and a trapezoidal flexion space with the laxity of the prearthritic knee that varies widely between individuals.^{25–29} Chapters 11 (Hull) and 16 (Howell) comprehensively discuss tibial compartment forces and laxity in the calipered KA TKA.

Mechanical Alignment Is Incompatible With Restoring the Three Axes and Normal Kinematics

THE EARLY CONCEPT OF A VARIABLE FLEXION-EXTENSION AXIS IN THE FEMUR

Early studies promoted the idea of a variable orientation and position of the F-E axis in the femur, about which the tibia moves. For over 100 years, researchers studied the knee in an anatomic and not carefully defined sagittal plane that was not perpendicular to the F-E axis and concluded that the posterior femoral condyles are oval and not circular. The oval shape suggested multiple centers of rotation in the femur during flexion, which led to the design of the “J-Curve” knee prostheses with a plurality of distinct radii, such as five or more.³⁰ However, more advanced analysis of knee biomechanics showed the variable F-E axis in the femur is not accurate, which made the J-Curve knee prostheses outdated.^{1,31}

CONTEMPORARY CONCEPT OF A FIXED FLEXION-EXTENSION OR CYLINDRICAL AXIS IN THE FEMUR

The introduction of the sagittal “kinematic” instead of the anatomic F-E plane, which is perpendicular to the distal and posterior joint lines and F-E axes in the femur, projected the posterior femoral condyles as circular and not oval.^{15,32,33} In 1993, Hollister described an F-E axis about which the tibia moves with a fixed orientation and position and a constant center of rotation, in a cadaveric study.¹ In 2005, Eckhoff used computed tomography (CT) scans and confirmed the F-E axis is fixed by best-fitting two coaxial cylinders to the subchondral bone of the posterior condyles from 15 degrees to 115 degrees, and coined the term “cylindrical axis.”³ CT scans of the hip, knee, and ankle ($n = 90$) confirmed that the mechanical axis of the leg is not a straight line and that the MA effect of changing the prearthritic limb alignment to neutral changes the orientation of the F-E or cylindrical axis in the femur. Not coaligning the rotational axes of the component with those of the prearthritic knee alters the soft tissue balance, which can manifest as mechanical imbalance and altered kinesthetics or motor function.^{3,6,31,33}

THE TRANSEPICONDYLAR LINE IS NOT THE FLEXION-EXTENSION AXIS IN THE FEMUR

Some MA surgeons still follow the tenet that the F-E axis, about which the tibia moves, is coaligned with the transepicondylar line and the transepicondylar line through the medial

sulcus.³⁴ Anatomic studies showed no association between the fixed F-E axis in the femur and the transepicondylar lines, with deviations of up to 29 degrees.³⁵ The average deviation between the fixed F-E axis and the transepicondylar line in three-dimensional space was 5 degrees, with a wide range from 2 degrees to 11 degrees.³¹ Setting the femoral component to the transepicondylar axis too often places the prosthesis outside the patient’s prearthritic joint line, which explains the frequent release of healthy ligaments with MA that is unnecessary with KA.^{33,36}

THE VALGUS KNEE DOES NOT HAVE A HYPOPLASTIC LATERAL FEMORAL CONDYLE

The concept of a circular condylar shape changed the understanding of the anatomy of the valgus knee. Magnetic resonance imaging (MRI) studies showed that the medial and lateral posterior condyles in osteoarthritic knees with varus and valgus knees treated with primary TKA had similar radii that were within ± 0.2 mm. This observation dispelled the MA myth that the valgus knee has a “hypoplastic” or “laterally deformed” femoral condyle. In reality, the cranial translation of the lateral condyle relative to the medial condyle produces the valgus knee.^{32,37} In the valgus osteoarthritic knee, MA sets the femoral component in varus and external rotation, which overtightens the distal and posterior gaps in the lateral compartment (Fig. 3.3). A release of the lateral ligaments is required to enable the extension, flexion, and internal rotation of the tibia. Calipered KA TKA restores the patient’s prearthritic distal and posterior femoral joint lines because the radii of the medial and lateral femoral condyles are the same without the release of ligaments.

Calipered Kinematically Aligned Total Knee Arthroplasty Optimizes Implant Survival, Medial Compartment Loading, and Patellofemoral Kinematics

CATEGORIZING ALIGNMENT BASED ON 0 ± 3 DEGREES IS OF NO VALUE

The justification for the MA TKA target of a 0 ± 3 -degree HKA is weak and based on studies mostly published before 2000 with cohorts of between 193 and 421 TKAs (Table 3.1). Implant failure and radiolucent lines were associated with varus outliers. The shortcomings of these studies were the use of implant designs inferior to those currently in use, high implant failure rates of 50% at 10 years, and postoperative alignment measurements made from knee rather than full-leg radiographs.³⁸

Studies published since 2000 showed no clinically relevant association between implant survival and categorizing the postoperative long-limb alignment in ranges of neutral and varus or valgus outliers, according to MA criteria (Table 3.1). Hence, categorizing postoperative limbs as aligned or malaligned based on a mechanical axis target of 0 ± 3 degrees does not predict implant survival of modern TKA implants.³⁹

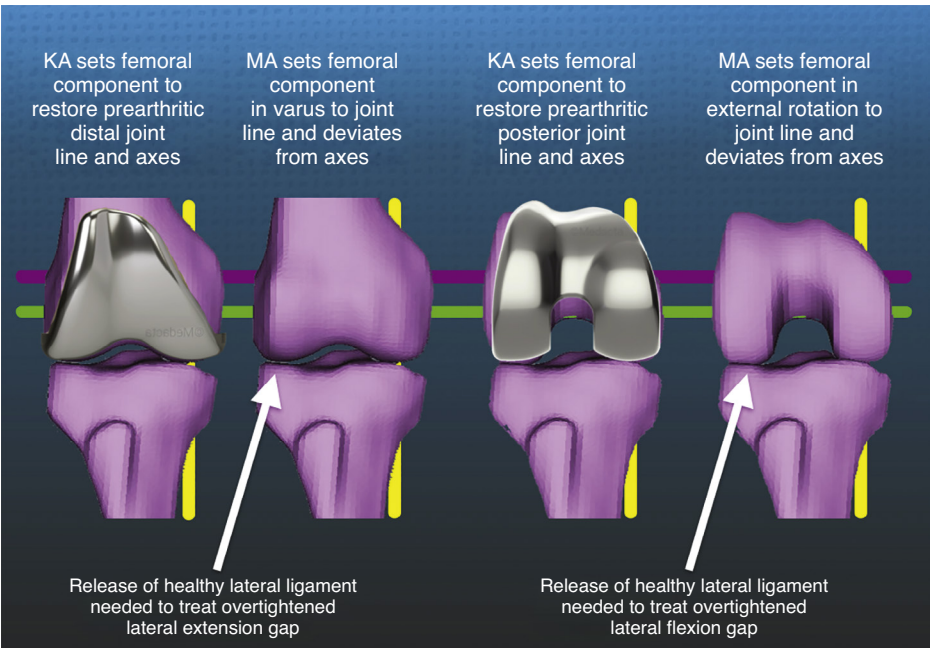


Figure 3.3 The schematic shows kinematic alignment (KA) and mechanical alignment (MA) femoral component placement in the valgus knee. KA sets the femoral component coincident to the patient’s prearthritic distal and posterior femoral joint lines and coaligned with the three axes of the knee. MA makes the erroneous assumption that the lateral femoral condyle is “hypoplastic,” and sets the femoral component in varus and external rotation from the patient’s prearthritic joint line and deviated from the three kinematic axes. MA requires release of the lateral collateral ligaments and soft tissue, whereas KA does not.

COMPARABLE IMPLANT SURVIVAL IN THE KINEMATICALLY ALIGNED TOTAL KNEE ARTHROPLASTY AND THE MECHANICALLY ALIGNED TOTAL KNEE ARTHROPLASTY

KA TKA has similar mid- and long-term implant survival to MA TKA. In 2020, a 7-year follow-up from the Australian and New Zealand arthroplasty registries reported no differences in the implant survivorship, revision rate, and causes of revision between 416 KA TKAs performed with patient-specific instruments (PSI) and a cruciate ligament–retaining (CR) prosthesis and those patients with the same implant design implanted with all other

instrumentation systems. The cumulative percent revision rate was 3.1% for KA TKA and 3.0% for the other TKAs (hazard ratio 1.0; 95% confidence interval: 0.6–1.8).⁴⁰ In 2019, a randomized controlled trial using radiostereometric analysis (RSA) showed that tibial component migration after KA was comparable to MA and was not associated with postoperative alignment.⁴² A 2017 study showed that patients with a calipered KA TKA with a postoperative alignment categorized as an outlier according to MA criteria had restored native medial and lateral tibial compartment forces without compartment overload.²⁸ In 2018, a single-surgeon series of KA TKAs reported a 2.5% implant revision rate at 10 years with no cases of varus failure of the tibial component.⁴¹

TABLE 3.1 Outcome studies with respect to frontal alignment							
Studies Reporting an Association Between Postoperative Alignment Outside 0 ± 3 Degrees and a Lower Rate of Implant Survival				Studies Reporting No Association Between Postoperative Alignment Outside 0 ± 3 Degrees and Implant Survival			
Author	Publication	Date	Implant	Author	Publication	Date	Implant
Lotke et al. ⁴⁵	JBJS	1977	Geometric	Morgan et al. ⁴⁶	SICOT	2008	Kinemax
Freeman et al. ⁴⁷	CORR	1981	Freeman Swansson	Parratte et al.	JBJS	2010	KinemaxPFC, Genesis
Tew and Waugh ⁴⁸	JBJS	1985	Six different designs	Matziolis et al. ⁴⁹	Arch Orthop	2010	PFC Sigma, Natural Knee II
Jeffrey et al.	JBJS	1991	Denham	Bonner et al. ⁵⁰	JBJS	2011	PFC, PFC Sigma
Fang et al. ³⁸	JOA	2009	AGC	Magnussen et al. ⁵¹	CORR	2011	HLS
Ritter et al. ⁵²	JBJS	2011	AGC	Kim YH et al. ⁵³	JBJS	2012	PFC Sigma, Nextgen LPS
				Howell et al. ⁶⁰	J Arthrop	2018	Vanguard CR

Arch Arthrop, CORR, J Arthrop, JBJS, JOA, SICOT.

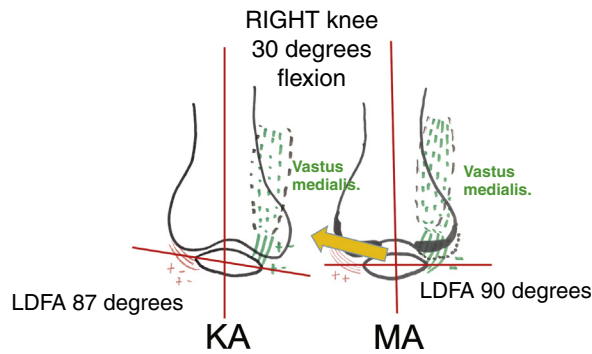


Figure 3.4 The schematic shows a craniocaudal view through the right knee in 30 degrees of flexion and the differences between the patella-femoral contact patterns for kinematically aligned (KA) total knee arthroplasty (TKA) (left) and mechanically aligned (MA) TKA (right) philosophies. In the KA TKA, the femoral component (not shown) is set coincident to the patient's prearthritic distal femoral joint line (parallel to the red oblique line), which is 87 degrees' valgus to the MA of the femur (vertical red line). The enables KA to maintain the native Q-angle, the laxity of the retinacular tissue, and the tension in the vastus medialis. In the MA TKA, the femoral component (thick gray area) is set at 90 degrees to the mechanical axis (parallel to the red transverse line), which is in varus relative to the patient's prearthritic distal femoral joint line. The varus deviation of the femoral component from the native joint line causes either overstuffing medial or overstuffing lateral. Either way, the Q-angle increases, the laxity of the retinacular tissue changes, and the tension in the vastus medialis decreases. LDFA, Lateral distal femoral angle.

MEDIAL COMPARTMENT LOADING AFTER KINEMATICALLY ALIGNED TOTAL KNEE ARTHROPLASTY IS LOWER AND CLOSER TO NORMAL THAN AFTER MECHANICALLY ALIGNED TOTAL KNEE ARTHROPLASTY

A gait study showed that patients with a KA TKA walked like a “fashion-model” with the feet close together and had a lower knee adductor moment than the MA TKA. Those patients with the MA TKA walked with wider spacing between the feet because of the deviation between the component and prearthritic joint line, which increased the knee adduction moment and overloaded the medial compartment.^{42,43} These findings are consistent with high strains in the medial and lateral collateral ligaments and abnormal patterns of tibiofemoral contact from changing the prearthritic alignment to a 0-degree HKA in those patients with prearthritic constitutional varus and valgus alignment.^{3,6,33} Chapters 11 (Hull) and 16 (Howell) comprehensively discuss tibial compartment forces and laxity in the calipered KA TKA.

PATELLOFEMORAL KINEMATICS AFTER KINEMATICALLY ALIGNED TOTAL KNEE ARTHROPLASTY ARE CLOSER TO NORMAL THAN AFTER MECHANICALLY ALIGNED TOTAL KNEE ARTHROPLASTY

KA restores the patellofemoral tracking of the patient's prearthritic knee by minimizing distortion of the extensor apparatus (Fig. 3.4). KA restores the patient's prearthritic Q-angle, whereas MA increases the Q-angle in those limbs with constitutional varus, which increases the risk of patellofemoral instability.⁴⁴ MA of the femoral component sets the femur in varus to the prearthritic joint line in 84% of patients, with the adverse effects of overstuffing either distal medial or distal lateral. Overstuffing lowers the tension in the vastus medialis, and alters the resting lengths of the retinacular ligaments.¹⁴ Chapters 9B (Hull) and 18 (Howell) comprehensively discuss tibial compartment forces and laxity in the calipered KA TKA.

Summary

The studies discussed in this chapter encourage a reexamination of MA dogma and a change to a KA philosophy. Although the combination of MA philosophy and modern implants is successful, regrettably, most studies show that nearly 20% report some level of dissatisfaction. MA causes disappointment by not aligning the axes of the components to the three kinematic axes of the knee, which overtightens the TKA, necessitating the release of healthy ligaments to restore motion. Manual, patient-specific, navigational, and robotic instrumentation can perform KA; however, intraoperative caliper measurements of bone resections are required to verify the components are set coincident to the patient's prearthritic joint lines. KA TKA restores kinematics, tibial compartment forces, and laxities without ligament release closer to those of the native than MA TKA after ligament release. Calipered KA TKA optimizes implant survival, medial compartment loading, and patellofemoral kinematics when compared with MA TKA. The educational objective is to encourage surgeons to examine their experience with MA TKA and learn about the three kinematic axes that determine knee function. Those interested in improving clinical outcomes may consider performing KA and intraoperatively verifying the femoral component resurfaces the patient's prearthritic femur by measuring bone resections with a caliper, with the preferred method of instrumentation.

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Preoperative Evaluation of the Patient for Treatment With a Calipered Kinematically Aligned Total Knee Arthroplasty

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CHAPTER OUTLINE

Overview

Introduction

History

Physical Exam

Radiographs

Patient Counseling

Overview

- With calipered kinematic alignment (KA) technique, preoperative management and evaluation of the arthritic knee patient does not vary vastly from the standard evaluation. However, there are some subtle differences that can aid the surgeon in planning and discussing the surgery with patients.
- This chapter introduces how to assess the patient in the office in terms of history, physical exam, and the recommended radiographs. This chapter will also discuss how to counsel patients on the kinematic alignment (KA) technique and answer questions regarding their expectations.

Introduction

Initial evaluation of a patient with knee arthritis should include taking a standard, thorough history of the patient's symptoms, including previous surgeries and other nonsurgical treatment. As a KA surgeon, one should elicit and document the patient's recognition of a knee deformity and any worsening of this condition. Given that the tenet of the KA technique is to restore the prearthritic alignment of the patient's knee, prompting the patient to recognize their alignment will facilitate the discussion with regards to patient expectations postoperatively.

History

Taking a standard history for the presenting knee pain is obviously paramount. Some critical points in the history that are somewhat more relevant for KA total knee arthroplasty (TKA) are highlighted below.

Patient's recognition of deformity, including recent worsening of deformity: Some patients may have been aware of their

“bowlegs” or “knock knees” their entire life, whereas others may not realize they have any deformity whatsoever. They also may have realized a subtle deformity that has been worsening more recently. Once the discussion of surgery starts, specifically on technique, patient's self-awareness of their deformity can facilitate the information shared to the patient about the KA technique.

Previous trauma (tibial plateau, distal femur fractures) or realignment surgeries (high tibial osteotomy, tibial tubercle osteotomy): can alter the patient's natural alignment. We will cover techniques and adjustments for some of these deformities in [Chapter 14](#) (Managing Severe Deformities).

Previous contralateral TKA: Any patient who has had previous TKA may have certain preconceived notions about TKA surgery. They could be 100% satisfied with their outcome, completely dissatisfied, or have some level of satisfaction in between these two extremes. Any operative notes, familiarity with the surgeon, or previous radiographs before the TKA can help with understanding what technique was used for component alignment. Understanding what was performed previously and the patient's subsequent outcome can assist the KA surgeon with their justification of utilization of the KA technique.

All other history such as previous nonsurgical treatments, aggravating and alleviating activities, current level of activity, etc. would be used to decide a patient's candidacy for TKA, which is no different than current standard recommendations. All the authors support current American Academy of Orthopaedic Surgeons (AAOS) guidelines for management of knee osteoarthritis.¹

Physical Exam

The physical examination of the knee can be involved and complex, and should be as thorough as possible for any patient being considered for TKA. Some examination findings for particular attention for KA surgeons are featured here.

Gait: Knee deformity can have dramatic effects on gait, some of which are compensatory and others pathologic. Critically observing and recording bilateral deformity and gait abnormalities will allow for comparison once a KA knee has been restored to native alignment.

Standing knee analysis: Visualizing and possibly photographing both knees in a standing posture can again be helpful for understanding the patient's deformity and for later postoperative comparison.



Figure 4.1 A standing weight-bearing full-length X-ray of a patient with bilateral varus deformities is demonstrated. The mechanical axis is highlighted.

Patella tracking: Any preoperative maltracking issues need to be documented accurately. Subsequent [Chapters 10](#) and [18](#) are devoted to minimizing the risk of deviated and treating maltracking in the KA TKA; therefore, preoperative pathology will be critical to documenting, correcting, and avoiding postoperative problems with the patella.

Many other physical examination findings are critical for preoperative evaluation, but not any different for any other technique for TKA. Previous incisions, range of movement, laxity, etc. are all taken into consideration and should be documented.

Radiographs

No consensus exists regarding optimal X-rays needed for preoperative evaluation of total knee replacement among knee arthroplasty surgeons, regardless of technique. At a minimum, an anterior-posterior (AP), lateral, and patellofemoral views allow for an initial evaluation. Within each of these subsets, weight-bearing versus non-weight-bearing, flexion angle, and countless other variations are often debated. The simplicity of the KA technique does not absolutely require any specific radiographs for preoperative planning. However, there are radiographic modalities that can possibly aid the KA surgeon with preoperative planning and subsequent postoperative validation.

A full-length, long-leg, weight-bearing AP radiograph of both lower extremities can provide a true measurement of the preoperative deformity, limited to the two-dimensional coronal plane. The contralateral extremity can also be measured and can fall under a number of categories, including normal, arthritic, replaced, and so on. Understanding the presence or absence of deformity in the contralateral knee can aid the surgeon in planning, as well as demonstrate to the patient what “normal”

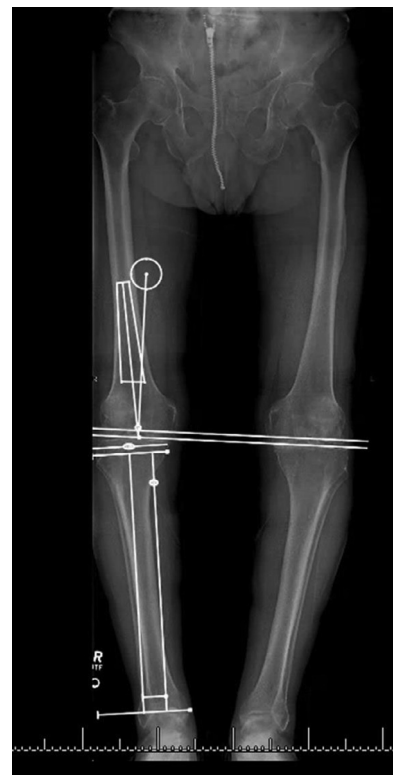


Figure 4.2 The femoral valgus angle and tibial varus angle in the coronal plane are demonstrated.

should be in their knee. Measurement of the femoral joint line valgus angle and tibial angle can also help verify intraoperative measurements, as can understanding where the mechanical hip-to-ankle axis falls relative to the native joint ([Figs. 4.1–4.4](#)).

An alternative way to draw the tibial joint line angle has been described using anatomical features that are readily accessible. A line drawn between the center of the ankle and the center of the tibial spine provides the tibial anatomic axis, whereas a line drawn parallel to the medial and lateral tibial plateaus after visually compensating for bone loss represents the native joint line. The angle subtended by these two lines, the joint line angle, should correspond to the position of the tibial cutting block of the tibial extramedullary alignment jig when the latter is centered over the ankle but moved medially the selected number of degrees.

Lateral radiographs can be used to assess femoral flexion, femoral offset, and posterior tibial slope, which will also assist in verifying intraoperative measurements. Patellofemoral radiographs can aid in assessing patellar bone loss and patellar maltracking. These findings can assist femoral placement intraoperatively.

With regards to advanced imaging such as computed tomography (CT) or magnetic resonance imaging (MRI), there is no present clinical benefit for their utilization in the KA TKA. CT scans can provide the surgeon with better information on femoral rotation and trochlear anatomy. CT can also more accurately measure tibial rotation. MRI can give more detailed information on cartilage thickness than CT scans. These measurements have not been necessary with the calipered KA technique but may provide research tools, assist with validation of the KA technique, and assist with future implant design. There are computer- and robot-assisted techniques that do require additional imaging modalities such as CT that will be described in later chapters.



Figure 4.3 A patient with bilateral knee arthritis, but with valgus alignment on the left knee and neutral alignment on the right, is demonstrated.



Figure 4.4 The femoral valgus angle and tibial angle in the coronal plane are demonstrated.

Patient Counseling

Giving informed consent for a knee replacement requires a detailed explanation of the procedure. Choosing what surgical details to include and exclude is entirely surgeon dependent. Given the broad range of techniques available for total knee replacement, some description of the surgeon's chosen method should be included.

Initially asking the patient about—initially asking a patient about their deformity starts the explanation of restoring the prearthritic alignment with the KA technique. Using knee radiographs and models of the knee and arthroplasty components is also helpful when explaining the technique to the patient. The basic premise should be that the patient had a knee alignment before developing arthritis that may have changed with the advancement of disease. The calipered KA techniques uses intraoperative measurements of the femoral bone resections to restore the patient's pre-arthritic distal and posterior femoral joint lines. As with any procedure, alternative methods should be described so the patient can understand that there are other techniques available.

With regards to patient expectations, numerous studies can guide a patient with what to expect after surgery. These studies

can be found in [Chapters 11, 18, and 19](#). Along with informing the patient on standard precautions about infection, deep vein thrombosis, medical complications, etc., giving patients the most up-to-date information on outcomes and results is imperative. However, no studies longer than 15 years exist with which to counsel patients on long-term longevity.² If a patient has had a previous TKA performed with a mechanical alignment technique, performing a KA TKA for the contralateral can be justified and is preferable.³

Summary

The preoperative evaluation and management of a patient with knee arthritis who elects to undergo KA total knee replacement does not vary greatly from current standards. This chapter offers some additions to the standard history and physical and radiographic evaluations that can aid the surgeon in preoperative planning and assist in the description of the KA technique to the patient. The authors have found patients to be both highly understanding of and receptive to the KA technique.

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Calipered Kinematic Alignment Total Knee Arthroplasty Performed With Specific Manual Instrumentation, Verification Checks, and a Decision Tree

STEPHEN M. HOWELL, MD

CHAPTER OUTLINE

Overview

Tips for Exposing the Knee to Perform Calipered Kinematically Aligned Total Knee Arthroplasty

Caliper Measurements and Verification Checks That Set the Femoral Component Coincident to the Patient's Prearthritic Joint Lines With Minimal Flexion

Caliper Measurements and Verification Checks That Set the Tibial Component Coincident to the Patient's Prearthritic Tibial Joint Line

Follow the Decision Tree to Restore the Native Tibial Compartment Forces, Ligament Lengths, and Laxities That Balance the Calipered Kinematically Aligned Total Knee Arthroplasty

Management of the Severe Fixed Valgus Deformity and Flexion Instability Caused by Incompetent Posterior Cruciate Ligament From Resection or Injury

Overview

This chapter contains discussion and video links that assist the surgeon in performing calipered kinematically aligned (KA) total knee arthroplasty (TKA) with specific manual instruments, a verification worksheet, and a decision tree. The treatment of 4726 primary TKAs performed from 2009 through 2019 with KA to restore the patient's prearthritic joint lines regardless of knee deformity and without ligament release, by the senior author, provide the background. During this time, 4316 had retention and 410 had an excision or an unintended transection or tibial detachment of the posterior cruciate ligament (PCL). This experience evolved into a highly reproducible surgical technique that works best with the retention of the PCL. The first section discusses tips for exposing the knee. The second section describes the use of caliper measurements and verification checks that set the femoral component coincident to the patient's prearthritic or native distal and posterior femoral joint lines with minimal flexion of the femoral component. The third section describes the use of caliper measurements and verification checks that set the tibial component coincident to the prearthritic tibial joint line. The fourth introduces a decision tree that, when followed, restores the native tibial compartment forces, laxities (except anterior laxity), and

tibiofemoral and patellofemoral kinematics, thereby balancing the calipered KA TKA. The fifth section discusses the management of the severe fixed valgus deformity and the knee with flexion laxity from injury to the PCL. The educational objective is to encourage those surgeons that use manual, patient-specific navigation and robotic instrumentation to retain the PCL, not release the collateral ligaments, measure bone resections with a caliper, perform verification checks, and follow a decision tree to align and balance the calipered KA TKA reproducibly.

Tips for Exposing the Knee to Perform Calipered Kinematically Aligned Total Knee Arthroplasty

The following tips for the surgical exposure of the osteoarthritic knee might be of help when performing calipered KA TKA. The authors favor either a midvastus or a traditional medial parapatellar arthrotomy. With the knee in 90 degrees of flexion, make the incision long enough to clearly view 3 cm of femur proximal to the trochlea and 4 to 5 cm of the proximal tibia. The fat pad can either be excised or retained. The medial tibia is subperiosteally exposed deep to the superficial medial collateral ligament to view the posteromedial corner. A clear view of the posteromedial tibia is useful for setting the slope of the tibia resection to match that of the patient's prearthritic slope when a cruciate ligament-retaining (CR) implant design is used. The iliotibial band and popliteus tendons are protected and retained. To preserve the posterior cruciate ligament (PCL) during exposure, place a single-prong Hohmann retractor lateral to the PCL. The straddling of the PCL with a two-prong retractor should be done carefully, as pushing the retractor distally can peel the PCL off the insertion on the posterior tibia. Remove all marginal, notch, and posterior osteophytes to restore the prearthritic resting length of the ligaments and full motion arc of the knee. Resurfacing the patella is preferred, as is the use of an anatomic-shaped patella implant. Because KA restores the patient's prearthritic Q-angle and does not set the femoral component distal to the prearthritic joint line, the patella tracks well without a lateral release, with the exception of the few patients with a chronically dislocated patella. The workflow of KA is "femur first" followed by the tibial resection. The TKA is balanced by fine-tuning the varus-valgus (V-V), slope, and depth of the tibial resections, which restores the native tibial compartment forces without ligament release.^{1,2}

Caliper Measurements and Verification Checks That Set the Femoral Component Coincident to the Patient's Prearthritic Joint Lines With Minimal Flexion

Video 5.1 shows the use of intraoperative and verification checks that restore the native distal and posterior femoral joint lines.

Manual, patient-specific navigation and robotic instrumentation use the same KA femoral targets, which are to restore the patient's prearthritic or native distal (0 degrees) and posterior (90 degrees) femoral joint lines and to limit flexion of the femoral component to less than 5 degrees from the sagittal anatomic axis of the distal femur.³⁻⁶ Knowledge of the thicknesses of the distal and posterior condyles of the femoral component, patterns of cartilage wear, and the width of the saw blade are required.⁷ The surgeon can obtain the thicknesses of the distal and posterior femoral condyles from the implant manufacturer and should verify the thicknesses intraoperatively by measuring them with a caliper. Be aware that some brands increase the thickness of the condyles in the largest size and in the PCL-stabilized designs. Adjust 2 mm for full-thickness cartilage wear and 1 mm for the kerf from the saw blade. The caliper measurement of each of the femoral bone resections should equal that of the condyle of the femoral component after compensation for cartilage wear and kerf. In the osteoarthritic knee, bone wear is rare on the femur at 0 degrees and 90 degrees.⁷

Perform the following steps with manual instruments to kinematically align and set the proximal-distal (P-D) and V-V rotation of the femoral component coincident with the prearthritic distal femoral joint line. With the exposed knee in 90 degrees of flexion, determine the locations of cartilage wear on the distal femur. Measure the anterior offset (i.e., displacement) of the anterior tibia from the distal medial femur with a caliper. Subtract 2 mm when the cartilage is missing on the medial femoral condyle. Record the measurement on the verification sheet. Remove the medial and lateral femoral osteophytes and those that fill the intercondylar notch. Remove partially worn cartilage down to subchondral bone with a ring curette. Start the drill hole for insertion of the 10-cm long positioning rod into the femoral metaphysis midway between the apex of the intercondylar notch and the anterior cortex (Fig. 5.1). Leave a 5- to 10-mm bone bridge between the posterior edge of the hole and the top of the femoral notch to reduce the risks of flexing the femoral component and patellofemoral instability.^{4,5} In the axial plane, orient the drill perpendicular to the distal femoral joint line. In the sagittal plane, orient the drill parallel to the anterior and posterior femoral cortex. Insert the positioning rod 8 to 10 cm into the distal femur. Select the distal referencing cutting guide with a 2-mm offset to compensate for complete cartilage wear on either the distal medial or lateral femoral condyle in the knee with varus or valgus osteoarthritis, respectively. Insert the distal referencing guide assembly over the positioning rod and insert distal pins so the guide sits flush against the distal femur. Insert anterior pins in the guide. After making the distal resections, use the caliper to measure the thicknesses. Each resection should equal the thickness of the femoral component after adding 1 mm thickness for the kerf of the saw blade and 2 mm for worn cartilage when present. Record the thicknesses of the distal femoral resections on the verification sheet (Fig. 5.2). When a resection is less than the target thickness or underresected, remove additional bone by either (1) redirect-

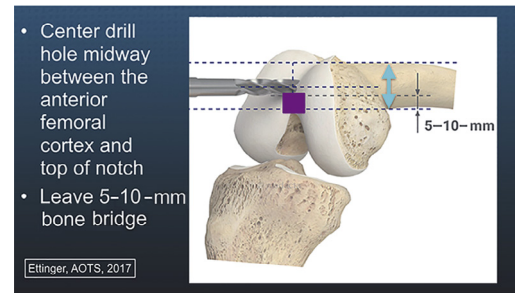


Figure 5.1 The schematic shows the verification check of leaving a 5- to 10-mm bone bridge between the posterior aspect of the starting hole for the positioning rod that sets flexion-extension of the distal femoral guide and the anterior aspect of the intercondylar notch (magenta square). These steps reduce the risks of flexing the femoral component and patellofemoral instability. (From Ettinger M, Calliess T, Howell SM. Does a positioning rod or a patient-specific guide result in more natural femoral flexion in the concept of kinematically aligned total knee arthroplasty? *Arch Orthop Trauma Surg.* 2017;137(1):105–110; 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):283–291.)

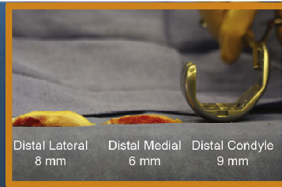
ing the saw blade through the cutting block without flexing the guide, (2) using a 1- to 2-mm recut guide, or (3) free-handing the cut until the resection is within ± 0.5 mm of the target. When a resection is 1 or 2 mm greater than the target thickness or overresected, place a 1- or 2-mm washer over the stabilizing pin of the 4-in-1 cutting block. The washer displaces the 4-in-1 cutting block distally, which creates a shallow anterior and posterior chamfer cut that maintains a gap between the overresected distal femoral resection and the femoral component that is filled with cement.

When a manual distal femoral cutting guide designed specifically for KA is not available, consider two options. One is to make 2-mm thick $\times$ 10-mm $\times$ 5-mm pieces of metal as a spacer to compensate for worn cartilage that is inserted between the subchondral bone and the distal femoral resection guide. The other is to remove all cartilage from the distal femur and adjust the angles of the insertion of the intramedullary rod and the distal referencing guide until the distal femoral cutting block sits flush against the distal femur.

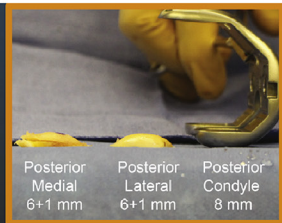
Perform the following steps with manual instruments to kinematically align the anteroposterior (A-P) position and internal-external (I-E) rotation of the femoral component coincident with the patient's prearthritic posterior femoral joint line. Insert the tip of a knife and check the thickness of the cartilage of the posterior condyles. When the cartilage is intact, use a posterior referencing guide set at 0 degrees of rotation. When the cartilage is worn, insert a 2-mm shim between the foot of the referencing guide and the posterior condyle. Many sets have around a 1.5-mm thick angel wing with markings that can be used as a shim and to measure the width of the distal femur to help select the size of the femoral component. Knees with varus osteoarthritis rarely need the posterior shim unless chronically ACL deficient, whereas 40% of knees with valgus osteoarthritis require the shim to compensate for posterolateral cartilage wear. Be aware that the lateral femoral condyle is not hypoplastic in those knees with valgus osteoarthritis, so the restoration of the prearthritic joint line does not require an adjustment on the lateral femoral condyle.⁸ Measure the width of the femur with the angel wing and use the manufacturer's sizing guide to choose the correct size posterior referencing 4-in-1

Intraoperatively fill out verification worksheet

Compare thickness of distal femoral resections to femoral component, Distal lateral, etc.



Compare thickness of posterior femoral resections to femoral component



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

PATIENT: [] NAME: [] SEX: [] HGT: [] WGT: []
 SURGEON: [] ANESTHESIA: [] DATE: [] TIME: []
 KNEE: [] RIGHT [] LEFT []
 SURGERY: [] UNILATERAL [] BILATERAL []
 A/P OFFSET: [] EXPOSURE: [] TUNING: [] DIFFERENCE: []
 ACL CONDITION: [] INTACT [] TORN [] GRAFT []

DISTAL FEMORAL RESECTION
 Target Thickness: 8mm Unworn, 6mm Worn (No Cartilage)
 When initial thicknesses meet target, record in row below

MEDIAL CONDYLE		LATERAL CONDYLE	
UNWORN	WORN	UNWORN	WORN
INITIAL THICKNESS	6 mm	INITIAL THICKNESS	8 mm
RESECT	6 mm	RESECT	8 mm
WARRANTY	6 mm	WARRANTY	8 mm
FINAL THICKNESS	6 mm	FINAL THICKNESS	8 mm

POSTERIOR FEMORAL RESECTION
 Target Thickness: 7mm Unworn, 6mm Worn (No Cartilage)
 When initial thicknesses meet target, record

MEDIAL CONDYLE		LATERAL CONDYLE	
UNWORN	WORN	UNWORN	WORN
INITIAL THICKNESS	6 mm	INITIAL THICKNESS	6 mm
RESECT	6 mm	RESECT	6 mm
WARRANTY	6 mm	WARRANTY	6 mm
FINAL THICKNESS	6 mm	FINAL THICKNESS	6 mm

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

MEDIAL		LATERAL	
UNWORN	WORN	UNWORN	WORN
INITIAL THICKNESS	6 mm	INITIAL THICKNESS	6 mm
RESECT	6 mm	RESECT	6 mm
WARRANTY	6 mm	WARRANTY	6 mm
FINAL THICKNESS	6 mm	FINAL THICKNESS	6 mm

PCL CONDITION
 [] INTACT [] TORN [] GRAFT []
 TIBIAL V-TWIST: []
 TIBIAL SLOPE: []
 TIBIAL SLOPE RESECT: []
 FINAL CONDYLE WITH SPACER BLOCK AND TIBIAL COMPONENTS
 NEGLIGIBLE V-P LAXITY IN EXTENSION
 2-3 mm of LATERAL TIBIAL SPINE GAPS LEAD TO TIBIAL FLEXION

RESECT SIZE: [] TIBIAL SIZE: [] INSERT THICKNESS: [] INTILLA SIZE: []

Figure 5.2 The composite of images shows the verification worksheet (right) and the recordings of the thicknesses of the distal and posterior femoral bone resections compared with the thicknesses of the condyles of the femoral component (left). The femoral component is kinematically aligned when the femoral resections match the thicknesses of the condyles of the femoral component within ± 0.5 mm after compensating around 1 mm from the loss of bone from the kerf of the saw blade and 2 mm for cartilage loss.

- Femoral component restores prearthritic joint lines

cutting block. Secure the 4-in-1 cutting block. Insert a retractor between the femoral condyle and the popliteus tendon to reduce the risk of injury to the tendon. Make the posterior femoral resections and measure the thicknesses with the caliper. Record them on the verification sheet. When necessary, adjust the thickness of the posterior resection to within ± 0.5 mm of the target. To correct for a 1- to 2-mm underresection, rotate and refix the 4-in-1 cutting block 1 or 2 degrees and fine-tune the posterior resection. When the rotation of the 4-in-1 cutting block is posterior to the initial resection, a gap results between the posterior resection and the femoral component that is filled with cement. At this point, some surgeons prefer to insert the trial femoral component before making the tibial resection and assess knee extension, V-V laxity, and patella tracking. Often the flexion contracture disappears, and when it does not, apply a gentle hyperextension moment and plastically stretch the posterior capsule. The knee should be stable during V-V laxity testing throughout the range of motion, with the exception of those knees with substantial tibial bone wear. Removing any osteophytes, and not releasing any collateral, retinacular, and posterior cruciate ligaments.

These use of caliper measurements and verification checks align the femoral component coincident to the prearthritic distal and posterior femoral joint lines with high reproducibility (i.e., root mean square error of 1.4–1.5 mm or degrees). This level of reproducibility does not require the expense of high-cost imaging modalities such as magnetic resonance imaging (MRI) and computed tomography (CT).⁹ Calipered KA reliably coaligns the flexion-extension (F-E) axis of the femoral component closely to the cylindrical axis.¹⁰ The reproducibility of hitting the KA targets is greater than the use of mechanical alignment (MA) targets such as the transepicondylar axis, anterior-posterior (A-P) axis, femoral mechanical axis, and intramedullary canal, which are nonkinematic and hard to identify.^{9–17}

Caliper Measurements and Verification Checks That Set the Tibial Component Coincident to the Patient's Prearthritic Tibial Joint Line

Video 5.2 shows the use of intraoperative and verification checks that restore the native proximal tibial joint line.

For manual, patient-specific navigation and robotic instrumentation, the tibial targets for kinematic alignment are to restore the V-V plane and posterior slope of the native knee while preserving the PCL. Be aware of factors that risk injury to the PCL, which include an overly thick tibial resection, posterior slope greater than prearthritic slope, the use of too wide a saw blade in small knees, and soft bone. To deliver the tibia anteriorly and preserve the PCL, place a single-prong Hohmann retractor lateral to the PCL. Straddling the PCL with a two-prong retractor should be done carefully, as pushing the retractor distally can peel the PCL off the posterior tibial insertion.

Perform the following steps with manual instruments to KA the orientation and position of the trial tibial baseplate. Draw an A-P line that bisects the tibial spines and another that parallels the major axis of the elliptical-shaped lateral tibial condyle. On the anterior tibia, extend the tibial spine line distal toward the medial border of the tibial tubercle to use later as a secondary target for setting I-E rotation of the tibial component.^{11,18} Apply an extramedullary guide with a proximal tibial resection guide to the ankle. Set the provisional V-V plane for the saw slot of the tibial resection guide parallel to the proximal tibial joint plane, which typically requires a 15-mm translation of the long arm of the tibial resection guide from the center at the ankle. Set the thickness of the tibial resection by positioning the offset stylus on the unworn tibial condyle at the base of the tibial spine and secure the guide to maintain the adjustment. Check that the offset of the stylus makes a conservative tibial resection with the target of using an insert 1-mm thicker than the thinnest one available. Insert an angel wing

into the medial side of the saw slot and adjust the slope of the tibial resection plane parallel to the patient's prearthritic slope while visually compensating for cartilage and bone wear and secure the guide to maintain the adjustment. Fine-tune the V-V orientation of the proximal tibial resection guide until the resection plane is parallel to the proximal tibia compensating visually for cartilage and bone wear, and secure the guide to maintain the adjustment. Next, internally or externally rotate the proximal tibial resection guide so that it is parallel to the two A-P lines drawn previously on the tibia, and pin the guide. Insert a retractor between the femoral condyle and the popliteus to reduce the risk of injury to the tendon. Perform the tibial resection.

Measure the thickness of the medial and lateral tibial resections at the base of the tibial spine with a caliper and record them on the verification sheet (Fig. 5.2). Visually inspect the medial tibial resection and determine whether the slope matches the patient's prearthritic slope. When necessary, fine-tune the V-V plane and slope of the tibial resection. Remove residual osteophytes from the tibial margin, the posterior femur, the femoral condyles, and the intercondylar notch.

The use of caliper measurements and verification checks set the tibial component to the prearthritic V-V plane and posterior tibial slope with high reproducibility. These steps restore the native left to right symmetry of the proximal medial tibial angle within 3 degrees in nearly all patients with a normal contralateral limb with a negligible risk of varus alignment of the tibial component with respect to the patient's prearthritic tibial joint line.¹² A study that used three-dimensional shape registration showed that these steps consistently corrected the varus deformity.¹⁹

Follow the Decision Tree to Restore the Native Tibial Compartment Forces, Ligament Lengths, and Laxities That Balance the Calipered Kinematically Aligned Total Knee Arthroplasty

Video 5.3 shows the use of the decision tree to restore native tibial compartment forces, ligament lengths, and laxities.

Filling out the verification worksheet and following the decision tree restore the native tibial compartment forces, ligament lengths, and laxities, with the exception of anterior, unless a medial ball-in-socket insert design is used, and native tibiofemoral and patellofemoral kinematics (Fig. 5.3).^{1,2,20-26} A precondition for consistently fulfilling these balancing objectives is the setting of the femoral and tibial components coincident with the patient's prearthritic joint lines and the retention of the PCL and collateral ligaments without release. MA does not restore native tibial compartment forces because the orientations and positions of the femoral and tibial components change the patient's prearthritic joint lines in most knees.^{27,28}

The first balancing step determines whether to fine-tune the V-V plane of the tibial resection by making the following assessments with a spacer block: (1) place the knee in 90 degrees of flexion, (2) insert the tightest-fitting spacer block into the flexion gap, and (3) rotate the handle of the spacer block internally and externally. The verification check is a pivot point located in the medial half of the spacer block, which indicates restoration of a trapezoidal flexion space that is more lax laterally than medially in flexion, like the native knee.^{25,29} When the pivot is central or lateral, suspect an excessive varus resection of the tibia and that a valgus recut might be needed.

The second balancing step determines how much to fine-tune the V-V plane of the tibial resection. Place the knee in extension and insert the spacer block with sufficient thickness to tighten at least the medial or lateral gap. Apply a V-V moment to the tibia and visually look for any distraction between the medial and lateral distal femoral resection and the spacer block, and between the spacer block and the medial and lateral tibial resection. Negligible V-V laxity indicates the restoration of the patient's prearthritic rectangular extension space.^{25,29} When one compartment gaps, follow the corrective measures listed in the decision tree. Choose a 2-degree varus guide and recut the proximal tibia when the lateral side gaps 3 to 4 mm. Choose a 2-degree valgus guide and recut the proximal tibia when the medial side gaps 3 to 4 mm. When a 1- to 2-mm correction is required, place an angel wing between the recut guide and tibia.

The third balancing step determines the settings of I-E orientation and medial-lateral (M-L) and A-P positions of the trial tibial baseplate. When using an anatomic-shaped tibial baseplate designed for use with KA, select the one that maximizes coverage and then best-fit the baseplate parallel to and within the cortical edge of the proximal tibial resection. This method achieves a mean deviation of 2 degrees external $\pm$ 5 degrees from the F-E plane of the prearthritic knee and a mean coverage of the proximal tibia of 87% $\pm$ 6%.³⁰ When using an asymmetric- or anatomic-shaped tibial baseplate not designed for use with KA, set the I-E rotation with a kinematic template. This method achieves a mean deviation of the anatomic baseplate from the F-E plane of 0 $\pm$ 5 degrees.³¹ When a kinematic template is not available, set the I-E rotation parallel to the mark made along the anterior tibia before resection, which should be close to the medial border of the tibial tubercle. Because the orientation of the F-E plane is not related to the M-L position of the tibial tubercle, KA does not use the MA target of a point on the tibial tubercle as the primary target.^{32,33} The accuracy of this method has not been reported. When using an anatomic-shaped tibial baseplate designed to locate the medial one-third of the tibial tubercle, set the rotation of the baseplate internal to its best fit. Be aware that internal rotation of the tibial baseplate uncovers the posterolateral tibia, which increases the risk of posterior rim wear of the insert.²²

The fourth balancing step determines the optimal insert thickness and when to fine-tune the slope by making the following assessments with trial components: (1) place the knee in 90 degrees of flexion, (2) verify the PCL is intact, (3) insert the tibial insert that matches the thickness of the spacer block, (4) place the knee in maximum extension, and (5) verify that the knee hyperextends a few degrees, like the native knee. When there is a preoperative flexion contracture, gently manipulate the knee to regain extension. When the knee still has a flexion contracture, insert a thinner insert, (6) verify that the V-V laxity is negligible in full extension and that the lateral compartment gaps 2 to 3 mm with the knee in 15 to 30 degrees of flexion. When necessary, fine-tune the V-V plane of the tibial resection, which restores the laxities of the native knee.^{24,25} (7) Place the knee in 90 degrees of flexion. Determine whether passive I-E rotation of the tibia approximates $\pm$ 15 degrees, (8) measure the anterior offset (i.e., displacement) of the anterior tibia from the distal medial femur with a caliper and determine whether it matches the measurement recorded at exposure, and (9) verify that there are $\pm$ 15 degrees of I-E rotation and that the correct A-P offset restores the native tibial compartment forces and laxities of the flexion space.^{1,23,25,29} When the anterior offset is too much, and

Decision tree for balancing a calipered kinematically aligned 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 1–2-mm more bone.	Increase posterior slope until exposure A-P offset is restored at 90 degrees 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 a Cruciate Stabilized insert	Remove medial osteophytes. Reassess. Recut tibia in 1–2 degrees more varus. Insert 1 mm thicker insert.	Remove lateral osteophytes. Reassess. Recut tibia in 1–2 degrees more valgus. Insert 1 mm thicker insert.

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 1–2-mm more bone.	Confirm complete resection of the PCL. Increase posterior slope until natural A-P offset is restored at 90 degrees 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 degrees more varus. Insert 1 mm thicker insert.	Remove lateral osteophytes. Reassess. Recut tibia in 1–2 degrees more valgus. Insert 1 mm thicker insert.

Figure 5.3 Six-step decision trees are shown for balancing a calipered kinematically aligned total knee arthroplasty with use of cruciate ligament retaining (CR) (top) and substituting (CS) insert (bottom). Fine-tuning the V-V plane and posterior slope of the plane of the tibial resection and adjusting the insert thickness restores the native tibial compartment forces, ligament lengths, and laxities, except anterior of the rectangular extension and trapezoidal flexion spaces, and the native tibial compartment forces without ligament releases.^{1,19,23,24} A-P, Anterior-posterior; PCL, posterior cruciate ligament; TKA, total knee arthroplasty. (From 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(5):1200–1207; 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; 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):1589–1601; Roth JD, Howell SM, Hull ML. Analysis of differences in laxities and neutral positions from native after kinematically aligned TKA using cruciate retaining implants. *J Orthop Res.* 2019;37(2):358–369.)

the I-E rotation is too little, increase the posterior slope of the tibial resection in 2-degree increments using either a recut guide or the extramedullary guide. When the anterior offset (i.e., displacement) of the anterior tibia is too small, and the I-E rotation is too much, try a thicker insert and determine whether the knee still fully extends. When the knee does not fully extend, decrease the posterior slope of the tibial resection in 2-degree increments with the use of either a recut guide or by applying a bone graft to the posterior third of the tibial resection. These verification checks for balancing the knee lose effectiveness when the PCL is incompetent from resection or injury.

Management of the Severe Fixed Valgus Deformity and Flexion Instability Caused by Incompetent Posterior Cruciate Ligament From Resection or Injury

Video 5.4 shows management of severe valgus deformity and flexion space instability.

The same surgical steps, verification checks, and decision tree are used for treatment of the osteoarthritic knee with a varus, valgus, and patellofemoral deformity. One caveat is the management of a fixed posterolateral capsular contraction in those patients with a severe valgus deformity (Fig. 5.4). A persistent flexion and posterolateral capsular contraction can limit knee extension and confound the assessment of the V-V plane of the tibial resection with the spacer block. When there is a posterolateral capsular contracture, the lateral compartment is assessed as being overtight, which would suggest that the tibia should be cut in more valgus. Before doing so, recheck the resection thicknesses of the medial and lateral tibial compartments. When they are the same, insert the trial components. Gently manipulate the knee into hyperextension, which often plastically deforms the posterolateral capsule and corrects the fixed valgus deformity.

Management options and video case examples of flexion instability caused by an incompetent PCL from resection or injury are provided in Chapter 19. Briefly, the three methods for tightening the flexion space are: (1) decrease the posterior slope by recutting the tibial resection, (2) decrease the posterior slope

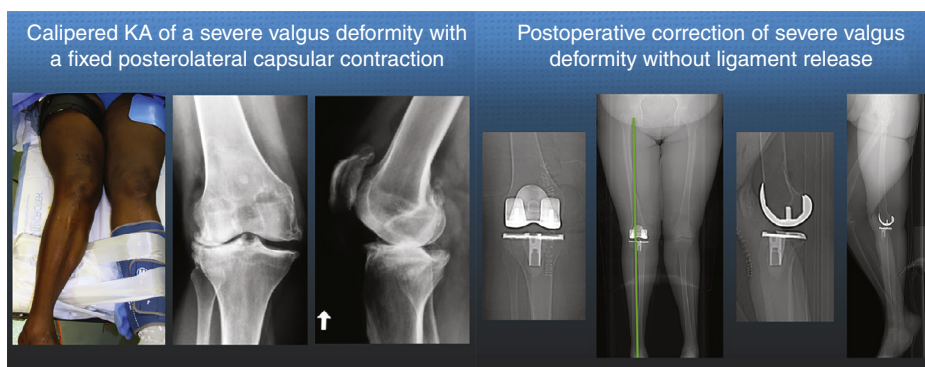


Figure 5.4 Composite shows calipered kinematic alignment management of an osteoarthritic knee with a severe valgus deformity and posterolateral capsular contracture (left three images). The use of verification checks without ligament release restored the native joint lines and knee extension comparable to the contralateral knee and limb (right four images). KA, Kinematic alignment.

by bone grafting the posterior third of the tibial resection, and (3) recut 2 mm from the distal femur and use a 2-mm thicker insert.

Summary

The educational objective of this chapter is to encourage those surgeons that use manual, patient-specific navigation and robotic instrumentation to retain the PCL, not release the collateral ligaments, measure bone resections with a caliper, perform verification checks, and follow the decision trees to align and balance the calipered KA TKA reproducibly. The use of caliper measurements and verification checks (1) sets the femoral component coincident to the patient's prearthritic

or native joint lines with minimal flexion, and (2) sets the tibial component coincident to the prearthritic tibial joint line. Following the decision tree restores the native tibial compartment forces, ligament lengths, and laxities, with the exception of anterior laxity, unless a medial ball-in-socket insert design is used, and native tibiofemoral and patellofemoral kinematics, which balances the calipered KA TKA. Plastically deforming the posterolateral capsular contracture by manually manipulating the knee into hyperextension corrects severe fixed valgus deformities without ligament release. Reduction of the native posterior slope and use of constrained implants manage flexion space laxity when the PCL is torn, excised, transected, or detached from the tibia.

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Calipered Kinematic Alignment Using Patient-Specific Instrumentation

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CHAPTER OUTLINE

Overview

History of Patient-Specific Instrumentation

Design Rationale of Modern Patient-Specific Instrumentation Systems

Patient-Specific Instrumentation in the Kinematic Total Knee Arthroplasty: Surgical Technique

Preoperative Planning

Femoral Resections With Caliper Verification

Tibial Resections With Caliper Verification

Evaluation of Flexion and Extension Gaps With Cross-Reference of Measured Resections

Final Preparation and Cementing of Implants

Results of Modern Patient-Specific Instrumentation

Conclusion

Overview

This chapter reviews the history of patient-specific instrumentation (PSI) and then outlines the design rationale, surgical techniques, and results seen in kinematically aligned (KA) total knee arthroplasty (TKA). The goals of KA TKA are to (1) restore the native femoral and tibial articular surfaces, (2) restore the native knee and limb alignment, and (3) reestablish the native tibial compartment forces and laxities of the knee.¹⁻⁷ Achieving KA with PSI is made possible using techniques and technologies developed over the past decade. Using an accurate and reliable PSI system, coupled with secondary caliper checks, enables successful kinematic balancing in every patient. PSI offers advantages in surgical precision, potentially improved operative time, and advanced preoperative planning. It also obviates the need for additional pinholes or intraoperative registration otherwise seen in navigated knee replacements.

History of Patient-Specific Instrumentation

PSI for TKA has been available for over 10 years with often mixed results.⁸⁻¹² Many early versions of this technology relied on magnetic resonance imaging (MRI) modeling of the distal femur and proximal tibia. This yielded an inexact delineation between subchondral bone and cartilage.⁹ It also led to intraoperative uncertainty on the part of the surgeon during its application, because of a less reproducible positioning of the guide on cartilage. Furthermore, most early systems did not come with

three-dimensional (3D) models of the distal femur and proximal tibia, etchings on the models, or the ability to attach extra-medullary alignment rods to verify registration of the guide to the articular surface. In one instance, a manufacturer uses axial imaging of the knee in conjunction with standing full-length X-rays to properly align the hip-knee-ankle (HKA) axis. Flexion contractures of the knee and rotation of the limb make this type of system prone to error. Newer designs often use computed tomography (CT) scans for computer modeling, which has yielded greater predictability in its application once remaining cartilage is removed.^{13,14} Studies have shown CT-scan modeling to be dimensionally more accurate than MRI.⁹ Nonetheless, the ultimate goals of any PSI system remain unchanged: allow preoperative planning, enhance surgical workflow, and increase precision and reproducibility.

Design Rationale of Modern Patient-Specific Instrumentation Systems

In designing the ideal PSI system, we must consider limitations of former versions. As many have failed to achieve the goals of accuracy and reliability,¹⁵ there have been numerous reports from authors who discourage the routine use of PSI during TKA.^{16,17} Many of these unfavorable accounts relate to the inaccuracy of the underlying PSI system itself. It should be stressed that not all PSI systems are created equal.¹⁴ Unique limitations exist for each system that may not translate to other manufacturers. These inaccuracies can stem from a number of potential issues. However, based on our extensive experience, we have concluded that several factors can adversely affect the quality of the PSI product.

First, as alluded to previously, MRI-based PSI cutting blocks tend to be less accurate than CT-based ones.⁹ MRI scans are less accurate for determining joint line definition because cartilage margins can only be estimated, leading to potential reconstruction errors, cutting block mismatch, and lack of accuracy. MRI scans are also more expensive, require longer scan times, are more susceptible to patient motion artifact, and are often adversely affected by periarticular hardware. The MRI-based PSI blocks themselves rest on cartilaginous surfaces, which are inherently softer and less precise. Conversely, CT-based cutting blocks facilitate more reproducible positioning and bone resections once cartilage and synovium are surgically removed with Bovie cautery. In addition, large osteophytes and prominent bony landmarks can serve as contact points for accurate CT-based PSI block placement with minimal intersurgeon variability.

Second, the modern design advocated by the lead authors uses 3D-printed bone models. Exact replicas of the distal femur

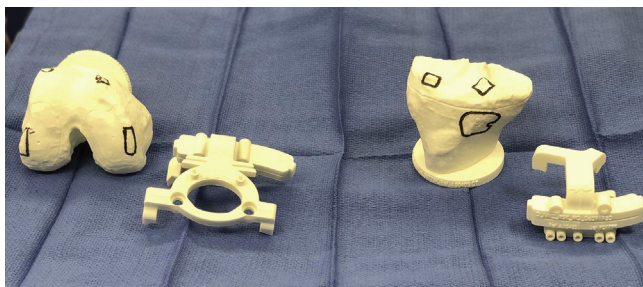


Figure 6.1 Patient-specific three-dimensional bone models of the distal femur and proximal tibia, with their respective cutting blocks.

and proximal tibia are provided sterile to the surgeon for intraoperative use (Fig. 6.1). These yield direct visualization of intended resections, angles, and component positions before making the actual bone cuts. The 3D models with etchings define contact points for cutting blocks. The intended resections can be confirmed visually on the bone and cross-referenced with the model. In addition, alignment slots exist for secondary check of accurate cutting block placement by adding extramedullary alignment rods. Therefore, in addition to the unambiguous registration of these guides to the bone, these resection etchings and alignment slots serve as secondary checks of planned resections, before actually completing the bone cuts.

Patient-Specific Instrumentation in the Kinematic Total Knee Arthroplasty: Surgical Technique

In kinematic balancing of TKA, the first objective is to restore the native prearthritic femoral and tibial articular surfaces.^{2,3} This begins with precise “anatomic resurfacing” of the distal and posterior femur. This restores the native femoral-tibial flexion-extension axis and the patellofemoral flexion extension axis of the knee.^{1,18} The advantage of PSI remains that preoperative planning can accommodate any surgeon preferences, which can be adjusted to address any degree of deformity (Fig. 6.2). In cases performed by the lead authors, plans are made for 7-mm distal femoral and 6-mm posterior bony femoral resections. If we assume 2 mm for average cartilage thickness on the distal and posterior femur, this corresponds to a total cartilage and bone thickness of 9 mm distally and 8 mm posteriorly, which are the exact thicknesses of the femoral implant used by the authors distally and posteriorly, respectively. The amount of bone resection needs to match the thickness of the implants, minus 1 mm adjusting for sawblade kerf. Immediate feedback is provided by cutting and then subsequently measuring resected bone with a caliper following each stepwise cut performed to ensure 100% accuracy before moving on to the next step. This is a CT-based PSI system so the bone resections are exact and the calipered measurements are solely affected by cartilage, if any remaining.

PREOPERATIVE PLANNING

A CT scan is performed according to a specific algorithm (@Medacta International) that acquires 0.5 to 1 mm thick axial images of the knee and 2 mm thick axial images of the hip and ankle using a 512×512 matrix. Other available PSI-based implants are commercially available and readily adaptable to kinematic principles. However, unlike another PSI system on the

market that relies on a full-length CT scan of the lower extremity, this system uses a limited and low-dose CT scan of the knee, hip, and ankle. Images are uploaded through a secure server to a dedicated engineering team in Switzerland who create the PSI plan based on our kinematic knee preferences (Fig. 6.2). The primary goal is to resurface the distal femur, and bone resections are set to match the exact thickness of the femoral implant (9-mm distal femur and 8-mm posterior femur). Therefore, the PSI-CT bone resections are set at 7 mm of bone from the distal femur and 6 mm of bone from the posterior femoral condyle. These cuts assume 2 mm of native cartilage thickness, which will resurface the femur to its native position respecting the three kinematic axes about the femur. Tibial resection depth is set at 6 to 8 mm depending on surgeon preference and patient variables. An 8-mm resection of bone results in a total resection of approximately 10 mm (assuming 2 mm of cartilage thickness) which exactly replicates the thickness of the tibial implant with the thinnest 10-mm polyethylene insert. A more conservative 6-mm cut on the tibia may be preferred to allow for the possibility of a recut if necessary, to balance the knee. The ultimate goal on the tibial resection is to evenly resect the medial and lateral tibial plateaus to resurface the tibia, while preserving host bone and ending up as close as possible to a 10-mm polyethylene. In the section later we cover the critical evaluation of resections and balancing of the flexion and extension gaps. Once the femur is anatomically resurfaced, the corrections needed to balance the knee are performed with tibial recutting guides. In our experience, resecting 2 mm less on the planned tibial resection is appropriate for (1) surgeons new to this technique; (2) severe deformity; (3) significant valgus deformity; and (4) significant bone loss (may reduce by 4 mm in select cases of significant tibial bone loss). Fortunately, each case is critically evaluated by a dedicated PSI engineering team. If anything unusual is identified by the engineer, the surgeon is alerted and can adjust the plan based on abnormal anatomy, retained hardware, or bone loss, before creating the final PSI cutting guides. Final approval of the operative plan is done by the surgeon on a 3D preoperative planner and the cutting blocks and bone models are then printed on a 3D printer and shipped (Fig. 6.1). Typical time from CT scan to delivery to the operating room is 3 weeks.

FEMORAL RESECTIONS WITH CALIPER VERIFICATION

With KA, the anatomical placement of the femoral component is critical to the overall balancing of the knee. It determines the native arc of flexion and extension of the tibia on the femur and the native arc of flexion and extension of the patella on the femur.^{2,19} In conventional KA TKA instruments, variability exists for the distal femoral starting drill hole, through which an intramedullary guide determines sagittal alignment of the femoral component. Instead, PSI guides allow very little variability in this plane of motion and can restore the native sagittal plane in a reproducible fashion.^{9,13}

The knee joint is exposed using the surgeon's approach of choice. We have used standard medial parapatellar, minimedial parapatellar, subvastus, and midvastus approaches with these CT PSI blocks. After adequate femoral exposure, the surgeon will hold up the plastic femoral bone model, paying specific attention to the four etch marks representing the contact points for the femoral PSI guide (Fig. 6.3). Using Bovie in combination with a smoke evacuator and extra suction, we remove all of the

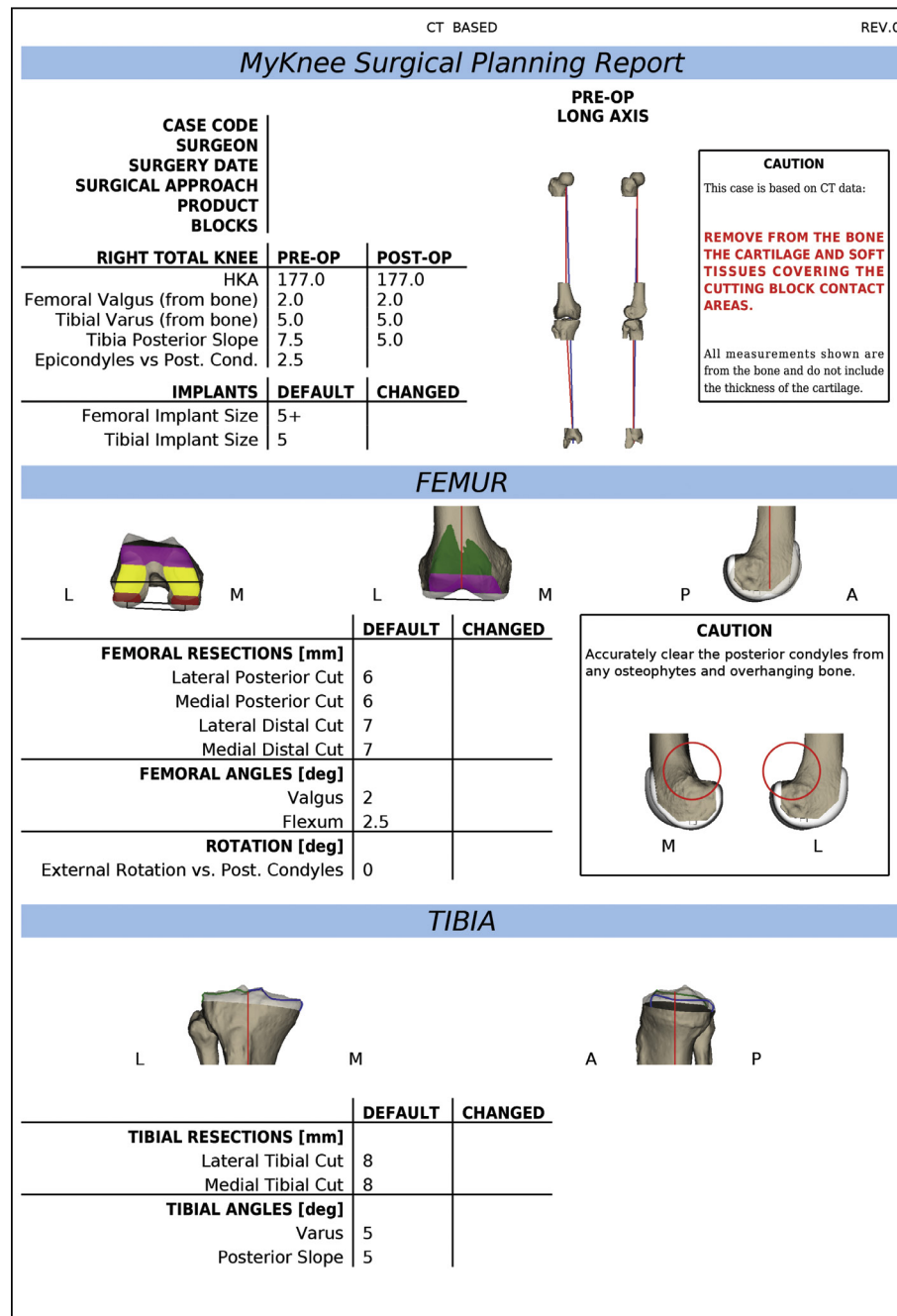


Figure 6.2 Resting knee alignment and planned resections in patient-specific kinematically balanced knee arthroplasty (©Medacta International. All rights reserved.).

soft tissue at these four contact points to expose subchondral bone. The Bovie will remove cartilage, synovium, and any other soft tissue while leaving the underlying subchondral bone footprint. It is imperative that surgeons do not remove bone with a rongeur or curette as these blocks are designed to sit on bone, and often large osteophytes are used as hard contact points. The surgeon should then position the femoral guide on the femoral bone model to see how the guide fits. Registration of the guide to the bone typically involves engaging the anterior footprints and then flexing the guide down such that the distal footprints are contacting bone. The femoral guide is then placed on the distal femur and secured with two parallel and one cross pin at the anterior surface of the femur. Care must be taken to ensure

that all four contact points are flush to bone. If any contact point is not flush to bone, the pins and the guide must be removed and then repositioned.

Anterior reference holes for component rotation are drilled to establish placement of the 4-in-1 guide. The PSI femur guide has a number of built-in secondary references that allow the surgeon to critically evaluate the intended resections before performing the definitive cuts. Fig. 6.4 illustrates the anterior reference slot on the PSI block to ensure proper anterior resection and to avoid anterior notching. Fig. 6.5 illustrates the visual comparison of the intended distal femoral resection and the etched resection on the plastic bone model. Once proper block position and placement are confirmed, the surgeon



Figure 6.3 Femoral bone model (with purple marker highlight showing distal femoral resection) beside exposed femur.

performs the distal femoral resections through the distal cutting slot of the CT PSI femoral guide. Distal resections are identified as medial and lateral with a marker. Resections are then measured by the surgeon and recorded on our worksheet. In our experience, these resections are often exact or within 1 mm of intended thickness and small corrections are easily attainable. The surgeon must assess whether there is complete cartilage loss (2 mm), partial cartilage wear (1 mm), or no cartilage loss in evaluating the thickness of the resections. We are targeting matched resections of the distal femur while accounting for differential cartilage wear patterns. If medial or lateral distal condyle is underresected by 1 mm, we run the saw blade through the plastic PSI distal cutting slot and resect 1 mm of additional bone from the underresected distal condyle. In the case of relative overresection of one condyle, we have 1- and 2-mm washers

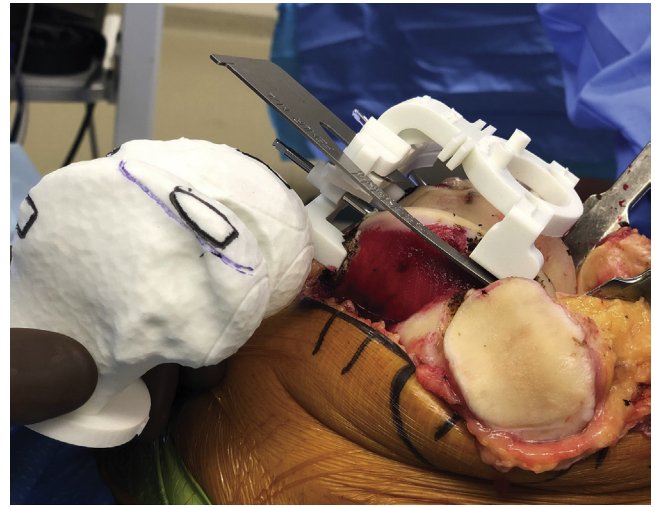


Figure 6.5 Pinned femoral guide showing planned distal femoral resection, held next to bone model for comparison.

that can be placed on the affected distal condyle before chamfer cuts to ensure proper resurfacing of the distal femur. For example, if one condyle is overresected by 1 mm, we place a 1-mm washer on this side of the 4-in-1 cutting guide to appropriately resurface the distal femur (Fig. 6.6). This results in the chamfer cuts being 1-mm proud and, once cemented, a 1-mm thicker cement mantle on the overresected distal femur surface and appropriate contact with remaining distal femur cuts. Again, our goal is to resurface the femur, preserve the three native kinematic axes around the knee, and avoid changing the joint line.

After calipered verification of distal femur resections are complete, the 4-in-1 block is placed over the anterior pinholes and secured to bone. Posterior femoral condyle resections are performed first and then carefully measured by the surgeon, again accounting for any potential cartilage loss. In our

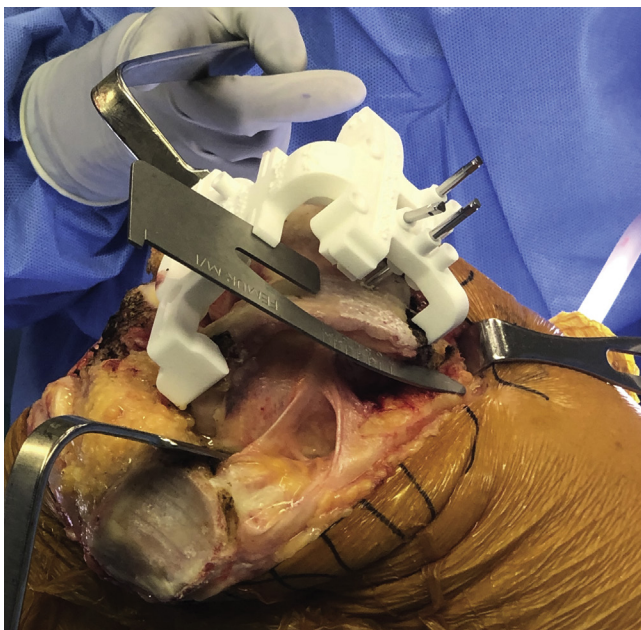


Figure 6.4 Pinned femoral guide showing anterior notch slot with angel wing.

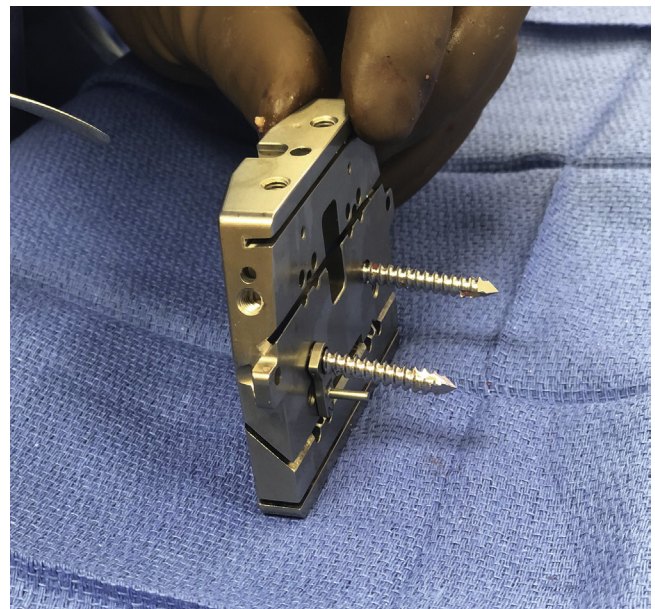


Figure 6.6 Operating room photo of 1-mm washer placed under one condyle of 4-in-1 cutting block.

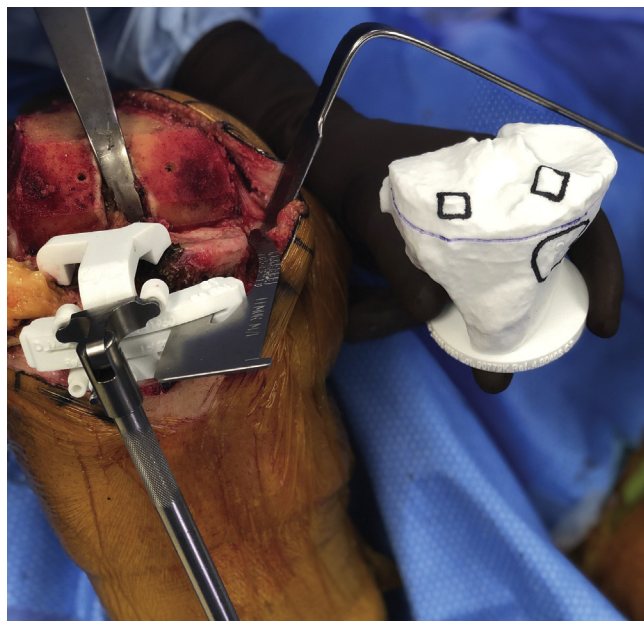


Figure 6.7 Tibial bone model with purple marker highlight contact points, relative to native tibia.

experience, these cuts are often equal in measurement with very little native cartilage loss from the posterior condyles. Be aware that there may be cartilage loss posteriorly on the lateral condyle of the severe valgus knee. Rarely, we will adjust our 4-in-1 block position to equalize these posterior resections before finishing our femoral resections. The guide can be translated anteriorly or posteriorly and can also be internally and externally rotated. The remaining cuts are then completed through the 4-in-1 block.

TIBIAL RESECTIONS WITH CALIPER VERIFICATION

The proximal tibial resection is made using similar principles. If no bony wear is noted, an even resurfacing cut is made on the tibia to restore prearthritic native alignment. Kinematic balancing can be achieved by accounting for constitutional varus or valgus alignment into the preoperative plan. We most commonly set the proximal tibial bone resection at 8 mm. Native tibial slope can be preserved at the discretion of the surgeon and the type of bearing surface being used.

Once the tibia is exposed, the surgeon will again reference the PSI tibial bone model that shows the three contact points for the tibial cutting guide. [Fig. 6.7](#) shows the contact points highlighted with a marker for easier reference and then in a similar fashion to the femoral preparation; the Bovie is used to remove all cartilage and soft tissue from the tibial contact points down to exposed subchondral bone. Tibial guide registration to the tibia is prone to relative flexion and extension, and so care must be taken to ensure that all contact points are flush to bone. The tibial guide is placed firmly on bone and pinned with two parallel pins and one cross-locking pin. Secondary checks are then performed including placing the angel wing through the cutting slot of the guide and comparing the intended tibial resection to the etching on the model. Resection depth, varus-valgus angle, and posterior slope can be confirmed. The surgeon can also attach the drop rod to the PSI block to confirm proper guide placement, as in [Fig. 6.8](#). The



Figure 6.8 Pinned tibial block with drop rod and angel wing while holding bone model.

drop rod is engineered to align with the center of the ankle on the planned kinematic tibial resection. After cutting the tibia, we use a C-shaped caliper ([Fig. 6.9A](#)) to measure the thickness of the bone resection corresponding to the central etched dot on the PSI bone model. Cartilage in this location should be removed to ensure an accurate bone measurement. At this stage, we record the thickness of the resection, evaluate the residual cartilage thickness and then record this data on our worksheet ([Fig. 6.9B](#)). We do not adjust the tibial cut based

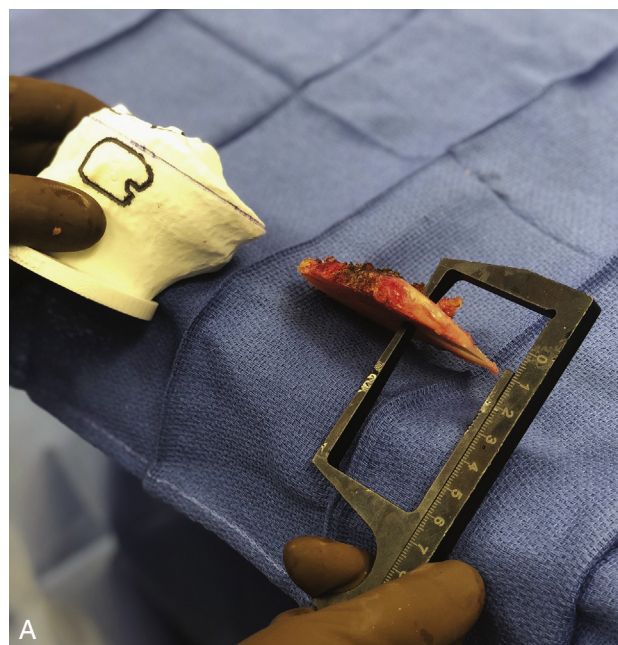
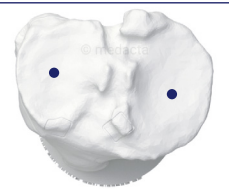


Figure 6.9 (A) C-caliper measuring tibial resection in comparison to tibial bone model. (B) Caliper verification worksheet (©Medacta International. All rights reserved.). (continued)

RECORD OF VERIFICATION CHECKS FOR KINEMATICALLY ALIGNED GMK SPHERE TKA

CASE CODE 	CAUTION The planned resections include the sawblade thickness and do not include the cartilage thickness. Always measure from the landmarks used for planning (etched on the bone models for reference).								
A/P OFFSET EXPOSURE _____ mm TRIALING _____ mm DIFFERENCE _____ mm	ACL CONDITION ☐ INTACT ☐ TORN ☐ GRAFT								
DISTAL FEMORAL RESECTION MyKnee KA plan = 7mm Target caliper value: Worn side = 6mm / Unworn side = 8mm									
MEDIAL CONDYLE ☐ UNWORN ☐ WORN CALIPER VALUE _____ mm RECUT ☐ N ☐ Y _____ mm FINAL VALUE _____ mm	LATERAL CONDYLE ☐ UNWORN ☐ WORN CALIPER VALUE _____ mm RECUT ☐ N ☐ Y _____ mm FINAL VALUE _____ mm								
									
POSTERIOR FEMORAL RESECTION MyKnee KA plan = 6mm Target caliper value: Worn side = 5mm / Unworn side = 7mm									
MEDIAL CONDYLE ☐ UNWORN ☐ WORN CALIPER VALUE _____ mm RECUT ☐ N ☐ Y _____ mm FINAL VALUE _____ mm	LATERAL CONDYLE ☐ UNWORN ☐ WORN CALIPER VALUE _____ mm RECUT ☐ N ☐ Y _____ mm FINAL VALUE _____ mm								
									
TIBIAL RESECTION MyKnee KA plan = 8mm Target caliper value: Worn side = 7mm / Unworn side = 9mm									
MEDIAL PLATEAU ☐ UNWORN ☐ WORN CALIPER VALUE _____ mm	LATERAL PLATEAU ☐ UNWORN ☐ WORN CALIPER VALUE _____ mm								
									
CUT ADJUSTMENT ☐ VAR/VAL _____ deg ☐ SLOPE _____ deg ☐ CUT HEIGHT _____ mm									
PCL CONDITION ☐ INTACT ☐ TORN ☐ EXCISED	FINAL CHECK WITH SPACER BLOCK AND TRIAL COMPONENTS ☐ NEGLIGIBLE V-V LAXITY IN EXTENSION ☐ 2-3 MM OF LATERAL OPENING WITH VARUS LOAD IN 15-30° OF FLEXION								
<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 25%;">FEMUR SIZE</td> <td style="width: 25%;">TIBIA SIZE</td> <td style="width: 25%;">INSERT THICKNESS</td> <td style="width: 25%;">PATELLA SIZE</td> </tr> <tr> <td style="height: 40px;"></td> <td style="height: 40px;"></td> <td style="height: 40px;"></td> <td style="height: 40px;"></td> </tr> </table>		FEMUR SIZE	TIBIA SIZE	INSERT THICKNESS	PATELLA SIZE				
FEMUR SIZE	TIBIA SIZE	INSERT THICKNESS	PATELLA SIZE						

B

Figure 6.9 (Continued)

on the measured resections recorded at this stage, but rather move to evaluating our flexion and extension gaps. We use the values of the medial and lateral tibial plateau resections to predict any potential asymmetry in the gaps. For example, if the femur has been perfectly resurfaced, and the medial tibial plateau resection measures 2-mm thinner than the lateral plateau after accounting for cartilage thickness, then we would expect that the medial side of the knee would be tight in both flexion and extension with our spacer blocks.

Special consideration should be given to the sagittal alignment when planning for cruciate-retaining (CR), posterior-stabilized (PS), ultracongruent (UC), or medial-stabilized (MS) designs. In a CR bearing, native posterior tibial slope can be matched. With a PS or MS design, because the posterior

cruciate ligament is resected, posterior tibial slope should be restricted to 5 degrees to reduce flexion instability. In the MS implant advocated by the lead authors, asymmetric anatomic tibial trays lower the likelihood of malrotation and also gain better plateau coverage on cortical bone. Rotational alignment of the tibial component can be achieved through a number of different means including use of the PSI to set rotation, free-floating the tibial component on the femur through a range of motion and then marking rotation, or using a line through the intercondylar eminences that intersects the medial third of the tibial tuberosity. Overall, PSI guide etchings provide secondary checks for planned cuts when compared with the 3D model. Caliper measurements are used to confirm depths of resection as tertiary confirmation.



Figure 6.10 (A), (B) Flexion and extension gap balance tool (accounts for 1-mm thicker implant distal versus posterior femur).

EVALUATION OF FLEXION AND EXTENSION GAPS WITH CROSS-REFERENCE OF MEASURED RESECTIONS

We use specific flexion and extension spacer blocks that come in 1-mm increments to critically evaluate the ligament tension and balance in full extension, in midflexion, and at 90 degrees of knee flexion. These are double-ended blocks marked FLEX (flexion) and EXT (extension) to account for the 1-mm difference in distal and posterior femoral component thickness of the implant used by the lead authors (Fig. 6.10). Care must be taken to ensure no residual marginal or posterior osteophytes are present before spacer block balancing. In full extension, we are looking for negligible varus-valgus laxity that is balanced equally medial and lateral. In flexion, we are looking for medial stability with valgus stress with 1 to 2 mm of medial opening and laterally we expect physiologic laxity because the native flexion gap is expected to be trapezoidal with more laxity lateral.¹⁹ We also confirm excellent sagittal stability with trial implants after achieving appropriate balance of our flexion and extension gaps. Often, the measured caliper resections on our worksheet will predict whether the knee will be balanced or not and require a tibial recut. For example, if the femoral resections were exactly as planned, and the tibial resections were equal medial and lateral, we can routinely predict the thickness of the balancing blocks required to achieve appropriate balance and ultimately predict the final polyethylene bearing thickness. If the target tibial resection is 8 mm both medially and laterally and we measure 9 mm of bone resection, this will often require 11-mm spacer blocks and a final 11-mm polyethylene spacer for stability. Alternatively, if the medial tibial plateau is relatively underresected by 2 mm relative to the lateral tibial plateau, we expect a tight medial compartment in flexion and extension with our spacer block checks and would then perform a 2-degree medial varus recut on our tibia using our 2-degree preset guide (Fig. 6.11). If the correction is only 1 mm, we place a 1-mm angel wing under the 2-degree varus recut guide medially to create a 1-degree/1-mm varus tibial recut (Fig. 6.12).

FINAL PREPARATION AND CEMENTING OF IMPLANTS

After meticulous resections, caliper measurements and balancing, the trial components are inserted. Sagittal stability, patellar tracking, and balancing is confirmed with trials and final preparation of the femur and tibia, along with patella resurfacing, is completed. Components are then cemented into position.

Results of Modern Patient-Specific Instrumentation

The quality of any PSI system is a function of its inter- and intrauser reliability. Substantial work has been published corroborating the success of modern PSI. In our published retrospective study of 132 patients, average HKA axis was restored to 179.4 degrees, within 1 degree of our intended target.²⁰ In another study of 222 knees,²¹ modern PSI techniques yielded closer restoration of average mechanical axis and lower rate of outliers, in comparison to conventional TKA. Although overall limb axis is less relevant in kinematic balancing, these studies simply highlight PSI's precision in achieving an intended target. Mixed results do exist, however. Cavaignac et al.²² performed a meta-analysis of PSI versus conventional instrumentation and showed no difference in radiological outcomes. However, the authors noted significant deficiencies in methodology, incorporating a heterogeneous mix of studies using both MRI- and CT-based protocols. Furthermore, HKA alignment was only assessed using long-leg standing X-rays. Instead, for more precise assessment of alignment after use of PSI, Nabavi et al.²³ reported 98% accuracy within 3 degrees of HKA using a postop CT-based analysis. Sagittal, coronal, and rotational orientations were predicted more than 90% in each using this modern PSI system.

A prospective randomized study of 200 patients by Callies et al.⁴ compared PSI KA knees with non-PSI mechanically aligned (MA) knees. PSI KA knees showed a greater mean Knee Society Score (KSS) and Western Ontario and McMaster Universities



Figure 6.11 Varus-valgus 2-degree recut guides.

Osteoarthritis Index (WOMAC) score improvements than MA. However, there were some outliers in the KA group with worse outcomes, which statistically correlated with deviations from the PSI plan. Laende et al.⁸ compared KA using PSI versus MA using computer-assisted surgery. There was no difference in longitudinal migration of the tibial component at 2-year follow-up in a cohort of 47 patients. Both groups had mean migrations below

acceptable thresholds. They also showed no correlation between knee alignment or nonneutral tibial component positioning with degree of migration, indicating stable fixation in both groups.

Previous papers showing no clinical difference with use of PSI may be attributable to the concept of precision versus accuracy. PSI, as with other guided systems, has been found to be precise in achieving a specific target and reducing the number

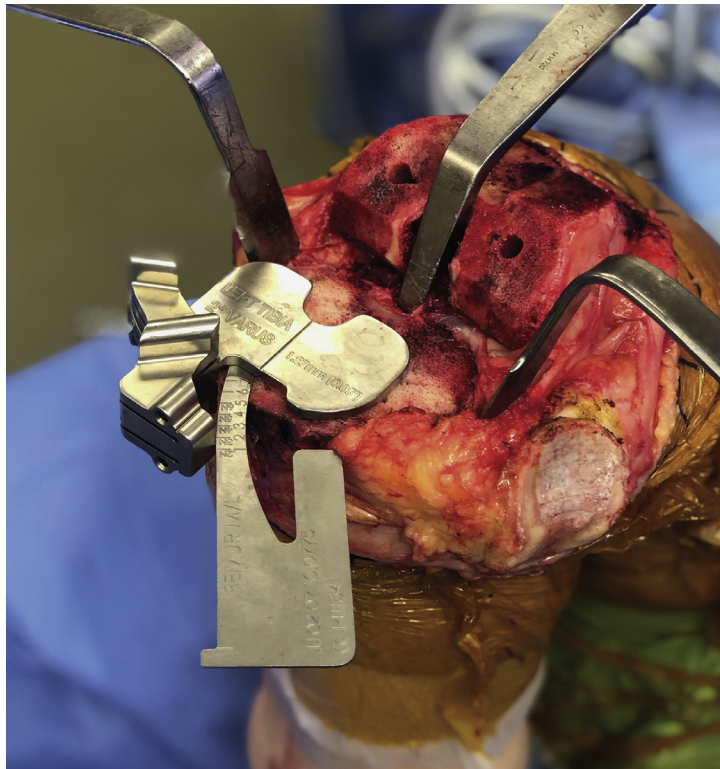


Figure 6.12 Varus recut guide with angel wing under medial aspect of the guide, reducing a 2-degree correction to 1 degree.

of outliers from that target. However, the routine use of MA may be a false target that produces poor outcomes. The transition to KA, in conjunction with the precision afforded by PSI, may yield more accurate reproduction of native anatomy and better clinical results moving forward.

Aside from more precisely achieving a target resection with fewer outliers, PSI has some inherent advantages. The preoperative modeling can account for any small extraarticular deformities. It obviates the need to remove hardware if not directly impinging with the implant or cutting blocks. For example, the PSI design process can predict the trajectory of each pin and saw blade cut and determine whether it will interfere with a femoral nail, plate, or previously positioned anterior cruciate ligament (ACL) screw. It also avoids the need for intramedullary instrumentation, which has been shown to reduce fat embolization and overall blood loss in TKA.^{24,25} If converting a previously failed unicompartment knee arthroplasty (UKA) to TKA, the modern PSI design can help achieve either MA or KA with similar accuracy, in our experience. In addition to predicting alignment and implant sizing better than conventional instruments, PSI allows a smoother transition to a single-use disposable system.²⁶ Because the use of a CT scan allows component sizes to be planned before surgery, overall efficiency can be optimized, especially in the setting of free-standing ambulatory surgery centers (ASCs) with limited sterilization capacity.

Many companies are promoting the use of computer navigation and robots as a modern solution to accurate TKA. In our experience, these computers and robots add significant capital costs, add significant acquisition time in the operating room,

and are more susceptible to user error, compared with modern PSI techniques such as the one described here. When comparing PSI with the variety of robotically assisted or navigated systems available, or even custom implants, the cost of PSI is favorable with some distinct advantages.^{26,27}

PSI does have some limitations. First, it does require a CT scan, which adds extra cost and radiation that would not be needed with conventional techniques. Second, there is generally a 3-week planning period where the guides and 3D bone replicas are manufactured, also with a 6-month expiration. An expiration date is necessary, as these models are limited by possible further arthritic deformation of the knee and change of the patient's bony morphology subsequent to scan completion. Furthermore, PSI does not readily allow for major intraoperative changes to the plan if aberrant anatomy is identified with respect to the cutting blocks.

Conclusion

PSI is a useful technology in TKA with advantages in preoperative planning, surgical precision, and operating room efficiency. Although PSI has had heterogeneous results in past publications, modern CT-based systems can be more accurate than conventional techniques. Its application in KA offers several benefits, mainly allowing preresection verification with immediate feedback for balancing. The results of kinematic PSI are at least as promising as conventional techniques with some distinct advantages, making it a viable option for instrumentation for years to come.

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Calipered Kinematic Alignment With Navigation Instrumentation

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CHAPTER OUTLINE

Introduction

Why Use Navigation?

Literature Review of Navigated Kinematically Aligned Total Knee Arthroplasty

The Soft Tissue Envelope of the Osteoarthritic Knee

Which Navigation System?

Kinematic Alignment Technique Using Navigation Instruments

Preoperative Planning

Registration Including Tibiofemoral Offset

Setting the Target Hip-Knee-Ankle Angle

Defining the Provisional Prosthetic Lateral Distal Femoral Angle and Prosthetic Medial Proximal Tibial Angle—the Subtraction Principle

Setting Femoral Flexion and Tibial Slope

Quantifying Provisional Balance and Adjusting Implant Position to Optimize Balance

Execution of Planned Resections

Trial Reduction and Balance/Recut or Release

Complex Deformity

Isolated Hyperextension

Severe Fixed Flexion Deformity

Introduction

Computer-assisted surgery (CAS) or navigation has for the best part of two decades been the gold standard for accuracy and precision in total knee arthroplasty (TKA) in terms of creating neutral coronal and sagittal limb alignment. Accuracy refers to how close a measurement is to a “true” value, whereas precision refers to how close a series of measurements are to each other. In terms of individual anatomy, neutral alignment of the distal femur, proximal tibia, and limb in the coronal plane generally does not represent a “true” value, as it varies significantly between normal individuals.^{1,2} Similarly, a symmetrical flexion gap does not represent a “true” value for the vast majority of individuals, as flexion gaps are typically asymmetric in the normal state.^{3,4,5} Navigated mechanical axis (MA) TKA therefore, for the vast majority of individuals, is a case of precisely reproducing an anatomically inaccurate target.

Kinematic alignment (KA) differs from MA in this regard, as it aims to target anatomically “true” values (i.e., the precise, prearthritic, normal values in each individual patient). Thus, a precision tool such as navigation has the potential for greater accuracy and precision in terms of reproducing and achieving a target when the target is a “true” and not an artificial target. This is perhaps doubly important when chasing a nonneutral and

variable limb alignment target, as compounded errors in execution stacked on top of a planned restoration of normal anatomy could be problematic, for obvious reasons.

Although the underlying principles of KA using navigation instrumentation are identical to those outlined already in previous chapters, reviewing them through the lens of navigation surgery is useful as a means to understanding how to maximize the potential benefit of this technique. This chapter discusses the rationale for using navigation instrumentation, the applicable literature on the subject, assumptions regarding the soft tissue envelope of the arthritic knee as they apply to navigation principles, navigation system requirements for optimal planning, the routine technique for planning and executing KA TKA using navigation, and techniques for dealing with the most common complex deformities when navigating a KA TKA. KA is an advanced technique, and the chapter is written with the assumption that the reader has an understanding of the generic capabilities of computer-assisted TKA.

Why Use Navigation?

The Australian Orthopaedic Association National Joint Replacement Registry has reported significantly reduced hazard ratios (HRs) for revision for aseptic loosening when navigated TKA is performed, compared with nonnavigated TKA. This applies to both younger and older patient cohorts (<65 years, hazard ratio [HR] 0.63, $P < .01$; > 65 years, HR 0.71, $P < .001$).⁶ Numerous meta-analyses have reported superior accuracy and precision of navigation over other instrumentation platforms,^{7,8,9} and, to a lesser extent, improved patient reported outcomes.^{10,11}

Failure because of aseptic loosening is uncommon in KA. In a cohort of 222 joints, the 10-year survival rate for aseptic loosening as an end point was 98.5%.¹² The single case of aseptic failure reported in this series was because of a large error of tibial positioning in the sagittal plane. In a much larger cohort with a minimum 2-year follow-up, the rate of early tibial failure because of aseptic loosening was 0.3% and was related to excessive tibial slope (11 degrees in the failures vs. 5 degrees on average in controls).¹³ Femoral aseptic loosening has not been reported in a KA cohort, but sagittal plane errors of femoral positioning have been linked to patellofemoral instability (PFI) (11 degrees average component flexion in PFI vs. 5 degrees average in controls).¹⁴

Understandably, much of the focus in the KA versus MA discussion relates to tibial component and limb alignment in the coronal plane, as in KA there are commonly many patients whose coronal alignment would be considered an “outlier” from the MA perspective, but within the normal distribution of human anatomy. To date, no paper has reported increased tibial failure rates or inferior clinical outcomes in KA TKA cohorts attributed to coronal plane alignment variance. The same is not

true of sagittal plane malalignment that has been linked to clinical failure in KA TKA. Fortunately, poor sagittal alignment can not only be consistently avoided with navigation instrumentation but can also be fine-tuned to take what is otherwise a generically shaped and sized femoral component to match the anatomic variance of each knee before any resections.

The aforementioned accuracy and precision of navigation relate to achieving coronal and sagittal plane targets. In the axial plane, the same reliability has not been achieved in terms of femoral component internal-external rotation (IR-ER), tibial component IR-ER,⁷ or rotation of the two components relative to each other. This can be problematic, as the axial rotation of the femur affects the balance and varus-valgus alignment of the limb in all positions of the limb (except full extension) and has maximal effect when the knee is flexed 90 degrees to the distal femoral resection plane.¹⁵ In all instrumentation systems, surface landmarks are used to determine the rotational axis of the femur. These landmarks are variably unreliable in terms of accurate registration,^{16,17} and even if accurate registration can be obtained, the relationship between these landmarks can vary enormously in any one person.¹⁸ The posterior condylar axis (PCA) is the most reliable of these axes in terms of the accuracy and precision of registration¹⁸ but has been ignored in most navigation systems in favor of either the anterior-posterior (A-P) axis (otherwise known as Whiteside's line) or the transepicondylar axes favored by MA surgeons.

Surface mapping of the distal femur is an integral part of the registration process that produces the working model of the knee in navigated TKA. The posterior condyles are easily and reliably mapped and are an alternative to other, less consistent surface landmarks for setting femoral component rotation. The kinematic flexion-extension axis of the tibia between 20 degrees and 120 degrees is the cylindrical axis of the femoral condyles for which the PCA is an excellent surrogate.² This is reliably reconstituted in KA TKA by the matched distal and posterior femoral resection algorithm that reconstitutes the prearthritic PCA and consequently eliminates much of the variation imposed by other rotational axes.¹⁹ There is some evidence that femoral bone loss is uncommon in osteoarthritis.²⁰ Thus, only the loss of distal femoral cartilage needs to be accounted for when calculating the matched resections from the distal femur to restore the pre-morbid femoral joint line. Tibial bone loss, by contrast, is common and difficult to quantify. Consequently, calculating the matched bony resections necessary to restore pre-morbid tibial height, slope, and coronal angulation is less reliable. With conventional instruments this uncertainty can be managed by making an initial, conservative, preliminary tibial resection, assessing balance and then revising the tibial resection as required. With navigation, this can be avoided in the virtual planning stage in which virtual implant size and position can be adjusted on the registered model of the knee. First, the osteophytes are cleared and next the collateral ligament on the worn side of the joint is tensioned with the knee fully extended. A valgus stress is applied to the medial collateral ligament (MCL) for a varus knee, and valgus stress is applied to the lateral collateral ligament (LCL) for a valgus knee. The navigation application will automatically measure the hip-knee-ankle angle (HKAA). The HKAA thus achieved is the target HKAA. The target lateral distal femoral angle (LDFA) is then easily determined by placing the virtual femoral trial in the planning software, to produce the necessary matched distal and posterior femoral resections. The target medial proximal tibial angle (MPTA) is then calculated by the

formula: $MPTA = HKAA - LDFA$. This formula is based on the "Subtraction Principle" that fundamentally states that knowing two of the variables allows the surgeon to calculate the missing third value, usually the MPTA. Having thus identified the MPTA, the angle of the tibial cut in the coronal plane can be set and the height of tibial resection can be adjusted to allow for the thinnest liner and therefore minimal bone resection. The slope of the tibial cut in the sagittal plane can also be matched to the unworn compartment in the planning software. Resection gaps are then checked virtually and small adjustments made to the planned implant position to optimize resection gaps.

When the definitive bone resections are made according to the plan, in most cases no further release or tibial recut is necessary to achieve a perfectly balanced KA TKA. If the surgeon is working with a restricted kinematic approach with defined coronal plane alignment limits, "outliers" are identified virtually and the necessary adjustments made before any bony resections are made. Soft tissue releases may be required to achieve a balanced ligamentous envelope in such cases.

Kinematic TKA alignment, although often described in terms of bony resection, is essentially a soft tissue procedure in which the goal of achieving arbitrarily neutral alignment is ignored, as so doing inevitably alters the joint line. Soft tissue releases are then often required to make each patient's unique and complex physiologic soft tissue envelope match the new nonphysiologic joint line. In the normal knee, for example, there is greater laxity on the lateral side of the knee than the medial side at all angles.^{3-5,21,22} In full extension, these differences are very small and the normal knee can be considered symmetrically balanced when fully extended.⁴ As soon as the posterior capsule is relaxed by flexing the knee, the lateral side relaxes to facilitate a medial pivot.²³ This asymmetry is evident in early,^{5,21,22} middle,⁴ and late flexion.³⁻⁵ Furthermore, overall ligamentous laxity is significantly greater in females than males^{21,22} and is differentially affected by resection of the cruciate ligaments. Anterior cruciate ligament (ACL) resection increases extension laxity but has a minimal effect on flexion laxity. Posterior cruciate ligament (PCL) section has the converse effect.³ Navigation allows virtual preoperative fine-tuning of implant size and position so that these very complex relationships can be replicated to reproduce natural soft tissue tension with as few releases or tibial recuts as possible.²⁴

Literature Review of Navigated Kinematically Aligned Total Knee Arthroplasty

This section reviews the literature supporting navigated KA TKA. Five studies have been published that employed a navigated KA technique.²⁴⁻²⁸ All used an image-free system, a cemented tibial technique, and cruciate-retaining components. In all these studies, a restricted KA technique was used with defined limits on some or all of the intraoperative coronal plane prosthetic and limb angles (Table 7.1). These limits are listed below and some would argue that the restrictions placed on coronal alignment limit the applicability of these studies to true, unrestricted KA. Four of these studies used the same prosthesis (Stryker Triathlon, Stryker, Mahwah, New Jersey).^{24-26,28} and the Stryker navigation platform. In two studies,^{25,26} an abbreviated navigation platform (Orthomap ASM, Stryker, Michigan) was used. Intraoperative HKA limits were set at ± 3 degrees in both

TABLE 7.1 Summary of kinematic alignment studies using navigation

Author	Study Type	n (Kinematic Alignment)	Length of Follow-Up Years	pL DFA Limit (Degrees)	pMPTA Limit (Degrees)	HKA Limit (Degrees)	Standing HKA (Degrees)
Hutt J	Case series	100	2.4 (1–3.7)	±5	±5	±3	–0.5 (–7.4 to 6.3)
Hutt J	Case series	55	Short—not specified	±5	±5	±3	–0.1 (–5.2 to 7.6)
Matsumoto T	RCT	30	1	No limit	All set at –3	No specified limit	–1.8 (–6 to 1.5)
McEwen P	Case series	192	3.5 (2–5)	±6	±6	±6	–0.7 (–9 to 5)
McEwen P	RCT	45	2–4	±6	±6	±6	–1.0 (–6 to 4)

– denotes varus.

HKA, Hip-knee-ankle angle; pL DFA, prosthetic lateral distal femoral angle; pMPTA, prosthetic medial proximal tibial angle; RCT, randomized controlled trial.

studies, but at 1 year, the standing HKA ranged from 7.4 degrees varus to 6.3 degrees valgus in one study²⁵ and 5.2 degrees varus to 7.6 degrees valgus in the other.²⁶ In the two studies by McEwen,^{24,28} a navigation platform with the capability for soft tissue integrated KA planning was used (Precision CAS, eNact Knee Navigation System v4.0 software, Stryker Leibinger, Freiburg, Germany). Intraoperative component and HKA limits were set at ±6 degrees, and at 2 years or greater the standing HKAs ranged from –9 degrees varus to 5 degrees valgus in one study²⁴ and from –6 degrees varus to 4 degrees valgus in the other.²⁸ In one of these studies (randomized controlled trial [RCT] of bilateral KA vs. MA),²⁸ the intraoperative navigation-based and standing HKA frequency distributions were compared. In the KA cohort, the intraoperative measures were statistically maintained at 2 years on standing 3 foot radiographs. In the MA cohort, however, the tight intraoperative frequency distribution was not maintained at 2 years and in fact was statistically similar to that of the KA group. Furthermore, the position that the MA knees would have been navigated to had they been done with a KA technique (virtual KA) matched where they ended up at 2 years. The argument can therefore be made that the replaced knee will gravitate toward its prearthritic alignment over time, regardless of the alignment technique used at the time of surgery, in which case a KA technique that targets the prearthritic alignment and does not require releases makes a great deal of sense.

Based on Bellemans' work,¹ an accurate unrestricted KA technique would result in approximately 24% of limbs having an HKA outside ±3 degrees from neutral. This is consistent with the two navigated studies with the widest target HKA window (±6 degrees) in which the percentages outside ±3 degrees were 36%²⁴ and 24%.²⁸ In both these studies, there were significantly more male patients (Chi-square test, $P = .028$ and $P = .004$),²⁴ thus increasing the number of cases with an HKA more varus than 3 degrees.¹ However, numerous meta-analyses of conventional versus navigated MA TKA have reported HKA percentages outside ±3 degrees of between 25% and 30%^{7–9} in conventionally instrumented cohorts. In summary, therefore, a navigated KA technique produces a similar percentage of HKAs outside ±3 degrees as would be expected based on prearthritic anatomy, and a similar percentage of alignment outside ±3 degrees as would be produced using a conventional MA technique. The KA knee, however, will be balanced with few releases, whereas the MA knee must by definition be unbalanced despite more releases.²⁸

As mentioned earlier, no KA paper has reported increased aseptic tibial failure rates or inferior clinical outcomes related to

an HKA outside ±3 degrees. No aseptic tibial failures have been reported in the short-term navigated KA studies. In terms of short-term data predicting long-term stability, radiostereometric analysis (RSA) is the gold standard. Migration below established thresholds at 2 years is predictive of long-term stability.²⁹ A recently published RSA study compared cemented Triathlon tibial component migration in KA and MA cohorts.³⁰ The KA cohort had an HKA range from 9 degrees varus to 1 degree valgus and a prosthetic MPTA (pMPTA) from 8 degrees varus to 1 degree varus. There were no differences between groups for tibial component migration or inducible displacement, both of which were below acceptable thresholds. Similarly, there was also no correlation between alignment and tibial component migration or alignment and inducible displacement. These results cannot necessarily be extrapolated to other prostheses, and ultimately, long-term data will be required to definitively answer the question of alignment and aseptic tibial failure.

Excessive tibial slope has been linked to aseptic tibial failure,^{12,13} and excessive femoral flexion to patellofemoral instability.¹⁴ Three navigated KA studies report on sagittal plane implant positions. In one study, tibial slope was arbitrarily set at 7 degrees, in keeping with the manufacturers' instructions.²⁷ In the other two studies,^{24,28} tibial component slope was matched to the slope of the unworn side of the tibia and femoral component flexion was adjusted to optimize sizing while staying within manufacturer-defined limits for combined flexion slope. In each of these studies, the mean and maximum femoral flexion angles were 3 degrees and 8 degrees, respectively, as were the mean and maximum tibial slope angles. This eliminates sagittal plane malposition as a mode of failure and is one of the more compelling arguments for using a navigation system.

The joint line orientation angle (JLOA) represents the coronal angle between the tibial plateau or component and the ground, on a standing radiograph. In bipedal stance in nonarthritic knees, the mean JLOA angle is varus but almost parallel to the ground,^{31,32} although the range of values covers a spread of around 12 degrees.³² This is the case with both constitutionally neutral and varus limbs. This has consistently been reproduced in navigated KA studies that report mean JLOAs of –1 degrees,²⁶ –1.1 degrees,²⁷ –1.3 degrees,²⁴ and –0.9 degrees.²⁸ MA knees, by contrast, have valgus mean JLOAs in bipedal stance that go further into valgus in single-leg stance.²⁷ The more valgus the JLOA of a TKA, the more the tibia is driven into varus as the knee flexes. If this is combined with the external rotation of the femoral component, as is commonly done in MA TKA, the effect becomes more pronounced.³³

Navigation provides the ideal platform with which to quantify and control soft tissue balance. If a kinematic alignment technique is used, balance should reflect the symmetrical or nearly symmetrical extension gap and the usually asymmetrical flexion gap of the normal knee. The rectangular flexion gap sought in MA TKA is nonphysiologic^{3-5,21,22} and is achieved by overresecting the posterior medial condyle and underresecting the posterior lateral condyle. This overconstraint of the lateral side of the knee in flexion is compounded by reversing the native sagittal convexity of the lateral tibial plateau to the concavity of a polyethylene insert that forces the femur to roll up a slope rather than down one during deep flexion. Lateral flexion gap laxity in cruciate-retaining MA TKA has been reported to improve tibial internal rotation as the knee flexes,²³ and postoperative flexion range.^{34,35} Using a navigated KA technique, McEwen²⁴ reported a mean lateral flexion gap laxity of 4.5 mm and a maximum 8 mm. The mean medial to lateral laxity differential was 2.3 mm. Increasing lateral flexion gap laxity and the “medial to lateral” laxity differential was positively associated with multiple patient-reported outcome measures.

Only two RCTs comparing MA with navigation to KA with navigation have been conducted. Matsumoto²⁷ reported better flexion range and net gain of flexion, as well as better scores in two KSS subsets in the KA group, at 1 year. In a trial of bilateral surgery, McEwen²⁸ reported near identical outcome scores but a significant patient preference for the KA knee that was associated with the absence of a ligament release and a more physiologic JLOA.

The Soft Tissue Envelope of the Osteoarthritic Knee

KA TKA essentially adjusts prosthetic alignment to accommodate the collateral ligaments and the PCL. One of the assumptions is that the ligamentous envelope is normal and that KA will restore native premonitory alignment without release. There is, however, evidence with larger coronal deformities that the envelope is not universally normal. This section summarizes the literature so that the assumptions that are made in the technical sections that follow are clear. In the majority of varus osteoarthritic knees, the MCL does not contract,³⁶⁻³⁸ although there is some conflict in the evidence base on this subject. Bellemans³⁹ and McAuliffe⁴⁰ both reported reduced medial laxity at low flexion angles in knees with greater than 10-degrees varus deformity. In Bellemans's study, osteophytes were removed and any inability to correct coronal alignment to neutral by filling the medial extension gap with a spacer was interpreted as medial contracture. McAuliffe left osteophytes in place and defined neutral as the position in which a virtual Macquet's line passed through the middle of the knee and measured laxity between a varus loaded and neutral position. Both studies fail to account for the constitutionally varus knee, that is, the fact that “neutral” is not the same as “normal,” and that a wide range of individual variation exists, let alone the effect of retained osteophytes.

In contrast to these findings, Okamoto³⁶ showed no medial contracture in extension regardless of varus deformity in excess of 20 degrees, and McAuliffe³⁷ reached the same conclusion with respect to arthritic knees in the 90-degree flexed position. In anteromedial arthritis, the MCL will reliably maintain its length, as intact posteromedial femoral cartilage will contact intact posteromedial tibial cartilage in deeper flexion.³⁸ This is



Figure 7.1 Lateral radiograph of an arthritic knee with a pathologically severe tibial slope, posteromedial wear pattern, and fixed anterior subluxation attributed to chronic anterior cruciate ligament deficiency.

one of the underlying principles of medial unicompartmental knee replacement in which an MCL release should never be needed or executed. Chronic ACL deficiency, however, can lead to a posteromedial wear pattern,⁴¹ fixed anterior tibial subluxation, and subsequent PCL contracture (Fig. 7.1).⁴² This latter scenario is essentially the only one in which the MCL (and the PCL) cannot always be assumed to be normal in length (even though it often will be).

In contrast, there is reasonably consistent evidence that lateral extension gap laxity can increase with increasing osteoarthritic varus deformity,^{36,39,40} with 10 degrees of varus appearing to be the tipping point for increasing lateral laxity. In such patients, caliper-based KA resection techniques may result in a widened lateral extension gap. In such situations, a limited release of the MCL from the tibia may be required to achieve balance, rather than further varus bony resection from the tibia. The literature reviewed above and the core assumptions regarding the ligamentous envelope of the varus knee are summarized in Box 7.1.

Valgus knees have been classified into three grades⁴³ based on severity of deformity, passive correctability, and the state of the MCL. This classification, although useful, assumes that neutral

BOX 7.1 VARUS KNEES

Varus knees with a preoperative deformity of less than 10 degrees and an anteromedial wear pattern can be assumed to have a normal medial collateral ligament and normal lateral structures. A release should therefore only be required to manage surgeon-prescribed limb and component alignment limits in the context of severe constitutional tibia vara. For acquired varus deformities in excess of 10 degrees, lateral extension gap laxity may be pathologically increased, and minor medial release may be required to balance an asymmetry of 2 to 3 mm.²⁴

BOX 7.2 VALGUS KNEES

Valgus knees with a preoperative alignment of less than 10 degrees that reduce to neutral can be assumed to have a normal medial collateral ligament (MCL) and normal lateral structures. A release should therefore only be required to manage surgeon-prescribed changes in limb and component alignment in the context of an unacceptably high lateral distal femoral angle. For valgus alignment in excess of 10 degrees, the MCL may be attenuated pathologically, and lateral side releases may be required to balance extension gaps.

alignment is both normal and desirable, and this premise needs to be kept under consideration. Grade 1 is mild valgus, passively correctable to neutral and with a completely normal MCL. By definition, these knees have acquired valgus alignment (usually caused by lateral meniscal deficiency and loss of articular cartilage) and normal ligaments. These knees are eminently suited to a KA technique and rarely require additional soft tissue releases. Grade 2 and 3 knees generally have an element of constitutional valgus alignment that is largely driven by the femoral mechanical LDFA (mLDFA).^{1,24} Grade 2 is moderate valgus that may not passively correct to neutral as the knee never was in neutral to begin with. There may be some attenuation of the MCL that nonetheless still has a firm end point. A KA technique is optimally applied to this type of knee using navigation instruments, as the exact amount of pathologic MCL laxity can be calculated before any bone resections are made. The amount of medial tibial bone resection is decreased to match the extent of the MCL attenuation, and the lateral side may require releases to balance. Grade 3 is a severe fixed deformity with an incompetent MCL that requires varus-valgus or hinge constraint and is clearly not suitable for a KA technique. The LCL rarely, if ever, contracts.⁴⁴ The femoral component is not externally rotated with a KA technique, so the LCL is not tightened by prosthetic component placement and remains naturally lax and accommodating in flexion. Reducing a valgus deformity, therefore, predominantly involves dealing with a tight lateral extension gap and, occasionally, a lax medial gap. The literature reviewed above and the core assumptions regarding the ligamentous envelope of the valgus knee are summarized in [Box 7.2](#).

Which Navigation System?

The full utility of navigation for KA requires several key capabilities to be realized by the software platform:

System capabilities to achieve these goals are:

1. Measure the coronal and sagittal HKA.
2. Adjust components in a virtual environment with 6 degrees of freedom and millimeter-level resection accuracy.
3. Measure resection gaps in millimeters at 0 degrees, 10 to 15 degrees, and 90 degrees.

Virtual sizing of the femoral component is a useful but non-critical feature. KA is the quintessential posterior referencing technique, and virtual sizing allows perfectly matched posterior condylar resections to be matched to optimal prosthetic coverage of the anterior resection tidemark by adjusting component flexion and size to do so. Virtual femoral sizing is a manufacturer-specific function, whereas the three capabilities detailed above are generic functions that allow the navigation system to be used with any implant, provided the dimensions of the chosen implant are known.

These system requirements are also met by a number of robotic systems. At present, the planning capabilities of these systems add little to that of an optimally configured navigation platform. Patellofemoral balance remains a digital black hole and no measure for PCL balance has been built into any platform. Currently, the ability to execute a very accurate tibial recut is the primary advantage of robotic systems over conventional navigation and has obvious utility in the context of KA TKA.

Kinematic Alignment Technique Using Navigation Instruments

The navigation system requirements outlined above for an optimal, soft tissue integrated KA technique are met by numerous systems. This section describes the planning and execution of navigation-based KA TKA in detail. For those accustomed to navigation, incorporating the workflow described below is very simple and adds less than 2 minutes once adept. This additional time is more than recovered by reducing the need for recuts and releases. For those learning navigation, the amount of data being processed and the number of decisions being made are substantially increased, and a learning curve will be evident. The workflow detailed below can be applied to any system with the requisite capabilities. The vast majority of the author's experience pertains to the Stryker Precision platform (Precision CAS, eNact Knee Navigation System v4.0 software, Stryker Leibinger, Freiburg, Germany), and although some of the details presented here will relate to this platform specifically, every attempt has been made to produce a generic workflow that is applicable to any navigation platform with the requisite capabilities. As mentioned, with the exception of femoral sizing that must be done conventionally, the workflow can be applied to any implant, provided the dimensions of the implant are known in terms of distal condylar, posterior condylar, and proximal tibial resections. Moreover, because the technique incorporates gap laxity into the planning algorithm after osteophyte removal, whether a femur-first or tibia-first technique is used becomes irrelevant, except in complex deformities that are discussed later in the section.

The components of the workflow are as follows:

1. Assessing native LDFA and MPTA from standing radiographs (optional).
2. Registration.
3. Setting the target HKA.
4. Setting the provisional target prosthetic LDFA (pLDFA) and pMPTA.
5. Setting femoral flexion and tibial slope.
6. Quantifying provisional balance and adjusting implant position to optimize balance.
7. Execution of planned resections.
8. Trial reduction and balance/re-cut or release.

PREOPERATIVE PLANNING

Preoperative planning is a quality assurance measure and is completed by measuring the mLDFA and the MPTA on standing antero-posterior radiographs. The 90-degree converse measures of the mLDFA and MPTA are designated as the pLDFA and pMPTA and correspond to the distal femoral and proximal tibial resection angles. The sum of the pLDFA and pMPTA gives the predicted postoperative alignment (assuming a rectangular extension gap). Much more anatomic detail is provided in the virtual platform, but the radiographic planning serves two

functions. First, it functions as a validation of the virtual model after registration. Any large deviation between the two, especially with respect to the distal femur in which there is likely to be no bone loss,²⁰ should trigger a check that the tracker arrays are stably mounted and that registration has been accurately completed. Second, it also alerts the surgeon to the possibility of an extreme anatomy, in which case the need for releases can be anticipated and planned for.

REGISTRATION INCLUDING TIBIOFEMORAL OFFSET

Registration in navigated TKA is the step through which the computer is shown where the patient's bones are in space so that it can guide the positioning of the cutting blocks. It is preceded by the placement of three-dimensional reflectors in the distal femur and proximal tibia. Once secured, the surface of the bone is mapped to models of the femur and tibia in the software through a process called registration, to create a very accurate three-dimensional representation of the bony anatomy of the patient. Registration should follow the navigation instrumentation manufacturer's prescribed technique; however, registration of the femoral rotational axis and tibial axial rotation requires specific mention. These are defined by different measures in different systems and are fraught with accuracy and precision issues, so it is important that the surgeon understands how these measures are incorporated into the virtual model of the limb that the software uses to help navigate the bone cuts. When using any KA technique, including navigated KA, femoral component rotation is set from the prearthritic PCA, so any inaccuracy issues associated with registration of an inaccurate rotational axis can be largely ignored. The registered axis will, however, define the sagittal and the coronal planes of the femur, so the closer the registered axis matches the PCA, the less coronal and sagittal plane inaccuracy there will be in the model compared with true anatomy. Registration of tibial rotation is particularly inaccurate and should be largely ignored in terms of definitive component placement. However, the greater the patient's tibial slope and coronal tibial angulation differ from neutral, the more tibial rotation will impact the bone model generated by the software. Therefore, as with the femoral rotational axis, the better tibial rotational registration matches the patient's real anatomy, the less inaccuracy there will be in the model. If a PCL-to-tibial tuberosity measure is chosen to help define the rotation of the tibia, the medial edge of the tibial tubercle, not the junction of medial and middle thirds, should be registered. An alternative measure using the long axis of the lateral tibial articular facet is more accurate.⁴⁵ A line drawn through the tibial spines is generally parallel to the long axis of the lateral tibial plateau, and the point where this line intersects the tibial tubercle can also be considered.

One of the other deficiencies in both navigation and robotic systems is the lack of a direct measure of normal tibiofemoral offset as a measure of PCL balance. Effectively all that is required to incorporate this measure is repeated measures between a fixed point on the femur and a fixed point on the tibia with the knee flexed to 90 degrees. Howell⁴⁵ has described this using a modified caliper technique. If the Precision navigation system is used, a point-to-point measure can be made using the software, by selecting one point on the distal femur and one on the anterior aspect of the tibia. The distance between the two points is automatically resolved into orthogonal components,

with the A-P component being the value of interest. If both cruciates are intact preoperatively, the repeated A-P offset measure at 90 degrees of flexion should be the same with cruciate retaining trials in place as at the time of registration (before any resections). If A-P offset is larger than preoperatively, the flexion gap may be tight, and the tibial slope can be increased or the PCL released. If the offset measure is smaller than before component placement, the flexion gap is too loose. If increasing the thickness of the insert or decreasing the tibial slope does not resolve the issue, then the PCL has in all likelihood been damaged during the procedure, and consideration can be given to the use of a more constrained bearing, converting to a PCL-sacrificing knee design, or choosing an anterior stabilized bearing with a high anterior lip.

SETTING THE TARGET HIP-KNEE-ANKLE ANGLE

Following registration of the bony anatomy, the software can represent the exact alignment of the knee relative to the hip and ankle. The appropriate HKA for KA is easily defined by clearing osteophytes around the femur and tibia, extending the knee fully and stressing the collateral ligament of the concave side of the deformity until tensioned. The HKA achieved when doing so is the target HKA. A window of 1 degree is allowed to account for extension gap laxity. For example, if the knee has a varus deformity, the medial osteophytes are cleared and valgus stress applied with the knee fully extended. If the knee corrects to 2 degrees of varus, the target HKA will be 2 degrees varus with an acceptable window of 1 to 3 degrees of varus. No attempt is made to "correct" the alignment to neutral in KA. The converse is done for a valgus knee. If the target HKA is outside of the surgeon's chosen or self-imposed limits, the target is shifted to the limit, but a release will then be required to achieve it, and the resulting total knee will no longer be strictly in KA.

DEFINING THE PROVISIONAL PROSTHETIC LATERAL DISTAL FEMORAL ANGLE AND PROSTHETIC MEDIAL PROXIMAL TIBIAL ANGLE—THE SUBTRACTION PRINCIPLE

The pLDFA is defined by setting matched resections of the distal femoral condyles accounting for cartilage loss on the virtual model. If bone is exposed, 2 mm of cartilage is lost and is subtracted from the matched resection. If cartilage loss is partial, the remaining cartilage should be cleared to the subchondral plate with a ring curette and the resulting resection account for 2 mm of cartilage. For example, the Triathlon prosthesis is 8.5-mm thick, and therefore a matched condylar resection should be 8.5 mm. The bony resections are then set to 8–9 mm (or 6–7 mm in the case of 2 mm of cartilage loss). The pLDFA is then known. The pMPTA is then calculated with the formula $pMPTA = \text{target HKA} - pLDFA$, using the Subtraction Principle. For example, if the target HKA is 2 degrees varus and the pLDFA is 1 degree valgus, the pMPTA is 3 degrees varus (with an acceptable window of 2–4 degrees of varus). This method renders the inability to calculate tibial bone loss with more severe disease irrelevant and is an important quality assurance measure.

(Technical note: The virtual planning screen in the Stryker Precision navigation platform allows adjustment of the virtual femoral component with 7 degrees of freedom but does not allow adjustment of virtual tibial component's coronal or sagittal

angles. To circumvent this limitation, the surgeon must go to the tibial cut validation step. Once in this screen and without making a cut, the surgeon can hold the validating tracker in space to simulate the planned kinematic tibial resection. Once this position is recorded, the surgeon can return to the planning screen. The tibial component position will be altered to match the simulated kinematic resection, and the resection gap measures will accurately display the outcome of the KA resection plane.)

SETTING FEMORAL FLEXION AND TIBIAL SLOPE

Femoral flexion is determined by A-P fit of the templated prosthesis on the virtual model of the patient's femur. The posterior condylar resections are set, and the size and flexion of the femoral component are adjusted on the screen to optimize coverage of the anterior femur. In most systems it will be possible to choose between two sizes, with the smaller being more flexed and the larger being less flexed to avoid notching. The more size options that are available in the knee system, the less the flexion differential will be between sizes. If a "narrow" and "standard" option is available for each femoral component size, then even greater flexibility exists. In some cases, there may be an A-P–medial-lateral mismatch of femoral sizing, in which case the narrow version of the larger size will be required.

In the majority of knees, the shape of the prosthesis will match that of the subject's anatomy, in which case the larger of the two options should be provisionally chosen as it will minimize flexion of the femoral component. As discussed, minimizing flexion will allow maximum flexibility in setting tibial slope (some implant systems have defined limits for combined femoral flexion and tibial slope, so using a larger femoral prosthesis and templating for less flexion results in less readjusting after setting tibial slope).

The slope of the unworn compartment is the primary reference point for setting tibial slope in KA TKA. If both sides are worn, then the slope is set to a generic 3 degrees and adjusted after collateral and PCL balance has been quantified (see later). The navigation system should ideally allow surface mapping of the proximal tibia to give a visual representation of slope. Most navigation systems reference tibial resection from the lowest registered point on each side of the plateau and assume a flat plateau. The medial tibial plateau is concave and the femur generally dwells on the low point of the plateau. Thus the key registration point should be the middle of the plateau on the medial side. The lateral tibial plateau is convex and drops away precipitously on its posterior aspect. Consequently, if the posterior third of the lateral plateau is registered, too much tibia will be resected laterally. Therefore only the anterior two-thirds of the lateral plateau should be registered. Tibial slope should be kept to a single-digit figure and rarely needs to be greater than 8 degrees.

QUANTIFYING PROVISIONAL BALANCE AND ADJUSTING IMPLANT POSITION TO OPTIMIZE BALANCE

Once the provisional kinematic cuts have been set in the software, the virtual resection gaps are quantified by stressing the joint into varus and valgus at 0 degrees (if possible), 10 to 15 degrees, and 90 degrees. The surgeon should remember that the only position in which medial and lateral laxities are

symmetrical is in full extension with the posterior capsule tensioned. At 10 to 15 degrees, the lateral resection gap may be 1 to 2 mm more lax than the medial. At 90 degrees, the differential is on average 2 to 3 mm but can be up to 8 mm.²⁴ At 0 degrees flexion, the aim, therefore, is to produce a rectangular resection gap that is 1 mm wider than the matched resection for the implants assuming the narrowest liner. For example, the Triathlon prosthesis has a matched resection of 18.5 mm if a 9-mm insert is used, so the target is a 19-mm resection gap. At 10 to 15 degrees, the lateral side may be a millimeter or two more lax than the medial. At 90 degrees, the aim is to have a trapezoidal gap after resection where the medial resection gap is 19 to 20 mm and the lateral gap is a physiologic number that varies for each patient but averages 21 to 24 mm.

In the majority of cases, the default kinematic resection will balance the gaps within the tolerances outlined earlier. If the resection gaps are not balanced, then releases may be required if the chosen implant positions are executed as planned. Alternatively, minor changes can be made to the implant positions before executing the plan to better balance the gaps. In most circumstance these adjustments in the software are in the realms of a millimeter or two and can be made to both the femoral and tibial cuts until the resection gaps match the desired targets. Doing so uses the lateral collateral tension as a check for the model and drastically improves ligament balance and the need to perform any recuts to achieve a balanced knee.

In the varus knee, a predicted imbalance after virtual KA positioning will generally involve two consistent patterns. The first is a loose lateral extension gap in the context of a moderate to large deformity. In this instance the tibial resection level should be raised by the same amount that the extension gap exceeds the target. For example, if the lateral resection gap at 10 degrees is 23 mm, it exceeds the target limit of 21 mm (medial target is 19 mm, but at 10 degrees of flexion, 2 mm more laxity on the lateral side is normal and acceptable), so the planned tibial resection should be raised by 2 mm. After the planned resections are made, the MCL will then probably be too tight, and a microfenestrated release with a 19G needle during trial reduction should be anticipated. It is, of course, possible to balance the same scenario by raising the tibial resection and increasing varus, but this violates the Subtraction Principle and by definition may lead to greater varus than the prearthritic state if the target HKA was not set at the anatomic angle. Multiple resolutions to this imbalance scenario are, in fact, possible by tweaking femoral and/or tibial implant positions, but all will violate the Subtraction Principle and the intent to replicate premorbid anatomy.

The second pattern of imbalance is isolated tightness of the medial flexion gap despite anatomic varus. Both the MCL and PCL will be too tight in this scenario, but only in flexion. This pattern is caused by a very steep tibial slope being reduced to an acceptable angle (8 degrees in the author's practice) and can be aggravated by a slope differential between medial and lateral tibial plateaus. The fact that the medial and lateral tibia may have different posterior slopes has been documented elsewhere and is on average 2.4 degrees,⁴⁶ with potentially greater variation in certain individuals. The lateral flexion gap will also be tighter than anatomic if premorbid native slope is reduced, but it is inherently lax enough to accommodate the slope reduction in the vast majority of individuals. Two resolutions to this scenario are possible. The first is to increase the posterior medial femoral resection, but this effectively externally rotates the

femoral component and violates one of the fundamental principles of KA of preserving the PCA-derived femoral axis. It is not recommended, as so doing impacts the kinematic function of the knee throughout the knee's range of movement. The second option is to release the anterior margin of the MCL and, if necessary, the PCL during trial reduction. Releasing the anterior border of the MCL has a much greater effect on the medial flexion gap than the medial extension gap and will not result in extension gap imbalance.^{47,48} Double-digit tibial slope angles should be avoided for reasons mentioned in the first two sections of this chapter.

In the valgus knee, persisting imbalance after KA positioning will also generally involve two consistent patterns. The first is a loose medial extension gap and occurs in a valgus knee with an attenuated MCL. Such a situation is the converse of that formerly described for the varus knee and has the same solution. In this scenario the tibial resection is raised and a release of popliteus and/or the LCL should be anticipated. The second is isolated tightness of the lateral extension gap that is caused by an extreme native LDFA that has been reduced to a prescribed pLDFA limit. A release of the posterolateral capsule (PC) or the iliotibial band (ITB) should be anticipated, depending on whether the residual deformity is valgus and flexion (PC+ITB) or valgus in isolation (ITB only).

EXECUTION OF PLANNED RESECTIONS

One of the primary advantages of navigation is the ability to confirm that what was planned has been executed. As such, verification steps should never be omitted. It is much easier to correct the inaccuracy of a conservative resection than to correct an aggressive one. Any overresection deviation from the plan, however, is quantified in the verification steps and can be compensated for with converse alterations to the tibial resection. The reader is referred to the instruction manual for the navigation system being used for these verification steps.

TRIAL REDUCTION AND BALANCE/RECUt OR RELEASE

Trial reduction has two purposes. The first is to determine definitive tibial component rotation. This can be set from tibial landmarks, or the trial tibial components can be floated against the femoral trial with the knee fully extended. Given the well-documented accuracy and precision issues with tibial landmarks and the fact that most implant systems have substantially greater rotational constraint in full extension than in flexion, the floating technique at least prevents rotational mismatch between the components in the position of greatest constraint and is the author's preferred method (Fig. 7.2).

The second is to assess alignment and balance. If balance is suboptimal, a recut or a release is required. If the Subtraction Principle is being followed, then tibial recuts are undertaken to increase slope if the flexion gap is too tight or to drop the tibial resection if both flexion and extension gaps are too tight. Varus-valgus imbalance is corrected with a release, as described above, to avoid violation of the Subtraction Principle as described in previous sections. Isolated extension gap tightness can be resolved with posterior capsular releases if minor and by raising the femoral resection if substantial, although the latter is rarely required and difficult to do.

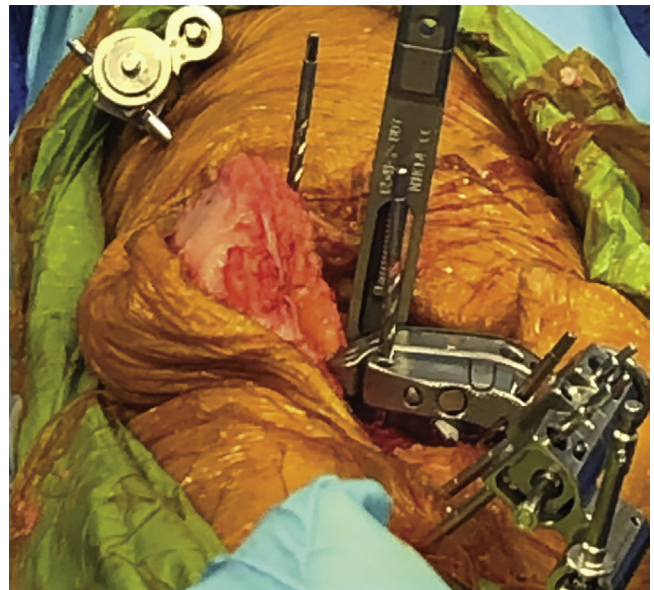


Figure 7.2 Photograph demonstrating the floating technique for setting tibial rotation: The handle in the tibial trial is rotated parallel to the pin in the femoral trial with the knee fully extended.

No release should be undertaken until trial implants are in place, as in some cases, removal of a retained posteromedial osteophyte or reduction osteoplasty of the medial plateau, if between sizes, may balance the joint.

Patellofemoral (PF) balance is typically satisfactory with a KA technique because the patella generally tracks as perfectly in the replaced trochlea as in the native one. However, it is important that KA principles are followed if the surgeon chooses to resurface the patella. The height of the patella should be restored, and the patella should be cut orthogonally to its axis in both A-P and lateral planes to reproduce native anatomy that will be stable in the anatomically positioned trochlea. The reported rates of lateral release and PF complications are low and comparable to those using an MA technique.^{28,49,50} The patient at risk of PFI after KA TKA (or MA TKA) is the same patient at risk of instability affecting the native knee.²⁴ A history of PFI, trochlear dysplasia, patella alta, and lateral tracking of the patella should trigger awareness of the potential need for additional PF balancing procedures. Femoral component flexion should be kept to a minimum in these individuals so that changes to lateral trochlear height⁵¹ and proximal patellar capture⁵² are minimized.

Complex Deformity

The methods for predicting, minimizing, and executing releases for commonly encountered varus and valgus deformities have been described in detail. This section describes the techniques for correction of hyperextension and severe fixed flexion deformities when using navigation in KA TKA.

ISOLATED HYPEREXTENSION

Isolated hyperextension in navigated TKA is generally synonymous with isolated extension gap laxity (Fig. 7.3A and B). Pathologic hyperextension can occur in some collagen-related and neuromuscular disorders, true bony deformity related to

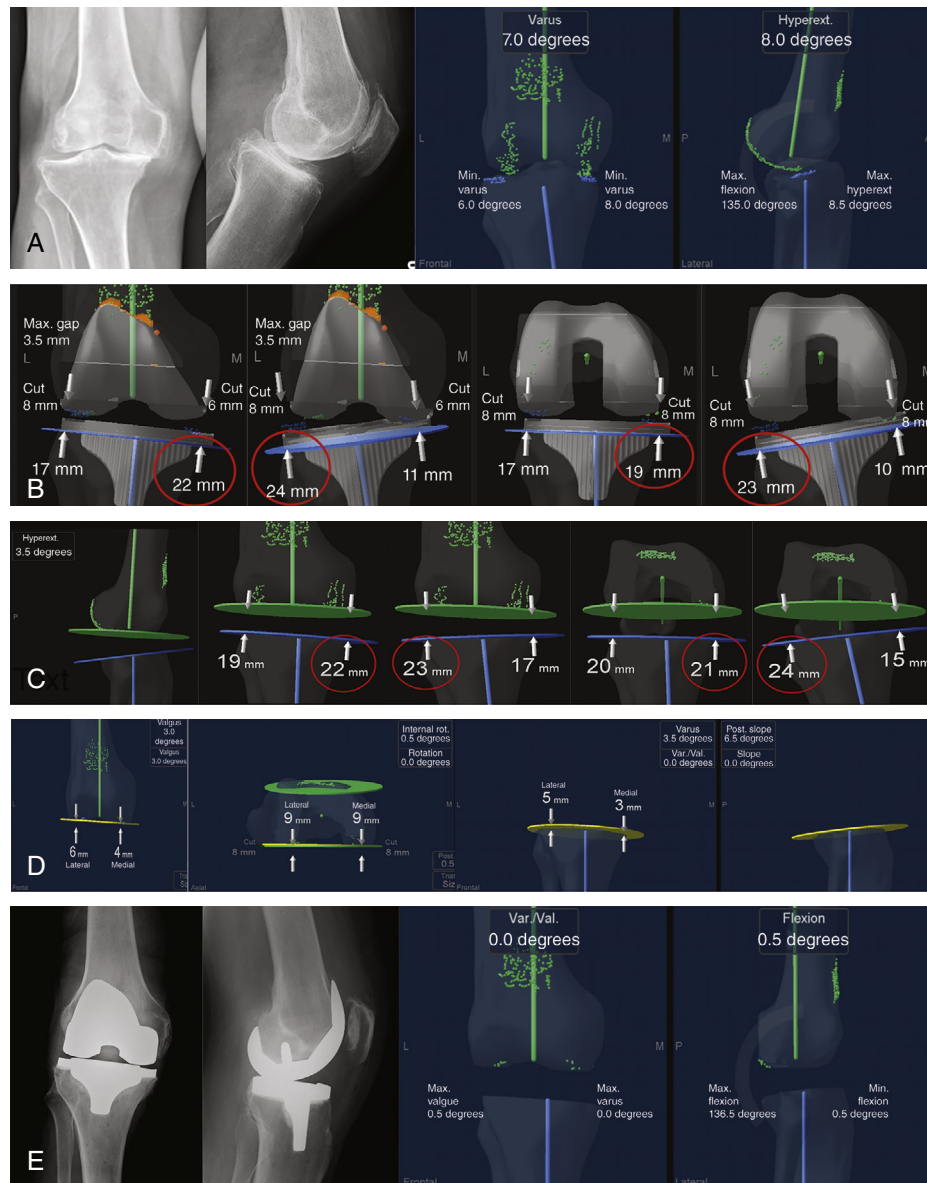


Figure 7.3 Radiographs and navigation data from a knee with a hyperextension deformity; (A) preoperative radiographs and navigation output quantifying the hyperextension deformity after registration. (B) Virtual gaps with virtual trials in kinematic position: the extension gaps are too wide (target gap is 19 mm). (C) Gaps with the femoral trial articulating with the native tibia. The femoral resection has been distalized 2 mm. The knee still hyperextends but now only 3.5 degrees instead of 8 degrees. The extension gaps are still too wide, so the tibial resection will be raised. (D) Navigation output showing final implant positions. Native joint line obliquity has been maintained, the femoral resection distalized, the tibial resection proximalized and steepened. Minor releases of the anterior margin of the medial collateral ligament and the anterolateral bundle of the posterior collateral ligament were needed to widen the medial flexion gap after raising the tibial resection. The lateral flexion gap was naturally lax enough to accommodate the raised tibial resection. (E) Postoperative radiographs and end procedure navigation output showing complete correction of the hyperextension deformity.

epiphyseal diseases, and inadvertent overresection of the distal femur at the time of surgery. Pathologic hyperextension is most easily corrected by bringing the femoral resection more distal.

Attempts at adjustments designed to limit hyperextension after the cuts are made would generally involve using a larger tibial insert, increasing tibial slope, and releasing soft tissue to loosen what was a balanced flexion gap. Secondarily bringing the femoral component distal can be difficult but can be performed. This challenging scenario can be avoided if recognized preoperatively by “distalizing” the virtual femoral trial to optimize extension gap balance during the balancing section of the workflow. An additional step is added after the distal femoral

resections are completed. The femoral trial is inserted, and the knee is extended before resecting the tibia (Fig. 7.3C). If the knee still hyperextends pathologically, the tibial resection guide should be raised by 2 mm and the posterior slope increased by 2 degrees up to a maximum of 8 degrees. The tibia is then resected, and flexion gap releases completed as required with trial implants in place. This additional step eliminates the need to use large inserts in a primary arthroplasty as well as secondary distalization of the femur. The end result will then be a distalized femoral resection, a potentially proximalized tibial resection (Fig. 7.3D), and a balanced knee that does not hyperextend pathologically (Fig. 7.3E).

SEVERE FIXED FLEXION DEFORMITY

A severe fixed flexion deformity will necessarily prevent setting of the target HKA and acquisition of balance data during the “quantifying provisional balance and adjusting implant position to optimize balance” step of the standard workflow. In this circumstance, the standard matched distal femoral resections are set and executed. Posterior osteophytes are then resected and, as with a hyperextension deformity, the femoral trial is inserted, and the knee is extended before resecting the tibia. If the knee can then be extended to at least the 10- to 15-degree position, which is commonly the case, the standard workflow can be commenced at Step 2 with the femoral trial in place. If a large flexion deformity persists, the posterior capsule can be released and trial extension repeated. Raising the femoral resection before resecting the tibia, debriding the joint, and completing a full trial reduction should be avoided.

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Summary

Anatomic accuracy and surgical precision are prerequisites for consistently executing a successful KA TKA. Navigation is an excellent platform to use to avoid the sagittal plane alignment errors historically associated with aseptic loosening and wear. An understanding of the nature of the ligamentous envelope of the osteoarthritic knee combined with the use of the Subtraction Principle eliminates target uncertainty in KA when tibial bone loss is present. With a little practice and a navigation system with the basic tools and capabilities herein described, a complete and perfectly balanced KA TKA can be planned in less than 2 minutes. In the vast majority of cases, the virtual plan, once executed, leads to an anatomically balanced and aligned joint without the need to recut bone or release soft tissue.

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Kinematic Alignment With Image-Based Robotic Instrumentation

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CHAPTER OUTLINE

Overview

Introduction to Robotic-Assisted Technologies for Kinetically Aligned Total Knee Arthroplasty

Motivation to Use Computer and Robotic Assistance for Kinetically Aligned Total Knee Arthroplasty

Introduction to Robotic-Assisted Technologies

Benefits and Limitations of Current Robotic Systems for Kinematic Alignment

Preoperative Image-Based Kinematic Alignment Planning

Basic Kinematic Alignment Planning Workflow

Pitfalls, Tips, and Tricks for Image-Based Kinematic Alignment Planning

Bernese Surgical Workflow Robotic-Assisted Kinetically Aligned Total Knee Arthroplasty

Setup, Incision, and Bone Registration

Intraoperative Verification of the Preplan

Tibia Precut and Osteophyte Removal

Soft Tissue Analysis and Balancing

Case 1

Case 2

Case 3

Overview

Robotic assistance was recently reintroduced in total knee arthroplasty (TKA) to improve surgical precision and to minimize errors. However, the technique stills focuses on mechanical alignment (MA) philosophies, with minor adaptations. This chapter is meant to highlight the surgical technique of robotic assistance and its suitability for achieving true kinematic alignment (KA) in TKA and discusses its potential benefits over conventional or other computer-assisted techniques.

The first section gives a brief overview on current devices for robotic-assisted TKA. Differences between the systems and their underlying principles are discussed. Special focus is on the potential advantage of image-based concepts with three-dimensional KA planning.

The second section outlines a step-by-step algorithm for a KA preplan and discusses the major parameters of interest. How this plan can be adapted to individual anatomic variations is outlined.

In the third section, we describe a distinct intraoperative workflow for KA using image-based robotics. It is based on a hybrid approach, with a true measured resection philosophy for the femur to restore the native joint surfaces, and a gap-balanced tibial resection to restore a rectangular extension

space. For illustration, three clinical cases are discussed in terms of implant alignment and balancing.

Introduction to Robotic-Assisted Technologies for Kinetically Aligned Total Knee Arthroplasty

Several technologies have been introduced over recent years that can be called robotic surgical assistance. However, there are marked differences in the methods for technically implementing the use of robotic platforms and in the principles relied on to execute the surgery. This results in varying workflows for KA TKA and different potential to overcome the known limitations of current technologies or manual KA instrumentation.

MOTIVATION TO USE COMPUTER AND ROBOTIC ASSISTANCE FOR KINEMATICALLY ALIGNED TOTAL KNEE ARTHROPLASTY

There is growing evidence that computer assistance in general results in higher precision in TKA component position and reduces outliers, compared with manual instrumentation.^{1,2} However, it has not been shown that this improved precision results in better patient outcomes in the context of MA.³ KA has the potential to improve patient outcomes compared with MA. Several studies have shown that complications and outcome are related to the precision of component position.^{4,5} Higher failure rates have been reported when the sagittal profile (femoral flexion or tibia slope) is changed^{6,7} and inferior outcomes have been seen when desired KA alignment was not achieved. Additionally, changing joint line obliquity from the native results in increased joint loading and possible higher wear.⁸

This apparent need for accurate three-dimensional implant positioning of both components in KA TKA raises interest in computer-assisted technologies. However, current available technologies have their limitations. Some important parameters, such the reconstruction of the anterior aspect of the knee or the sagittal profile, are not solved satisfactorily in manual or navigation-based techniques.⁹ Purely image-based technologies, such as patient-specific instruments (PSI), are limited in that the soft tissues are not included in the planning and wear is often difficult to predict precisely before surgery. This makes intraoperative adaptations still necessary. These limitations make further evolution in technology for KA TKA reasonable.

INTRODUCTION TO ROBOTIC-ASSISTED TECHNOLOGIES

Currently, five robotic systems for TKA are available, which can be categorized according to four basic principles. First, there are systems that actively position the cutting jig, which is

assembled on a robotic arm to the desired cutting plane in the knee¹⁰ (Rosa®, Zimmer Biomet, Warsaw, IN, USA; OMNIBotics®, Corin Group, Cirencester, United Kingdom [UK]).¹¹ The cut itself is conducted traditionally by the surgeon through the jig. Second, one system is based on a navigated burr that is used to mill the implant bed or to accurately position traditional cutting jigs (NAVIO, Smith & Nephew, Watford, UK). The burr has a retraction mechanism that prevents removal of any bone outside the desired resection plane or drill hole position. A third system employs a saw directly assembled onto a robotic arm with haptic control (MAKO, Stryker, Warsaw, IN, USA).^{12,13} The robotic arm controls the desired resection plane and sets boundaries in which the saw can be activated by the surgeon. Fourth is an automatic robot conducting the bone resections on its own, based on a surgeon's planning (TSolution One® Surgical System, Think Surgical, Fremont, CA, USA).¹⁴ So, considerable differences can be recognized already between these robotic systems in the planning programs and methods of executing the bone cuts.

In terms of the underlying navigation and planning, most systems rely on bone models selected from an atlas of knees. During surgery, several landmarks are captured on the surface of the femur and tibia by the surgeon, to which a best-fit bone model is selected to represent the patient's knee. One system has the option to use preop imaging (X-ray based) to preselect a bone model from the database, best matching the dimension of the patient's knee (Rosa®, Zimmer Biomet, Warsaw, IN, USA). This also enables preplanning of the prosthesis position following KA principles before surgery. Another system has the option to create a surface map of the bone during surgery, in addition to the atlas model (NAVIO, Smith & Nephews, Watford, UK). From that surface map, fake computed tomography (CT) is created on the planning screen that can be used to kinematically align the prosthesis with the femur. The two other systems are image-based (MAKO, Stryker, Warsaw, IN, USA; TSolution One® Surgical System, Think Surgical, Fremont, CA, USA). They rely on a CT scan of the hip, knee, and ankle, conducted before surgery. The bone morphology is segmented to an individual knee model. Based on this, a KA preplan can be created before surgery and adapted during surgery with respect to soft tissue, as described later.

All the systems presented are equipped with virtual planning software. This means that the prosthesis planning is initially based on the principles of measured resection. Intraoperatively, the flexion and extension spaces are recorded, and the position of the components can be adapted to achieve a balanced joint without releases. These adaptations are virtual and made before the final bone cuts are conducted. The effect on the gaps is predicted by the software. Differences between the systems are in terms of the knee positions that are included in the planning; some analyze the whole range of motion, others just the extension and flexion space at 90 degrees.

BENEFITS AND LIMITATIONS OF CURRENT ROBOTIC SYSTEMS FOR KINEMATIC ALIGNMENT

Generally speaking, all said technologies can be used to achieve KA TKA. In particular, the hybrid approach of measured resection of the femur and gap-balanced planning of the tibia cut in extension to establish a tight symmetrical extension space fits perfectly with the KA concept. With virtual planning and the

precision of the technology, errors and recuts can potentially be minimized. Also, the final alignment can be controlled, helping the decision-making process during surgery. Besides this, each system has some advantages and disadvantages.

The advantages of imageless robotic-assisted technologies over manual instrumentation are pretty much the same as for conventional navigation (e.g., higher precision, visualization of alignment, objective balancing, virtual planning of component position before cuts). So is the intraoperative workflow analog to navigated KA, as described in [Chapter 7](#). However, with the use of any standard knee model there is still a lack of information on the anterior aspect of the knee, the aspect that usually shows the greatest variability in knees.¹⁵ Although KA in general leads to better restoration of patella kinematics compared with MA TKA, the individual relationship between trochlea orientation and posterior condylar line remains unknown and thus the individual effect of the replacement surgery on patella tracking. Also, the individual anterior offset representing the lever arm of the quadriceps is unknown. With the addition of individual surface mapping, as described for the second technology, this limitation is addressed. With a better visualization of the patients' individual knee geometry, more parameters are available for correct component sizing, flexion, and mediolateral (M-L) position. However, the model creation and planning are done during surgery, which takes time. Also, the more posterior aspect of the knee is difficult to reach with the probe. Thus, surface-based technology has its limitations, especially in visualizing the tibial slope.

Compared with surface-based technology, there are several advantages to image-based technologies, especially in the context of KA TKA. Analog to the mentioned surface model, the individual anterior knee aspect is visible and accessible for appropriate planning. In addition, the tibia slope can be visualized in CT-based planning and precisely adjusted to the native situation (see Basic Bernese kinematic alignment planning workflow). Second, new algorithms can be created to set the tibia rotation with reference to the transverse kinematic femoral axes, as described below. This is difficult to control in imageless navigation, where only the surgeon-defined landmarks are available. Third, the osteophytes affecting soft tissue balance are clearly visible. With image-based navigation, osteophytes can be identified during surgery and removed with navigation control (see section Bernese surgical workflow robotic-assisted kinematically aligned total knee replacement). This helps to ensure a reliable soft tissue analysis with the system, especially in difficult cases. Last, the image-based model enables the measurement of individual cartilage thickness during surgery, potentially resulting in a better reconstruction of the individual joint line. In model or surface-based methods, the cartilage is routinely assumed to be 2 mm on average.^{16,17}

From the surgical point of view, the robotic devices themselves are of less interest in KA than the underlying navigation component. One difference between robotic systems could theoretically be the precision of each system. However, no comparative data are available. Another aspect would be possible active soft tissue protection by robotic systems.¹³ This would be applicable for the retracting burr or the saw with haptic boundaries, but not for jig-based systems used with traditional saws. However, there is little information yet on positive effects on patients' outcomes.

In summary, the authors see several advantages to image-based planning and surgery over imageless robotics or manual

techniques, making these technologies an interesting option for achieving KA. Potential pitfalls owing to individual knee morphotypes, massive osteophytes, or bone defects are more easily visible, helping to make the surgery reproducible and safe. Key is to correctly coalign the implant to the prearthritic surface of the knee. The more information available, the better this works. Additional to that, the balance of the knee is objectified. The robotic device assists the transfer of the plan to the knee, with the potential benefit for systems with resection boundaries to protect the soft tissue envelope. In the following, our KA planning and surgical workflow for one specific image-based robotic arm-assisted surgical system is described in detail.

Preoperative Image-Based Kinematic Alignment Planning

The basic principle of KA is to reconstruct the prearthritic surface of the knee joint with the prosthesis and thus coalign the kinematic axes of the implant to those of the native knee joint. In image-based robotic-assisted surgery, the correct anatomic position of the components is primarily determined preoperatively using a computer model of the individual knee, segmented from a preoperative CT scan. Being a key factor for success, this planning should follow a standardized workflow, as described here.

BASIC KINEMATIC ALIGNMENT PLANNING WORKFLOW

Femur

Following the principles of KA, first, the distal and posterior femoral resections are set symmetrically and are based to match the thickness of the distal and posterior femoral condyles of the implant. As the model is CT based, the cartilage thickness needs to be considered to restore the original joint line. Calculating with an average cartilage thickness of 2 mm on the femoral condyles, the magic numbers for bone resection thickness on the segmented bone model are thus set to 6 mm for each distal and posterior resection, when aiming for a symmetric 8-mm thick prosthesis (Fig. 8.1). This results in an individual varus-valgus (V-V) orientation of the femur and an internal-external (I-E) rotation of the component to 0 degrees of the posterior condylar axis (PCA). The rotation to the transepicondylar axis (TEA) is of no interest.

After setting the distal and posterior femoral resection, the third parameter concerns how to size and reconstruct the geometry of the anterior aspect of the femur, including the trochlea. This is best planned on axial cross-sections of the CT scan. The idea is to choose the implant size best reconstructing the anterior femoral offset without producing overhang. From

the authors' experience, the largest component still fitting in the M-L dimensions of the knee is most likely to be selected. The M-L position can be adapted to best reconstruct the position of the trochlea groove.

The third and final planning step for the femur is to adjust the femoral component flexion. Because the orientation, position, and size are already defined, this is used to create a smooth transition to the anterior femoral cortex with a low risk of notching. With the use of the largest possible component fitting to the knee, the average flexion is usually conservative at between 0 and 5 degrees with reference to the hip center. Care needs to be taken not to influence the other position parameters when adjusting the flexion. Therefore, the center of rotation about which the component is flexed is positioned in the kinematic center of the prosthesis (Fig. 8.1).

Therewith, the femur is preplanned based on the kinematic principle. During surgery, only minor adaptations are made to this plan, based on the cartilage thickness, potential defects, or the cartilaginous trochlea groove, as described in the section Pitfalls, tips and tricks for image-based kinematic alignment planning.

Tibia

The planning of the tibia position is preliminary and underresected based on best judgment, which leaves room for fine tuning the V-V and slope orientations of the tibial resection that are determined intraoperatively. Because bone defects are much more likely on the tibia than on the femur, the correct estimation of the original joint line orientation and height is much more difficult. Thus, the final tibia alignment is determined by the soft tissue balance in extension during surgery, to create negligible V-V laxity in full extension, like the native knee (see Bernese surgical workflow robotic-assisted kinematically aligned total knee arthroplasty).

Depending on the bony situation, we usually preset the tibia orientation close to what we think the original joint line obliquity is. This is best visualized on coronal CT cross-sections, positioning the tibia parallel to the unworn plateau (Fig. 8.2). In the authors' experience, it is better to stay on the conservative side (usually 0- to 3-degrees tibia vara) in the beginning, so not to overresect the medial compartment in excess tibia varus. Also, the resection thickness should be planned conservatively so that adaptations and recuts can be easily performed. Usually, we set the initial bone resection at around 4- to 5-mm maximum with reference to the bony topography of the CT-based model. This outputted resection level is not very helpful in setting the correct angulation or resection depth. Usually, the resection landmarks are positioned directly onto the worn plateau. Thus, the resection numbers might refer to bone defects. Also, the cartilage surface is initially not visible on the CT-based model. Again, an intraoperative adaption based on the unworn cartilage level can be used to correctly set the resection level and

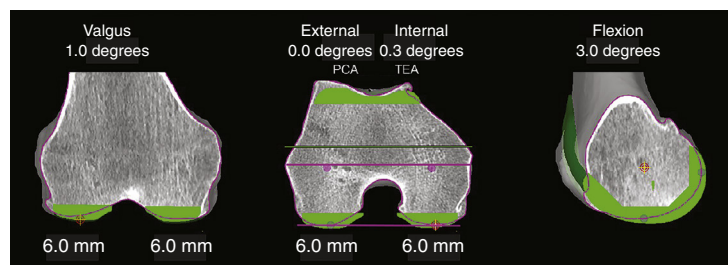
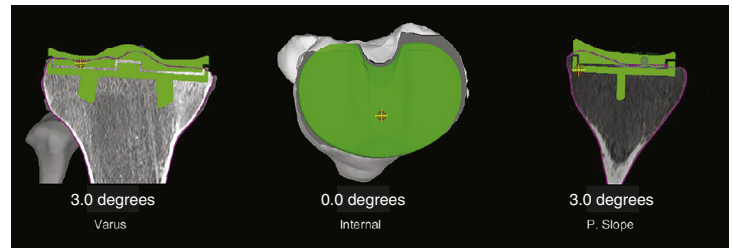


Figure 8.1 Following the KA principle, distal and posterior resections are set to 6-mm bone resection. This sets the femoral component in 1 degree of valgus and -0.3 degrees of rotation to the transepicondylar axis (TEA) in this example (transverse pink lines in center image represent posterior condylar axis [PCA] and TEA). Size is adapted to best meet anterior offset and mediolateral dimension. Flexion is adjusted for smooth transition to anterior cortex with the center of rotation approximately within the kinematic axis of the femur (red dot).

Figure 8.2 Example of a preliminary plan for tibia component orientation. Varus-valgus plane is estimated on coronal view to 3 degrees of physiologic varus. Rotation is set at 0 degrees, parallel to the described tibia rotation landmark. Tibia slope is orientated parallel to the posterior two-thirds of the medial plateau. Resection level is initially planned conservatively at 4- to 5-mm bone resection (cartilage level is not included in the resection measurement!).



tibia orientation, as described later (section Pitfalls, tips, and tricks for image-based kinematic alignment planning).

The second parameter on the tibia is the component rotation. In the proprietary planning protocol, tibia rotation is defined with reference to the posterior cruciate ligament (PCL) insertion and the medial one-third of the tuberosity. However, this is error prone and does not follow the principles of KA with a functional alignment. Thus, we changed this algorithm in our protocol and orient the tibia with reference to the transverse kinematic axis of the femur, about which the tibia and patella flex and extend. Within the “Case Planning” screen in the systems software, the rotation landmark can be set individually. On axial cross-sections, there is the possibility to scroll upward from the tibia onto the femur. In our protocol, we primarily coalign the rotation to the PCA, centered to the trochlea groove. This can be validated to the geometry of the tibia plateau and the tuberosity. The A-P axis of the tibial component is then oriented parallel to this landmark, which sets the rotation of the implant parallel with respect to the A-P axis of the femoral component to 0 degrees. Sizing and M-L position is also addressed in this step, after defining the correct rotation.

Third and last is the planning of the tibia slope. In KA, the idea is to reproduce the native tibia slope of the medial plateau. However, one must be careful with the common definition of the anatomical slope that usually refers to a tangent that is aligned to the most prominent anterior and posterior aspect of the tibia plateau. This measurement can be significantly affected by osteophytes, with a tendency to overestimate the native slope. Thus, in our algorithm the slope only refers to the posterior two-thirds of the medial tibia plateau, without taking posterior osteophytes into account. The component is set parallel to this area, visualized on sagittal CT cross-sections (Fig. 8.3). According to Pinskerova

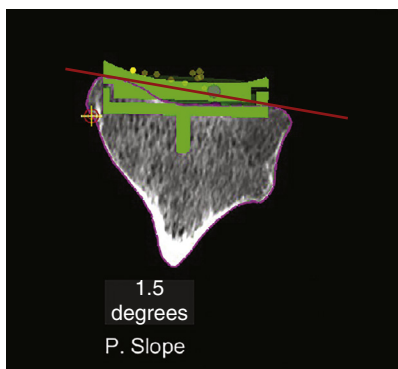


Figure 8.3 Slope should be orientated to the posterior two-thirds of the medial tibia plateau, but to the “anatomical slope” (red line). The traditional anatomical slope is too influenced by osteophytes and does not represent the motion of the knee. Also, cartilage mapping around the spine can help to understand the orientation of the physiologic slope in heavily worn knees (yellow dots).

and Freemann,¹⁸ this is the area where the femoral rollback on the medial plateau happens during flexion.

In posterior stabilized (PS) prosthetic designs, we usually replicate the physiologic slope or reduce it by 1 to 2 degrees to address the known effect of flexion space overlengthening after resection of the PCL. To evaluate the necessity of a slope reduction, it is important to do the soft tissue analysis with both cruciate ligaments already resected. The limit of tibia slope in a PS prosthesis is the combined component flexion of femur and tibia, which must be within the company’s given limits (8 degrees with the Triathlon system, for example). If the slope cannot be estimated because of bone defect, the recommendation is to start with a conservative alignment (1–3 degrees) and to verify the slope based on the flexion space tightness during surgery.

PITFALLS, TIPS, AND TRICKS FOR IMAGE-BASED KINEMATIC ALIGNMENT PLANNING

Landmarks and Resection Level

It must be clarified that all parameters and numbers displayed in the system are artificial and with reference to landmarks that are defined on the CT scan. Most values are of minor interest in KA, such as the actual V-V orientation or rotation degrees. In contrast to this, the reference landmarks from which the resection level is determined, as well as the tibia rotation landmark, are of major interest, as these directly influence the alignment of the components. Care must be taken that the reference landmarks on the femur truly represent the most distal or posterior aspect of the condyle. This is hard to determine on a three-dimensional model, which is the standard proprietary workflow. The authors thus recommend visualizing the landmarks on the CT cross-sections directly on the “Planning Screen.” In some knees, a rather oblique surface to the lateral femoral condyle in the coronal profile is visible (Fig. 8.4). Here, it is very hard to correctly set the reference landmark. Usually, the cartilage surface levels out the asymmetry, typically with more than 2-mm average thickness in those areas. Thus, we routinely set the level of the bone resection to 5.5 mm or 5 mm from the reference landmark on the lateral condyle in these conditions. In cases of bone defect

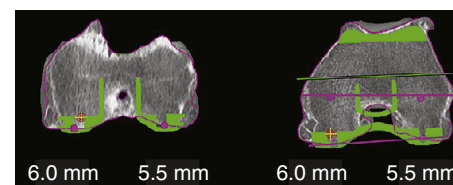


Figure 8.4 Example of a lateral femoral condyle with oblique bone surface. The resection landmarks (purple dots) do not represent the most distal and posterior aspects of the bone. Thus, the resection level should be adapted to 5.5 mm, or even 5 mm, on the lateral side.

or heavily worn knees, the resection thickness also needs to be reduced accordingly. In particular, valgus osteoarthritis (OA) cases are likely to present additional bone wear on the distal and posterior femur that must be considered by adaptations to the level of bone resection (see also Case 3). In varus OA, additional bone wear is rare and typically concentrated on the distal but the posterior aspect, depending on the integrity of the anterior cruciate ligament (ACL) (see also Case 2).

Individual Cartilage Thickness

In classic KA, the cartilage level is assumed to be 2 mm on average¹⁷; however, high variability, especially in the lateral compartment, has been described.¹⁹ One advantage of the image-based robotic system is that the unworn cartilage level can be digitized on top of the CT model during surgery, and thus the individual cartilage thickness can be computed as the difference between the digitized surface and the underlying bone. This information can be used to fine-tune the component alignment and resection level (Fig. 8.5). In our algorithm, the cartilaginous trochlea groove is determined during surgery, to adjust the M-L femoral position. Also, the cartilage thickness on the femur is evaluated in areas with unworn surface. Based on this, the resection level is adjusted to 5.5 mm or 5 mm, for example. Large men especially tend to have thicker cartilage than smaller men, by a millimeter or two.

On the tibia there is likely to be almost intact cartilage close to the tibia spine, even in heavily worn knees with bone defects of the plateau. This area can often be used as a good reference to estimate the correct tibia resection level and the V-V orientation or slope. Based on this, the preset alignment is verified or adjusted before any cuts are performed.

Asymmetric or Dysplastic Knee Morphotypes

In KA, the femoral component is strictly aligned to the tibiofemoral joint line, resulting in 0 degrees of rotation to the PCA. On average, the kinematic axis about which the patella flexes and extends is parallel to the primary kinematic axis in the femur.^{20,21} Thus, the patella rotation axis is automatically reconstructed with use of a symmetric prosthesis in most knees. However, there are some knee morphotypes in which the condyles are asymmetric (different radii of the condyles) and the patella axis is not perfectly parallel to the tibiofemoral axis.^{15,22} This relationship between the PCA and the trochlea groove line is visible on axial CT cross-sections. In mentioned morphotypes, KA could produce a relative internal rotation

of the groove and patella axis compared with the physiologic trochlea profile. In those cases, minor adaption of the rotation alignment might make sense, to neutrally align the prosthesis to the patella axis. It is important not to influence the medial condylar aspect, but only to reduce the posterior lateral resection. This algorithm can also be used to estimate and compensate for bone defects on the lateral condyle in valgus (OA). The bone resection levels then might be 6 mm on the distal and posterior medial femur and 4 to 5 mm on the lateral femur, compensating for posterior defect or a femoral asymmetry (see also Case 3).

Bernese Surgical Workflow Robotic-Assisted Kinematically Aligned Total Knee Arthroplasty

SETUP, INCISION, AND BONE REGISTRATION

Initially, the KA surgical technique does not differ from standard robotic-assisted surgery. In brief, the robotic arm is set up, draped, and calibrated before surgery by the company's staff and scrub nurse. The incision, exposure of the knee, position of the arrays in the tibia and femur, and bone registration are analog to conventional workflow. In contrast to imageless systems, bone registration means that 40 random points on the surface of each bone are collected with a sharp probe that penetrates through the cartilage directly to the subchondral bone or cortical surface. No specific landmarks need to be defined by the surgeon, only the bone morphology. The computer matches the cloud of points to the segmented knee model, which is verified in a second step.

INTRAOPERATIVE VERIFICATION OF THE PREPLAN

The first KA-specific step is to determine the cartilage thickness, where available. The cartilage surface is mapped as a second layer on the "Implant Planning" screen with the use of a blunt probe. Trochlea groove, distal and posterior femur, and the cartilage on the tibia plateau, close to the spine, are captured. Based on this information, the preplan is verified to better reproduce the actual joint surface with possible adjustment of the resection thickness as described in the section Preoperative image-based kinematic alignment planning (Fig. 8.5).

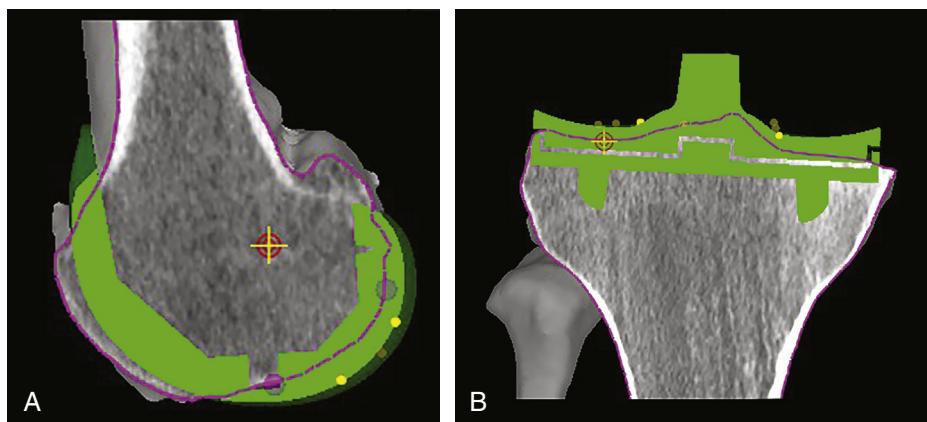


Figure 8.5 Example of cartilage mapping on unworn femur condyle (A) and tibia plateau (B). The resection level is individually adjusted to reconstruct the original cartilaginous joint line with the prosthesis. Even on the heavily worn medial tibia plateau, intact cartilage can be mapped close to the spine.

TIBIA PRECUT AND OSTEOPHYTE REMOVAL

For perfect KA alignment and to correctly capture the flexion and extension space, the most important step is to meticulously remove all osteophytes. Usually this cannot be achieved without conducting bone cuts beforehand. Especially in knees with torn ACL, osteophytes are likely to be on the posterior aspect of the knee, influencing the extension space, which is critical for KA component position. This is why it makes sense to start with a bone precut of some sort. In our routine, we start with the tibia for practical reasons. As outlined in the planning section, the orientation of this tibia cut is close to the estimated final alignment (V-V and slope) with a conservative resection of 4 to 5 mm. This is likely to address the most relevant osteophytes both on the tibia and on the femur. Also, the flat surface of the tibia makes it easier to insert a balancer of some sort or a spacer block. In theory, the femoral cuts can be conducted first, as their positions are defined by the KA principle. However, with the tibia-first technique, the osteophytes and capsule appear a bit easier to access. In knees with severe extension deficit, we usually precut the tibia as described, as well as conduct the distal and posterior femur resections following the KA principle. This is to create enough space to enable complete removal of osteophytes and capsule posteriorly, before analyzing the soft tissue. When aiming for a PS prosthesis, the PCL should also be resected before the gap evaluation.

For correct balancing, the image-based technique with the visibility of relevant osteophytes offers an advantage over conventional techniques. With the CT-based navigation, the transition between osteophyte and bone can be made visible using the green probe, and the resection of additional bone can be precisely controlled (Fig. 8.6). This should be routine for KA technique as the osteophytes are critical for correct alignment and balance.

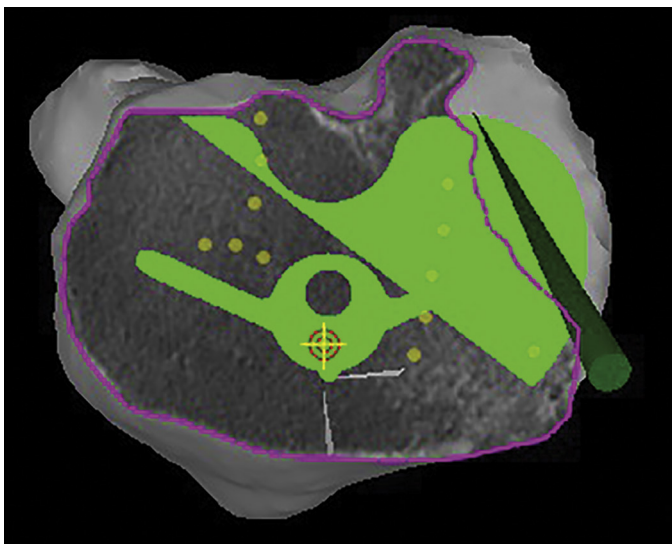


Figure 8.6 Example of a large posterior tibia osteophyte that can be visualized in situ with the use of the blunt probe. The position of the probe (green arrow) is visible on the screen, and thus the transition between the osteophyte and the plateau can be marked with electrocautery. In addition, the complete removal of the osteophyte can be validated.

SOFT TISSUE ANALYSIS AND BALANCING

Next is to include the soft tissue information to determine the definite component position of the tibia. After the described tibia (and/or femur) precut and complete removal of the osteophytes and contractions, the extension and flexion spaces are analyzed using a balancer, two laminar spreaders, or a spacer block. The navigation captures the space between the two bones and predicts the space heights and medial/lateral gaps (in mm) with the current prosthesis alignment.

The target of KA is to produce a perfectly symmetric and stable extension space. The flexion space is individual, with the lateral gap generally being looser than the medial gap and both gaps typically a little looser in flexion than in extension. In the authors' experience, the extension should be between 18 mm and 19 mm medial and lateral (for a 17-mm overall implant thickness). The medial aspect in flexion does usually match the extension by ± 1 mm. The lateral aspect in flexion ranges between 19 mm and 25 mm and is left that way.

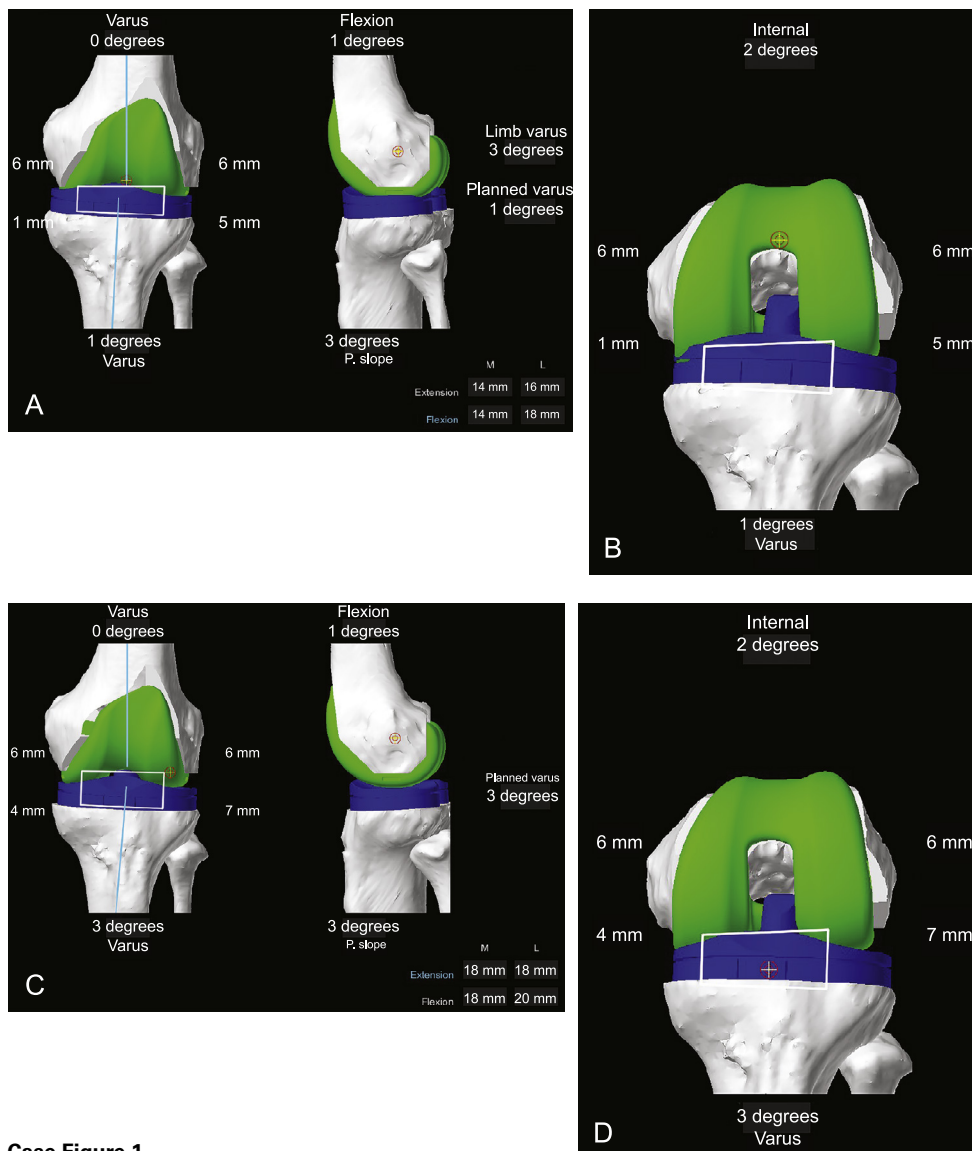
To achieve said parameters of a physiologically balanced knee, the position of the implants is adapted stepwise. In KA, the key parameter to adjust is the V-V orientation of the tibia resection. Adapting the slope can be used to adjust the flexion space. A reduction of the slope often becomes necessary when using a PS prosthesis and the flexion gap opens up after resection of the PCL. Care must be taken not to increase the slope to the natural situation, which has a higher risk of posterior tibial component overload that can cause early posterior subsidence or posterior insert wear.⁶ In the concept of KA, the distal and posterior femoral resections should not be increased to more than 6 mm on any occasion.

In this balancing context, attention must be drawn to a possible source of error. Depending on the technique used to capture it, the flexion space is often outputted to be a little tighter than the extension space in the system. Most surgeons evaluate the flexion by resting the knee on the lower leg. This results in more pressure on the flexion space because of the body weight and explains the displayed tightness. Thus, in most cases, these values do not represent an accurate measure of the natural flexion space laxity. Accordingly, the balancing should primarily focus on the extension space. Increasing the slope or posterior femoral resections is usually not necessary in those situations. If in doubt, the flexion space should be reevaluated with the trial prosthesis in place. Only if the gap is too tight at that point (pop out of tibia inlay or femur trail) which leads to pop out of the tibia inlay and/or the femoral trial component in flexion is the tibia slope adjusted, and never the posterior femur.

In the following, three specific cases are displayed to visualize some typical situations and "balancing" algorithms. Again, the basic principle in every decision is not to alter the natural anatomy as minimal as possible to carry out a true measured resection of the femur.

Case 1

In Case 1, the femur is planned strictly kinematically, with 6-mm distal and posterior resection on the femur. This results in a 0-degree orientation to the mechanical axis of the femur and 2-degree internal rotation with respect to the TEA (0 degrees to PCA, not displayed). On the tibia, a precut with 1-degree varus, 3-degree slope and 5-mm bone resection on the lateral plateau is planned and conducted. After resection of all osteophytes, the initial flexion and extension spaces are captured, as displayed in



Case Figure 1

the right bottom corner. This indicates that the medial extension gap is 2 mm tighter than lateral (14 mm vs. 16 mm). Also, the overall space height is 2 mm too short (Case Fig. 1A, 1B).

For balancing, adaptations of the tibia V-V orientation and resection level are made. First, the tibia is put in a 3-degree varus orientation to equal the medial and lateral extension gap. Then the tibia resection level is increased by 2 mm. This results in a symmetric 18-mm space in extension. In flexion the medial gap equals 18 mm which corresponds to the symmetrical extension gap. On the lateral side 20 mm demonstrate the physiological laxity which leads to a trapezoidal flexion gap (Case Fig. 1C, 1D).

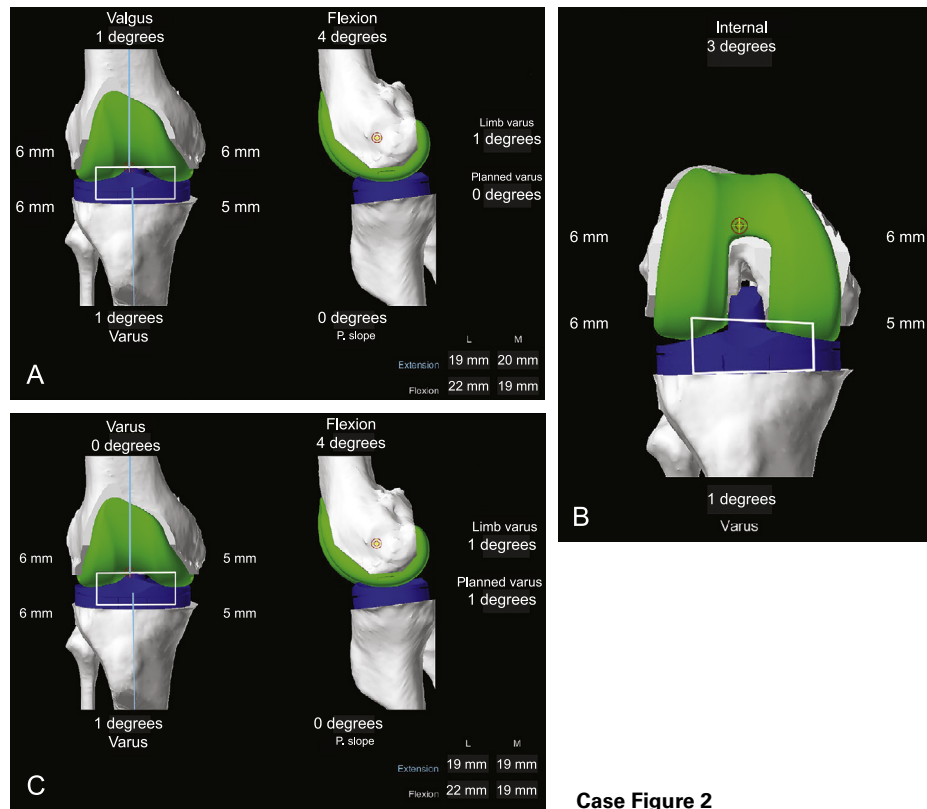
Case 2

Case 2 is pretty similar to Case 1: The femur is planned with 6-mm resections, resulting in 1 degree of valgus orientation and 3 degrees of internal rotation to the TEA. The tibia preplan is also with a 1-degree varus and 0-degree slope, based on the CT cross-sections. This results in a planned overall limb alignment of 0 degrees.

Now, the analysis of the gaps shows a 1-mm laxity of the medial compartment over lateral in extension. The flexion gaps already appear good. Interestingly, the overall limb alignment with the spreader in place is 1 degree of varus (displayed as “Limb Varus”)—so this should be the targeted alignment (Case Fig. 2A, 2B).

Several options are to be discussed for balancing the knee. First is to add 1 degree of varus to the tibia. This would balance the extension space to 20 mm and the flexion gaps to 22 mm laterally and 20 mm medially. If possible, the tibia resection level can be reduced by 1 mm or a higher inlay can be used. This would result in the desired 1 degree of overall varus (1 degree valgus femur, 2 degrees varus tibia).

In the case of a bone defect on the distal femur, the reduction of the medial distal resection by 1 mm is a valid option. This results in a 19-mm extension space, and a asymmetrical flexion space with 19 mm medially and 22 mm on the lateral side (Case Fig. 2C). Again, overall limb alignment results in 1 degree of varus.

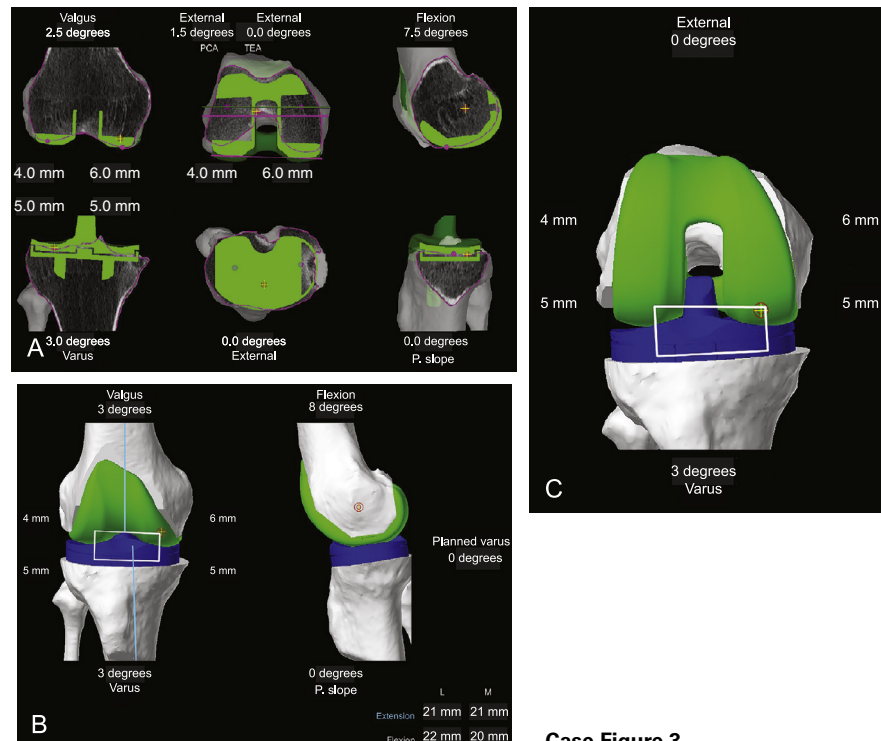


Case Figure 2

Case 3

Case 3 is an example for a typical overall valgus morphotype, but presenting with a varus OA. Planning this case purely on the bony anatomy would result in 5 degrees of valgus on the femur and 3 degrees of varus on the tibia (overall 2 degrees of

valgus). However, these patients very often have rather thick cartilage on the lateral compartment (3.5 mm in this example). Thus, the lateral resection is reduced. Interestingly, the trochlea orientation also becomes neutral with the reduction of the lateral resection, whereas the medial remains 6 mm (Case 3, Fig. 3A–C).



Case Figure 3

Based on this preplan, tibial cut is performed, posterior tibia osteophyte is removed, and gaps are evaluated. As displayed in Case Fig. 3B, 3C, with this alignment, extension space is already perfectly balanced; so is the flexion space (displayed 1 mm tighter than it actually is). The only criticism here is that the gaps are already a bit too loose, so that 2 mm less tibia resection would be desirable.

FINAL BONE CUTS, VERIFICATION CHECKS, AND TRIALS

After having finalized the virtual KA planning with optimal extension balance, the bone cuts are conducted with the assistance of the robotic arm. All femoral cuts are made, and the tibia recut, if necessary. Those that are learning use of the robot should check their bone resections with the aid of a caliper, to determine whether the plan was correct and accurately executed. All described verification checks are applicable according to the manual technique. In the measurements, it must be considered that the robotic saw blade is 2-mm thick, compared to 1.25 mm for saw blades in manual techniques. If any deviation from the planning is recognized, the prosthesis position can be adapted in the planning and a recut can be performed. Interesting is that not only recuts by increments of only 0.5 mm or 0.5 degrees are possible but one can also change the pivot point in case of angle correction. For example, if the medial resection is already perfect, the resection plane can be changed around this aspect. Or the slope can be rotated around a posterior point to only influence extension, or an anterior point to influence the flexion space.

Once all bone cuts have been made, the trial components are placed according to the plan. One trick is that the M-L position of the components, in addition to the tibia rotation, can be controlled with the CT-based navigation. With the use of the blunt probe, the desired position of the trials can be visualized on the planning screen. This again is a benefit compared to standard techniques by optimizing ML positioning of the femoral component and setting tibial rotation perfectly in line to the femoral component.

After insertion of the trial components, the balance can be rechecked and objectively evaluated with the navigation

software component of the robotic system. If an imbalance occurs, repositioning of the tibia can be conducted, as well as a recut, if necessary. The only parameters that are not controlled by the navigation are the A-P stability and rotation stability. Therefore, caliper measurement of the tibiofemoral offset, as described in the manual technique, can be used. For PS or medial pivot prostheses, this is of minor interest.

Summary

Of the currently available technologies to assist TKA, image-based robotic assistance appears to be a promising option for minimizing errors in KA. The key parameters are visible and can be controlled objectively. The workflow includes a three-dimensional analysis of the knee and a preoperative plan following the principles of KA. For a femoral component that is 8-mm thick distal and posterior, the femoral resections should be set to 6 mm on both the medial and lateral condyle after compensating for 2 mm of cartilage; component size is determined to best reconstruct anterior offset and the implant flexion is individually adjusted. The tibia planning is preliminary in terms of V-V orientation and resection height. It is adjusted intraoperatively to produce a stable and symmetric extension space. In the flexion space the natural laxity of the lateral compartment is accepted. The tibia slope is orientated to reproduce the native slope of the posterior aspect of the medial plateau. The KA-specific surgical workflow begins with additional mapping of the cartilage level onto the CT to fine-tune the resection levels to the individual situation. For final implant position and balancing, a tibia precut is conducted, osteophytes are removed with navigation control, and gaps are evaluated. All adaptations to balance the knee are made on the tibia side to achieve KA. Thus, the surgical protocol follows a hybrid approach with true measured resection on the femur and a gap balancing approach for tibia orientation, to create a stable and symmetrically balanced extension space. Different to other KA surgical techniques, the tibia is cut first in our robotic workflow, but this is only preliminary to ensure correct analysis of the soft tissue with computer assistance.

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Strategies for Improving Implant Design Based on Differences in Tibiofemoral Kinematics of a Low-Conforming Total Knee Arthroplasty Implanted With Calipered Kinematic Alignment and the Native Knee

MAURY L. HULL, PHD

CHAPTER OUTLINE

Overview

In Vitro Differences in Laxities and Resting Positions Between a Low-Conforming Total Knee Arthroplasty Implanted With Calipered Kinematic Alignment and the Native Knee Analyzed in the Same Cadaveric Knee

In Vivo Loading of the Posterolateral Rim of the Insert by Using a Low-Conforming Total Knee Arthroplasty Implanted With Calipered Kinematic Alignment During a Deep Knee Bend and Step-Up

Strategies for Improving the Femoral and Tibial Component Design for Use With Calipered Kinematic Alignment

Overview

This chapter reviews in vitro and in vivo differences in tibiofemoral kinematics between a low-conforming total knee arthroplasty (TKA) implanted with calipered kinematic alignment (KA) and the native knee. Kinematics are defined by laxities and resting positions of the tibia with respect to the femur, and the anterior-posterior (A-P) movements of the femoral condyles with respect to the tibia. Laxities are the translations and rotations that are measured under forces and moments applied to the tibia, respectively. The “resting position” is the position and orientation of the tibia relative to the femur without external load other than compression. The A-P movement of a femoral condyle is indicated by the change in position of the lowest point (actually closest point) of a femoral condyle with respect to the plane of the tibial baseplate. The low-conforming TKA is representative of the most common designs in use. The features are an insert with shallow medial and lateral concavities fixed to an asymmetrically shaped tibial baseplate, and a femoral component that retains the posterior cruciate ligament (PCL). The in vitro study showed that the low-conforming TKA exhibited greater anterior tibial translation and internal and external rotation at 30-degrees flexion and different resting positions than those of the native knee. The in vivo fluoroscopic study showed loading of the posterolateral insert rim by the prosthetic femoral condyle in 16% of TKAs, which

was partly caused by undercoverage of the posterolateral tibia by the baseplate and insert. A strategy for restoring anterior laxity and resting positions after excising the anterior cruciate ligament (ACL) is to use a medial ball-in-socket femoral component coupled with a 1:1 conforming medial insert concavity. A strategy for reducing the risk of posterolateral rim loading is to use an asymmetric baseplate that covers the posterolateral tibial resection, and an insert with a flat lateral surface without a rim that fully covers the baseplate.

In Vitro Differences in Laxities and Resting Positions Between a Low-Conforming Total Knee Arthroplasty Implanted With Calipered Kinematic Alignment and the Native Knee Analyzed in the Same Cadaveric Knee

Video 9.1 describes and shows the methods used to measure tibiofemoral laxities and resting positions.

A custom load application system measured eight laxities and four resting positions at five flexion angles in thirteen cadaveric knees during passive motion from full extension to 120-degrees flexion.¹ The eight laxities consisted of varus-valgus (V-V) and internal-external (I-E) rotations and A-P and compression-distraction (C-D) translations measured under prescribed loads of 5 Nm for V-V, 3 Nm for I-E, 45 N for A-P, and 100 N for C-D. A nominal 120-N compression force was applied by loading tendons to stabilize the knee during testing. Laxities and resting positions were measured first on the native knee and then after implantation of the low-conforming TKA using calipered KA, which enabled paired analyses between the two knee conditions within each specimen.

The low-conforming TKA implanted with calipered KA restored laxities comparable to those of the native knee with the exception of anterior translation and I-E rotation (**Fig. 9.1**). At 30 degrees flexion, the low-conforming TKA exhibited 2-mm more anterior laxity (**Fig. 9.1A**), 2 degrees more tibial internal rotation (**Fig. 9.1C**), and 4 degrees more external rotation (**Fig. 9.1D**) than those of the native knee.

The low-conforming TKA restored comparable tibial resting positions to those of the native knee with the exception of

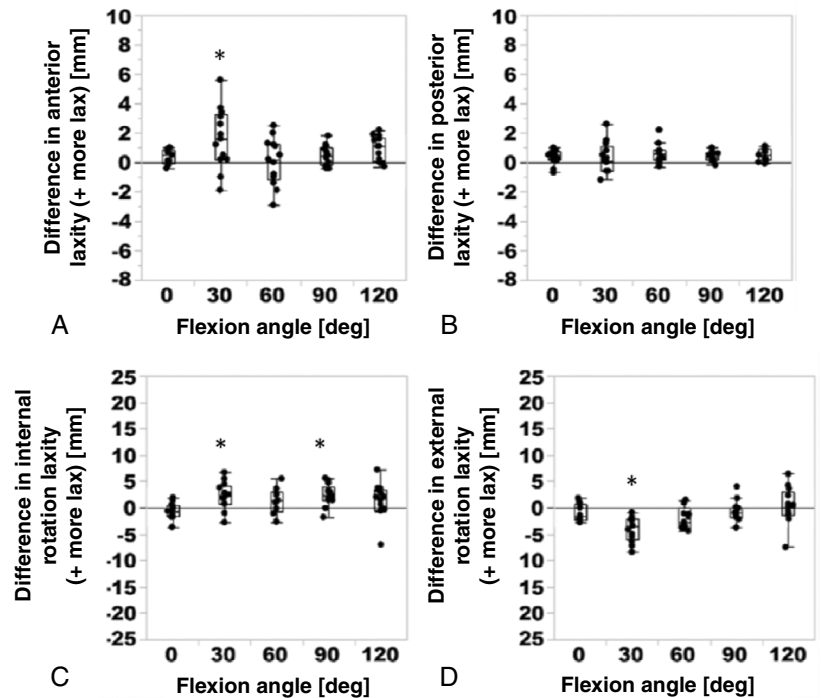


Figure 9.1 Box-and-whisker plots show differences in the anterior translation (A) and posterior translation (B) laxities and the differences in the internal rotation (C) and external rotation (D) laxities between calipered kinematically aligned total knee arthroplasty (TKA) using the low-conforming TKA and the native knee. The top and bottom of each box represent the 75th and 25th percentiles, respectively; the horizontal line inside each box represents the median; the upper and lower whiskers of each box extend to the highest and lowest values (excluding outliers), respectively. An asterisk indicates a statistically significant difference ($P < .05$).

anterior translation and I-E rotation (Fig. 9.2). The position of the tibia of the low-conforming TKA was 4 mm more anterior at 0-degrees flexion and 2 to 3 mm more posterior at 60-degrees (or more) flexion than the native knee (Fig. 9.2A). The rotation of the tibia of the low-conforming TKA was 4 degrees more internally rotated at 0-degrees flexion and 5 degrees more externally rotated at 30-degrees flexion than the native knee (Fig. 9.2B).

Hence, these results highlight the need for improved implant designs which better restore the anterior translation and I-E rotation laxities and resting positions closer to those of the native knee after calipered KA TKA.

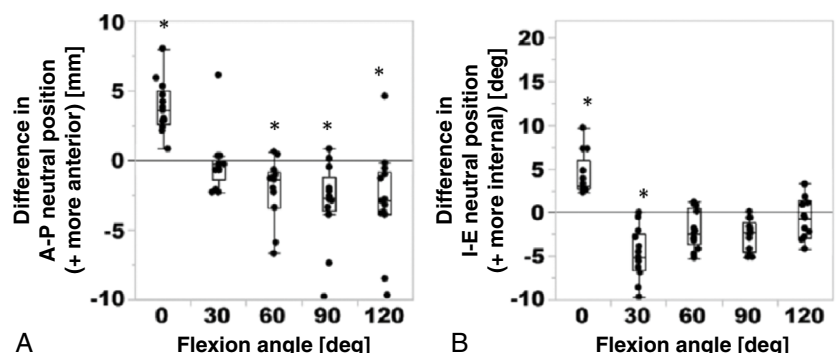
In Vivo Loading of the Posterolateral Rim of the Insert by Using a Low-Conforming Total Knee Arthroplasty Implanted With Calipered Kinematic Alignment During a Deep Knee Bend and Step-Up

Using single-plane fluoroscopic images, the in vivo A-P position of each prosthetic femoral condyle with respect to the plane of the tibial baseplate was determined in 25 patients during deep

knee bend and step-up.² The steps for determining the position required registration of three-dimensional models of the prosthetic femoral component and baseplate to the two-dimensional fluoroscopic image at 0 degrees, 30 degrees, 60 degrees, 90 degrees, and maximum flexion for the deep knee bend and at 0 degrees, 15 degrees, 30 degrees, 45 degrees, and 60 degrees for the step-up. Software computed the closest point of each femoral condyle to the plane of the baseplate. The closest point indicated the A-P position of a femoral condyle relative to the tibia. The A-P position of the prosthetic femoral condyle was standardized to the 53-mm A-P dimension of the midsized tibial baseplate. The occurrence of posterolateral rim loading was assessed after estimating tibial insert contact locations by adjusting the positions of the closest points to account for the curvature of the articular surfaces.³

There was a 16% incidence (4 of 25 patients) of the lateral femoral condyle loading the posterolateral insert rim, as three patients developed this loading during the deep knee bend and two patients (including one of three from the deep knee bend group) developed this loading during the step-up (Fig. 9.3). Loading of the posterolateral insert rim is undesirable because there is an increased short-term risk of posterior subsidence of the tibial baseplate and

Figure 9.2 Box-and-whisker plots show differences in (A) anterior-posterior (A-P) translation (B) internal-external (I-E) rotation neutral (i.e., unloaded resting) positions between calipered kinematically aligned total knee arthroplasty (TKA) using the low-conforming TKA and the native knee. The top and bottom of each box represent the 75th and 25th percentiles, respectively; the horizontal line inside each box represents the median; the upper and lower whiskers of each box extend to the highest and lowest values (excluding outliers), respectively. An asterisk indicates a statistically significant difference ($P < .05$).



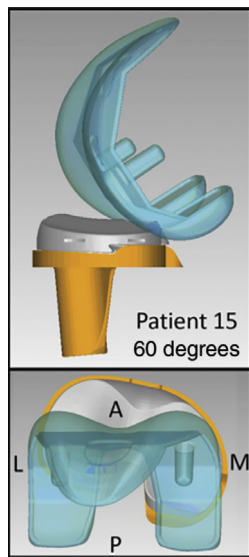


Figure 9.3 Image shows a lateral (top) and axial or superior view (bottom) of the position and orientation of the femoral and tibial components at 60 degrees of flexion of a typical patient with loading of the posterolateral insert rim. A, Anterior; L, lateral; M, medial; P, posterior.

an increased long-term risk of insert wear presenting as rotatory instability.⁴ Hence, these results highlight the need for an improved tibial component design that reduces the incidence of loading on the posterolateral insert rim after calipered KA TKA.

Strategies for Improving the Femoral and Tibial Component Design for Use With Calipered Kinematic Alignment

The differences in laxities and resting positions during in vitro passive motion between the low-conforming TKA implanted with calipered KA and the concerning incidence of posterolateral rim loading during an in vivo deep knee bend and step-up show the kinematic limitations of an insert with medial and lateral articular surfaces that fail to mimic the articular surfaces and soft tissue constraints of the native knee. In the medial compartment, a strategy for improving kinematics is the use of a ball-in-socket to mimic the stabilizing and centering functions of the concavity provided by the tibial articular surface, meniscus, and coronary ligament of the native knee.⁵⁻⁸ This component design constrains A-P motion of the medial femoral condyle and promotes pivoting, or I-E rotation, of the tibia about a medial axis that intersects slightly posterior to the center of the medial tibial plateau and that is roughly perpendicular to the native tibial joint line.^{5,9} Hence, a strategy for restoring anterior laxity and resting positions after excising the ACL is to use a medial ball-in-socket femoral component coupled with a 1:1 conforming medial insert concavity.

In the lateral compartment, a strategy needed to reduce the risk of posterolateral rim loading is to use an asymmetric baseplate that covers the posterolateral tibial resection, and an

insert with a flat lateral surface without a rim that fully covers the baseplate. The asymmetric design should allow the surgeon to perform a best-fit, so that when the largest-sized trial baseplate is set within and parallel to the cortical edge of the tibial resection, the A-P axis of the tibial component is accurately aligned parallel to the flexion-extension (F-E) plane of the native knee.¹⁰ KA uses the F-E plane instead of the tibial tubercle as the I-E rotation target because the mediolateral location of the tibial tubercle is too variable between knees.¹¹ In the in vivo study of 25 patients, the asymmetric tibial baseplate was designed to target the medial one-third of the tibial tubercle that averages 4 mm lateral to the F-E plane.¹¹ Hence, KA internally rotated the asymmetric baseplate relative to the tibial tubercle target, which increased the undercoverage of the posterolateral tibial resection. The undercoverage was exacerbated by a tibial insert that did not fully cover the baseplate in the lateral compartment. The average percentage of the A-P depth of the lateral tibia not covered by the insert was 15% for the 4 patients that had loading of the posterior insert rim and 10% for the 25 patients. An insert with a flat lateral surface and without a posterior rim is a promising design for reducing the risk of long-term insert wear, as it mimics the lack of constraint of the native knee, consisting of a slightly convex articular surface and a lateral meniscus that provides little constraint to A-P movement of the lateral femoral condyle because there is no counterpart to the coronary ligament.⁵

Summary

This chapter reviewed in vitro differences in kinematics between a low-conforming TKA implanted with calipered KA TKA and the native knee and used these differences to identify strategies for improving the implant design. The in vitro study showed that the low-conforming TKA did not restore anterior translation and I-E rotation laxities and resting positions over the full range of flexion to those of the native knee. These differences are related in part to the excision of the ACL and the low-conforming design of the tibial insert, which does not provide the constraints of the native knee, particularly those in the medial compartment. The in vivo fluoroscopic study showed a concerning 16% incidence of posterolateral loading of the insert rim during simple daily activities of bending the knee. A strategy for restoring anterior laxity and resting positions after excising the ACL is to use a medial ball-in-socket femoral component coupled with a 1:1 conforming medial insert concavity. A strategy for reducing the risk of posterolateral rim loading is to use an asymmetric baseplate that covers the posterolateral tibial resection, and an insert with a flat lateral surface without a rim that fully covers the baseplate.

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The contributions to this chapter by Josh Roth, who measured tibiofemoral laxities during his PhD dissertation research, and Stephanie Nicolet-Petersen, who discovered the occurrence of posterolateral rim loading during her MS thesis research, are gratefully recognized.

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Strategies for Improving the Prosthetic Trochlea Design Based on Differences in Trochlea Morphology Between Femoral Components Set in Kinematic and Mechanical Alignment and the Native Knee

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CHAPTER OUTLINE

Overview

Differences in Trochlear Morphology Between Four Femoral Components Set in Kinematic Alignment and the Native Knee

Differences in Trochlear Morphology Between Four Femoral Components Set in Kinematic Alignment and Mechanical Alignment

Strategies for Improving the Prosthetic Trochlear Design for Use With Kinematic Alignment

Overview

This chapter reviews differences between the morphology of the prosthetic trochlea for four different femoral components set in kinematic alignment (KA) and the native knee in the same femur-cartilage model. Trochlear morphology is described along the arc length of the native trochlea by the medial-lateral location of the trochlear groove, the radial distance of the trochlear groove from the flexion-extension (F-E) axis of the tibiofemoral joint, and the sulcus angle of the trochlea. Differences between the prosthetic trochlear morphology aligned in KA and the native trochlea were generally consistent for all four femoral components. Differences were a more proximal extension of the prosthetic trochlea, several centimeters above the native trochlea; a more lateral location of the prosthetic groove proximally and a more medial location distally, understuffing as indicated by a lower radial distance for the prosthetic trochlear groove than the native knee; and a prosthetic sulcus angle that differed particularly at the extremes of the arc of the trochlear groove. Owing to these differences, in conjunction with the wide variability in the medial-lateral location of the native trochlear groove and in the Q-angle, strategies for improving the prosthetic trochlea for use in KA are to widen the proximal trochlea laterally, orient the groove so that it is more lateral proximally, and widen the groove proximally. Additional strategies are

to increase the radial distance of the trochlear groove from the F-E axis to correct understuffing and steepen the sulcus angle, particularly inferiorly, to provide more definitive patellar tracking.

Differences in Trochlear Morphology Between Four Femoral Components Set in Kinematic Alignment and the Native Knee

To quantify differences in trochlear morphology between femoral components set in KA and native femurs, 10 three-dimensional (3D) femur-cartilage models were created by combining computed tomography (CT) scans and laser scans of native human cadaveric femurs.¹ Four different femoral components were kinematically aligned on each 3D femur-cartilage model.^{1,2} The four femoral components were Persona (Zimmer-Biomet, Warsaw, IN), NexGen (Zimmer-Biomet, Warsaw, IN), Vanguard (Zimmer-Biomet, Warsaw, IN), and GMK Sphere (Medacta, Castel San Pietro, Switzerland). The latter design differed from the other three designs in that the prosthetic trochlea interfaced with an anatomic patellar implant, whereas the other three trochlear designs interfaced with modified dome (i.e., sombrero hat) patellar implants.

Measurements of the prosthetic and native trochlea were made along the arc length of the native trochlear groove. The best-fit of a cylinder to the cartilage surface of the medial and lateral femoral condyles of the 3D femur-cartilage model established a coordinate system (Fig. 10.1). Eleven cross-sections of the 3D femur-cartilage model were constructed at 10% increments along the arc length of the native trochlear groove by rotating about the axis of the cylinder (Fig. 10.2). These cross-sections were propagated onto the prosthetic trochlea, and tracings of the native and prosthetic trochlea were generated (Fig. 10.3). The deepest point represented the groove, and the two highest points on the medial and lateral facets represented the boundary of the sulcus. These three points were used to characterize the morphology of the trochlea by determining the medial-lateral and radial locations of the groove, and the sulcus angle.

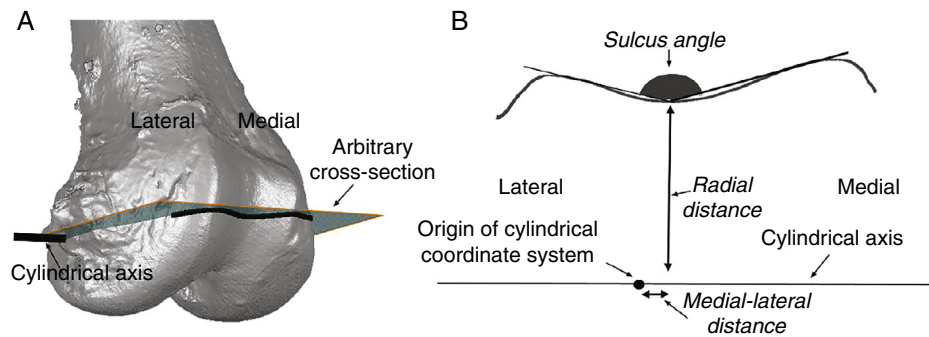


Figure 10.1 Diagrams illustrating the three dependent variables used to characterize the morphology of the trochlea. (A) A three-dimensional distal femur-cartilage model with the cylindrical axis and an arbitrary cross-section passing through the trochlea. The cylindrical axis is the axis of coaxial cylinders best fit to the posterior articular surfaces of the femoral condyles from 10 degrees to 110 degrees of flexion. (B) An outline of the articular surface of the trochlea for an arbitrary cross-section and the three dependent variables used to describe trochlear morphology. The three dependent variables are the medial-lateral location of the trochlear groove measured as the medial-lateral distance from the midpoint of the cylindrical axis (medial positive), the radial location of the trochlear groove measured as the radial distance from the cylindrical axis to the trochlear groove, and the sulcus angle of the trochlea. The dependent variables were determined at 11 cross-sections in 10% increments along the arc length of the native trochlear groove. An arbitrary cross-section is shown for illustrative purposes.

For all four femoral components, mean medial-lateral locations of the prosthetic groove were within 2.5 mm of native (Fig. 10.4). However, the paths of the trochlear grooves differed; the prosthetic groove was a straight line when unwrapped and projected onto the coronal plane, whereas the native groove curved with a lateral bulge (Fig. 10.5). As a result, the prosthetic groove was more lateral than native proximally between 0% and 30% of the arc length and more medial than native beyond about 30% of the arc length. Mean radial locations of the prosthetic groove were as large as 5-mm less than native. Sulcus angles of the prosthetic trochlea were steeper than native proximally and flatter than native distally for three of the four femoral components. For one femoral component (Vanguard), the sulcus angle was flatter than native over the full arc length.¹ The general consistency in differences from native observed for the four femoral components highlights the need to reassess the design of prosthetic trochleae for use in KA.

Differences in Trochlear Morphology Between Four Femoral Components Set in Kinematic Alignment and Mechanical Alignment

Because KA sets the femoral component in a mean of 4.6-degrees more valgus and 2.8-degrees more internal rotation than mechanical alignment (MA),¹ the alignment method that restores the trochlear morphology closer to native is of interest. For MA, the femoral component was set with 0-degrees flexion, the varus-valgus was set perpendicular to the mechanical axis of the femur and internal-external rotation was externally rotated 3 degrees about the medial femoral condyle. For KA and MA, the differences in the medial-lateral and radial locations of the groove and sulcus angle between the prosthetic trochlea minus the native trochlea were computed at each percent of arc length

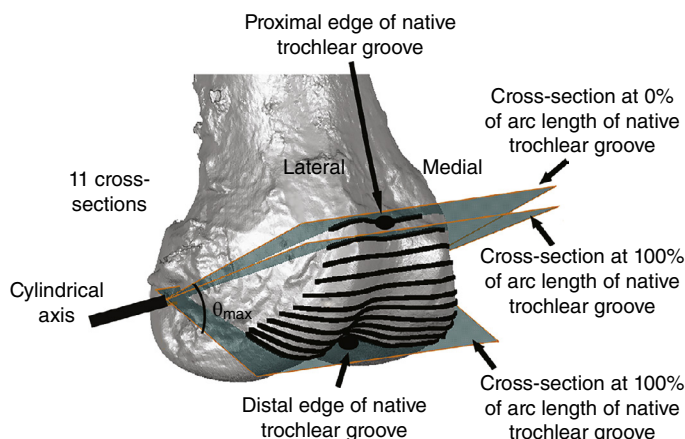


Figure 10.2 Image showing the relationship of 11 cross-sections along the arc length of the native trochlear groove with respect to the cylindrical axis on an oblique view of the three-dimensional femur-cartilage model. The 0% cross-section was set coincident to the proximal edge of the trochlear groove, and the 100% cross-section was set at the most distal edge. Not shown are the projections of the cross-sections for prosthetic trochleae.

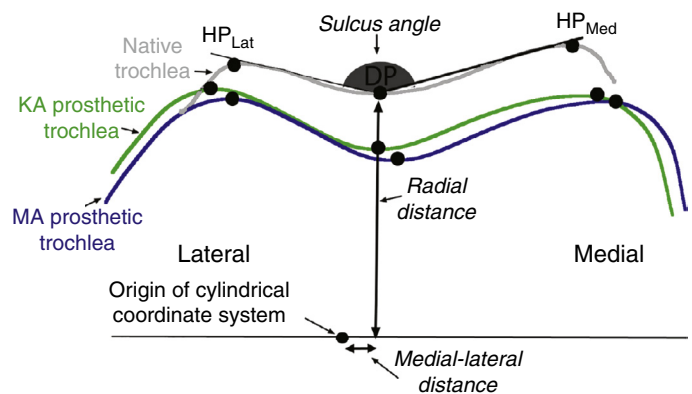


Figure 10.3 Diagram of a representative cross-section of the distal femur showing the relationship between tracings of the articular surface of the native trochlea (gray), kinematically aligned (KA) prosthetic trochlea (green), and mechanically aligned (MA) prosthetic trochlea (blue). The landmarks of the deepest point of the groove and the highest point (HP) of the medial and lateral facets (only shown on the native trochlea) were used to determine the medial-lateral and radial distances of the groove and the sulcus angle of the trochlea for the native and prosthetic femurs. The medial-lateral distance was positive in the medial direction.

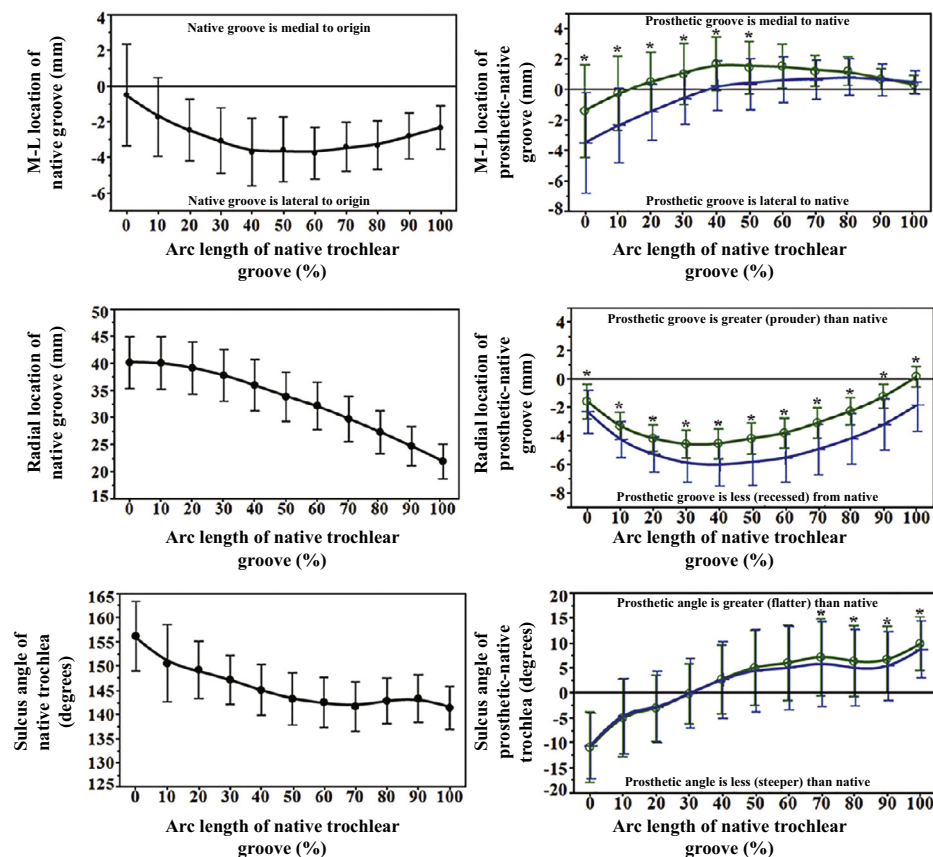


Figure 10.4 Series of representative graphs showing the mean $\pm$ one standard deviation for the native trochlea and for differences between prosthetic and native for kinematic alignment (KA) (green lines) and mechanical alignment (MA) (blue lines) in the medial-lateral and radial locations of the groove and sulcus angle at intervals from 0% to 100% of normalized arc length of the native trochlear groove for an example femoral component (Medacta GMK Sphere). The horizontal lines at 0 mm and 0 degrees represent the baseline for no difference from native. The values denoted by an * indicate significant differences between KA and MA ($P < .05$). M-L, Medial-lateral.

of the native groove. In general, KA resulted in smaller differences from native than MA for all four femoral components (Fig. 10.4). The mean medial-lateral location of the MA prosthetic trochlear groove was more lateral than that for KA along the arc length from 0% to 20% and deviated up to 6 mm lateral from native at 0%. The mean radial locations for MA were more recessed from native than KA over the full arc length. Sulcus angles compared closely between MA and KA.

The difference in the varus-valgus rotation and not the difference in internal-external rotation between the two alignment methods explains the difference in the medial-lateral location of the prosthetic trochlear groove. Proximally, the MA prosthetic groove was more lateral than the KA prosthetic groove because MA sets the femoral component in ~ 5 degrees more varus than the native distal femoral joint line, whereas KA restores the distal joint line. The MA prosthetic groove location more lateral than the native groove at the 0% cross-section is nonanatomic, which makes the prosthetic groove oblique to the native groove (Fig. 10.5).

Strategies for Improving the Prosthetic Trochlear Design for Use With Kinematic Alignment

Variances in the native trochlea morphology and differences in morphology between the KA prosthetic trochlea and native trochlea provide strategies for improving the trochlea design

of the femoral component. First is the wide variability in the medial-lateral location of the native groove and the wide variability in the Q-angle referenced to the line of action of the rectus femoris. The standard deviation in the medial-lateral location of the native groove was 3 mm (Fig. 10.4), which translates to limits of ± 6 mm to include 95% of the population. The orientation of the Q-angle referenced to the rectus femoris has a mean of 6.5 degrees and a standard deviation of 6.5 degrees,³ so that approximately 95% of the population would be included in the range -6.5 degrees to 19.5 degrees.

A second consideration is the articular shape of the patellar implant. At least six different types of patellar implant designs are in use.⁴ The polyethylene modified dome interfaced with three of the femoral components studied, and an anatomic patellar implant interfaced with the fourth femoral component. Hence design considerations should include the interface between the patellar implant design and the prosthetic trochlea morphology.

To manage the variability noted above, a comprehensive strategy regardless of patellar implant design is to optimize the length, shape, and groove orientation of the prosthetic trochlea for KA. Regarding the length, a design feature is that the prosthetic trochlea of all four femoral components extends several centimeters proximal to the most superior cross-section of the native groove (Fig. 10.5). This extension is necessary to promote early engagement of the patella. Regarding the shape and orientation, less varus alignment of femoral components in KA

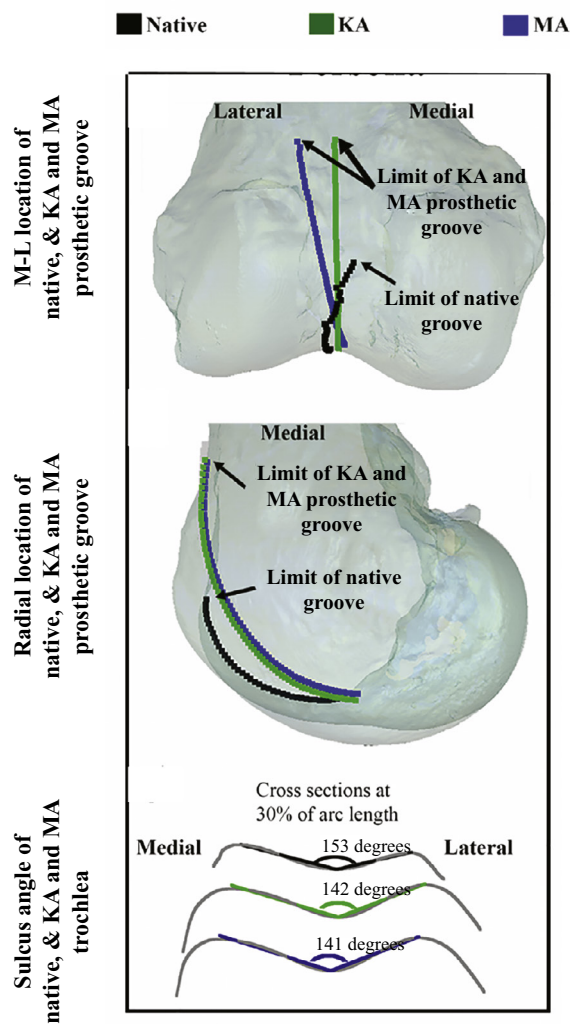
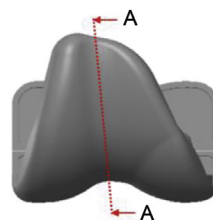


Figure 10.5 Images of a representative knee shows tracings of the medial-lateral (M-L) and radial locations of the groove and sulcus angle of the native trochlea (black), and the kinematically aligned (KA) (green) and mechanically aligned (MA) (blue) prosthetic trochlea for an example femoral component (Persona, Zimmer-Biomet, Warsaw, IN). Note that the prosthetic trochlea extends several centimeters above the most proximal point of the native groove, that the path of the prosthetic groove is straight whereas the path of the native groove is curved with slight lateral bulge, and that the radial distance of the prosthetic groove is understuffed.

versus MA changes the orientation of the path of the groove (Fig. 10.5) and reduces the lateral reach.⁵ Accordingly, the proximal trochlea should be widened laterally and the groove should be widened proximally to accommodate the wide variability in the medial-lateral location of the native groove and Q-angles to capture and contain the patella⁶ (Fig. 10.6). The width of the groove should gradually narrow distally (Fig. 10.6) to accommodate for the variability of patellar tracking. The prosthetic groove should be oriented more laterally, similar to the orientation achieved for MA femoral components when aligned in greater external rotation (Fig. 10.5). Particularly, the design should address the challenging anatomy of the valgus knee with a large Q-angle, which requires a lateral groove location proximally to reduce the risk of lateral patellar subluxation, a complication difficult to treat.⁷

Observing that the mean radial location of the prosthetic groove was recessed with respect to the native groove (Fig. 10.4),

Prosthetic trochlea designed for mechanical alignment



Prosthetic trochlea designed for kinematic alignment

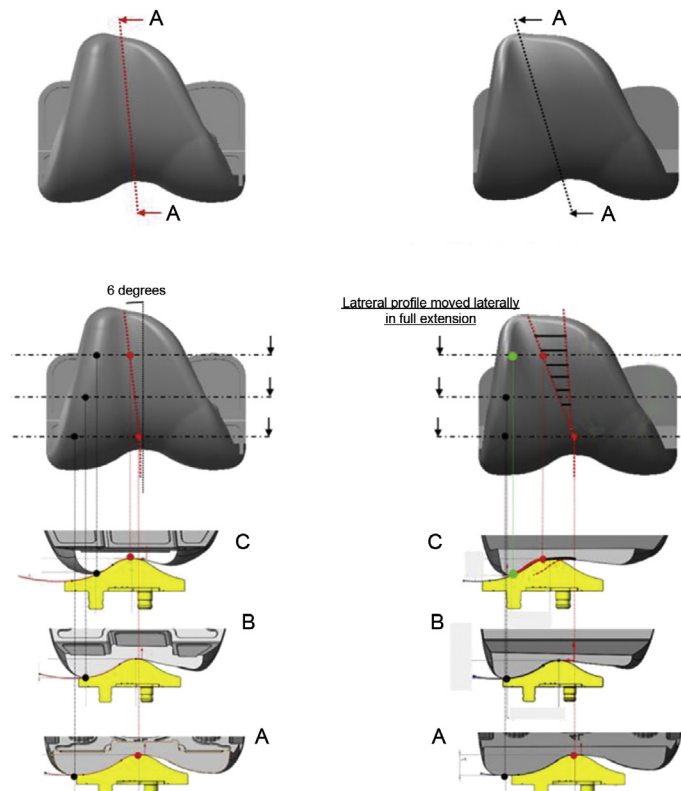


Figure 10.6 Schematic shows the prosthetic trochlea designed for mechanical alignment (left) modified into one for kinematic alignment (right) by lateralizing the proximal trochlea, widening the proximal trochlea, lateralizing the groove, and widening the groove to accommodate for kinematically aligned positioning of the femoral component in the valgus knee and the wide variability in the medial-lateral location of the groove and Q-angle.

increasing the radial distance of the prosthetic groove from the cylindrical axis is a strategy for enabling a femoral component to be used in KA to better restore the native trochlear groove. If the patella is not resurfaced, then more closely restoring the radial location of the prosthetic groove to native would have the biomechanical advantage of increasing the moment arm of the quadriceps muscle force by radially translating the patella farther away from the center of rotation of the knee, which lowers the quadriceps muscle force needed to develop an extension moment and decreases the patellofemoral joint compressive force. However, overstuffing the prosthetic patellofemoral joint should be avoided because this can lead to complications such as decreased flexion⁸ and patellar maltracking.⁹ Given the differences in prosthetic patellae types across the industry, ranging from domes to more anatomic shapes, each manufacturer would have to achieve the proper balance between gaining biomechanical advantage of the quadriceps without risk of complications caused by overstuffing.

The substantive differences in the prosthetic sulcus angles from native (Fig. 10.4) for all four femoral components studied indicates that improvements might be warranted, particularly later in the arc. For all four femoral components, the prosthetic sulcus angle was steepest proximally and gradually got flatter with increasing arc length. A steeper angle proximally would promote engagement of the patella early in flexion, which might be

important to reduce the risk of patellar subluxation/dislocation for a prosthetic in which the groove is recessed relative to native (i.e., patellofemoral joint is understuffed). For three of the four femoral components, the pattern was similar to that in Fig. 10.4, where the angle was steeper than native at the 0% cross-section and transitioned to being flatter than native in the 30% to 40% region of the arc length. For one femoral component (Vanguard), however, the angle was about equal to native at the 0% cross-section and steadily became flatter with increasing arc length. Because a steeper angle guides the patella more definitively, making the sulcus angle steeper past about 30% of the arc length is a strategy to improve patellar tracking over the full arc length.

Summary

This chapter reviewed previous studies that determined differences between the morphology of the prosthetic trochlea set in KA and native. These differences were used to identify

strategies for improving the design of the prosthetic trochlea for use in KA. Based on these differences, it may be advantageous to design a femoral component for use in KA with (1) the proximal trochlea widened laterally; (2) the path of the groove oriented more laterally proximally and the groove widened proximally, gradually decreasing in width distally; (3) the radial distance increased from the cylindrical axis to limit understuffing and gain more mechanical advantage from the quadriceps muscles; and (4) the sulcus angle steepened in the distal 60% of the arc length of the groove to provide more definitive patellar tracking.

Acknowledgment

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Advantages of Kinetically Aligned Total Knee Arthroplasty: A Biomechanical Perspective

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CHAPTER OUTLINE

Overview

Gait Analysis Studies

Computer Simulation Studies

Cadaveric Studies

Fluoroscopic Two- and Three-Dimensional Shape-Matching Analysis

Overview

The fundamental principle of calipered kinematically aligned total knee arthroplasty (KA TKA) is to reproduce the flexion-extension axis of the prearthritic knee and to maintain the original collateral ligament balance and joint line with controlled, symmetric bony resection.¹ A growing number of articles suggest that modification of the conventional neutral mechanical alignment (MA) strategy toward a more native kinematic alignment (KA) strategy with preservation of the original joint line and rotational axis of the knee is required to achieve better functional performance after TKA.^{2,3} Recent systematic reviews and meta-analyses comparing KA TKA to MA TKA have indicated that the short-term outcomes of KA TKA are comparable or superior to those of MA TKA.^{4,5} Moreover, long-term clinical outcome and survivorship have been reported to be promising at 10 years after KA TKA.⁶

Although evidence of better patient satisfaction after KA TKA has recently been published, biomechanical evidence justifying superiority of KA TKA over MA TKA remains limited. The fundamental reasons why a strategy to restore the patient-specific joint line, rotational axis, and ligament balance, otherwise designated as ‘kinematic alignment,’ is superior to traditional MA should be clarified from the biomechanical perspective. To date, numerous biomechanical studies have tried to assess the beneficial effects of KA TKA. Some of these articles compared KA TKA to MA TKA and others to nonimplanted native knees. Biomechanical approaches for measuring knee kinematics are roughly classified into five types: (1) gait analysis based on skin markers,^{7–11} (2) roentgen stereophotogrammetry,^{12–15} (3) computer simulation,^{16–19} (4) in vivo fluoroscopy,^{20–25} and (5) the measurement of contact stress or ligament strain in situ using cadaveric knees. Regardless of the methodology, all studies were conducted with the assumption that kinematic differences between implanted knees and native knees might play a role not only in objective clinical outcomes such as loosening

or wear but also in variance in patient satisfaction following TKA.²⁶ Currently, an increasing number of surgeons are adopting a KA strategy, many with various modifications to alignment, joint line, and soft tissue balance. It is important therefore for surgeons to understand the biomechanical differences in both kinematic and kinetic profiles between KA TKA, MA TKA, and native knees. This chapter provides readers with the pertinent information necessary to understand KA TKA kinematics and kinetics.

Gait Analysis Studies

Skin marker-based stereophotogrammetry is the most widely used technique for gait analysis after TKA. To date, there have been several studies dealing with gait analysis of KA TKA. Among these studies, various surgical techniques were used for KA TKA, as well as different referent controls. Blakeney et al.²⁷ reported the results of gait analysis of 45 restricted KA (rKA) TKAs versus 45 MA TKAs performed using an optical computer navigation system and calliper measurements of resected bone. By study design, the rKA-TKA arm was limited to bone cuts in the coronal plane within 5 degrees of the neutral mechanical axis and a final hip-knee-ankle (HKA) angle that was within 3 degrees of neutral alignment. Most gait parameters in the rKA TKA group more closely resembled those of normal knees than did those in the MA TKA group. Knee adduction angles and knee external rotation angles were significantly smaller in KA TKA than in MA TKA. Increased external rotation of the tibia in MA TKA is problematic, as it may reflect a pivot-shift avoidant gait because of the absence of the anterior cruciate ligament (ACL) following TKA, as noted by another investigator.²⁸ McNair et al.²⁸ compared gait profiles of 14 KA TKAs performed using patient-specific instrumentation with those of 15 MA TKAs performed with optical computer navigation. With respect to knee kinetics in the sagittal plane, KA TKAs tended to exhibit larger knee flexion moments than MA TKAs, whereas in the coronal plane, the knee adduction moment (KAM) was comparable between the two types of TKAs. In the transverse plane, the internal rotation moment was smaller in KA TKAs.

It is noteworthy that a comparative analysis of the KAM between KA TKA with an average –3-degrees HKA and MA TKA with an average 0-degrees HKA revealed significantly larger KAM in KA-TKA than in MA TKA.²⁹ Generally, varus component alignment has been assumed to increase external KAM. Moreover, when the effects of joint line obliquity were neglected, varus limb alignment substantially increased medial contact stress, in addition to KAM, suggesting that reproducing constitutional varus alignment might lead to a risk of premature loosening of the tibial component.³⁰ Actually, limb alignment

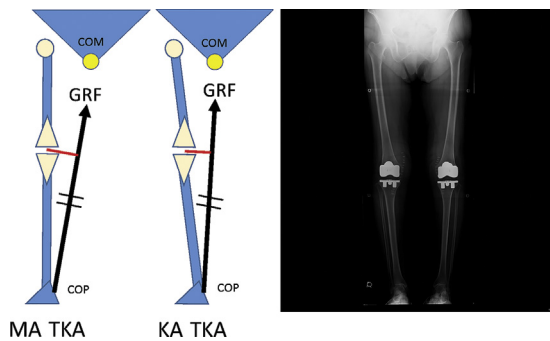


Figure 11.1 Left: Schematic representation of bilateral leg standing after kinematically aligned (KA) and mechanically aligned (MA) total knee arthroplasties (TKAs). Lever arm and direction of ground reaction force (GRF) are depicted. The line connecting the center of pressure (COP) and the center of mass (COM) indicates putative GRF. The lever arm of GRF is shorter in KA TKA than in MA TKA. Right: Representative radiograph of KA TKA. As in the left panel, the joint line is parallel to the ground, and the COP is medially positioned. Consequently, the lever arm of GRF becomes short and knee adduction moment is reduced, despite slight varus limb alignment.

and joint line obliquity should be considered independently when the effects of these elements on KAM are discussed. According to our previous study, varus joint line orientation substantially decreased KAM and thus any increase in KAM induced by reproducing constitutional varus alignment may be canceled after KA TKA.³¹ In another study, Yeo et al.³² performed a series of robotic-assisted TKAs using a version of rKA concepts. Component alignment for the medial proximal tibial angle (MPTA) was set to 2 degrees, and the lateral distal femoral angle was also set at 2 degrees, with 2 degrees of internal rotation relative to the transepicondylar axis. At a minimum of 8 years' follow-up, gait analysis revealed that knee varus angle and medial-lateral ground reaction force (GRF; i.e., horizontal GRF) were significantly reduced in KA TKA compared with MA TKA. These results corroborated our theory that a medially inclined joint line after KA TKA orients the joint line parallel to the ground so that the center of pressure (COP) is more medial (Fig. 11.1). This results in the center of mass (COM)-COP line becoming oriented more vertically relative to the ground, and the length of the lever arm to the knee center and horizontal GRF becoming smaller than with MA TKA. This mechanism is more evident during single-leg stance (e.g., walking or running) (Fig. 11.2) resulting in a KAM that is ultimately reduced.³³ In addition to joint line obliquity, step width during gait affects the location of the COP and subsequently the KAM. Step width was reported to be related to balance control in elderly patients³⁴ and dull anticipatory postural control by dorsal muscles, when postural instability was experimentally induced by lateral perturbations of the pendulum.³⁵ As step width increases with increasing age,³⁶ elderly patients having unstable trunk balance may favor MA TKA in which step width is relatively wide, to maintain the joint line parallel to the floor.

Computer Simulation Studies

Blakeney et al.³⁷ performed bone resection simulation on 1000 knee computed tomography (CT) scans from a database using an rKA TKA protocol and compared the results to an MA TKA resection protocol. On the three-dimensional planning software, the study calculated bone resection thicknesses and resulting soft tissue imbalances throughout the knee range of

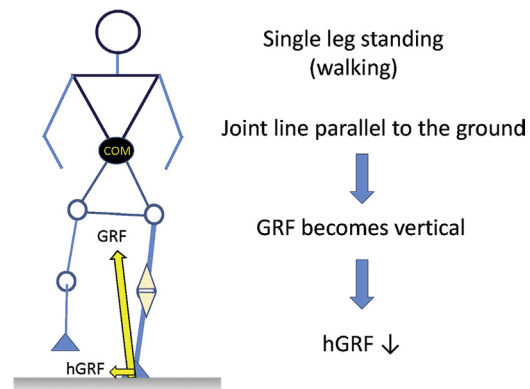


Figure 11.2 Schematic representation of single-leg standing after kinematically aligned total knee arthroplasty. Joint line is parallel to the ground, and the center of pressure (COP) of single-leg standing is more medially positioned than that of bilateral leg standing. Knee adduction moment and horizontal ground reaction force (hGRF) are decreased. COM, Center of mass.

motion from full extension to maximum flexion for both techniques. The results indicated that knees with less than 3 mm of imbalance in any plane could be obtained in 92% of rKA TKA knees versus only 49% of MA TKA knees. Similar results for MA TKA simulation were reported in the past studies.^{38,39} Kang et al.⁴⁰ conducted a computer simulation of the stance-phase gait and deep knee bend and evaluated mechanical forces applied on KA and MA TKAs. The results indicated that the forces on the medial collateral ligament in KA TKA were lower than those in MA TKA and the maximum contact stress on the medial polyethylene insert in KA TKA was lower than that in MA TKA. However, two separate computer simulation studies proposed contradictory results. Ishikawa et al.⁴¹ reported that greater femoral rollback and more internal rotation of the tibia were observed with KA TKA than with MA TKA, but patellofemoral and medial tibiofemoral contact stresses were increased with KA TKA. Chen et al.⁴² simulated biomechanical loads and long-term wear volume after 10-million cycles of knee extension/flexion. They reported that peak medial tibiofemoral contact stresses were increased by 8.2%, whereas overall wear volume was decreased by 5.5% in KA TKA, compared with MA TKA. In addition, patellofemoral contact stress was increased by 40% in KA TKA. They concluded that there were no noticeable advantages in KA TKA from the biomechanical perspectives.

Cadaveric Studies

Roth et al.⁴³ performed KA TKAs in 13 cadaveric knees using manual instruments, without soft tissue release. The tibial forces and femorotibial contact positions were measured using a custom tibial force sensor. After KA TKA, net posterior translation of the contact point of the lateral femoral condyle on the lateral tibia was sufficient for deep knee flexion, and average differences in tibial contact stresses between compartments were small and similar to the native knee, despite the variance of the joint line from neutral in the coronal plane. This paper substantially contradicts the markedly increased medial contact stresses reported by a few computer simulation studies,^{41,42} suggesting that perhaps the computerized software may not have accurately modeled all the complex forces acting on the knee. The same investigators further analyzed knee kinematics on

the premise that shapes of articular surface geometry should match soft tissue tension, otherwise kinematic conflict may occur after TKA. So they compared knee laxities and neutral positions between three conditions: native, ACL-deficient, and KA TKA.⁴⁴ The largest difference in laxity found in the KA TKA knees versus the native knees averaged 1.6-mm anterior translation at 30-degrees flexion. At 0-degrees flexion, the tibia was 3.8 mm and 1.2 mm more anterior to the femur in the KA TKA knee than in the native knee and ACL-deficient knee, respectively, which highlights the limitation of current ACL-resecting TKA designs. Koh et al.⁴⁵ tested seven pairs of cadaveric knees. One knee in each pair was randomly assigned to KA-TKA and the other to MA-TKA. The results indicated that KA TKA better restored femoral rollback and varus soft tissue tension when compared with the contralateral MA TKA, and better maintained medial pivot motion with less paradoxical motion of the medial femoral condyle.

Fluoroscopic Two- and Three-Dimensional Shape-Matching Analyses

Nicolet-Petersen et al.⁴⁶ assessed in vivo anterior-posterior (A-P) tibial contact locations of KA TKA knees using a two- and three-dimensional (2D-3D) fluoroscopic model and compared the data with the patient's healthy contralateral native knees. Some 25 patients underwent calipered KA TKA with controlled bony resection. With the knee in 0 degrees of flexion, the mean A-P tibial contact locations of the KA TKA knees were 4 mm more posterior in the medial compartment and 7 mm more posterior for the lateral compartment than those of the native knees, which is a nearly identical result to that reported by Roth et al.⁴⁴ Murakami et al.⁴⁷ analyzed the dynamic coronal orientation of the tibial component and the joint line over the stance phase of gait by using the 2D-3D shape-matching technique. The study compared joint line orientation relative to the

floor between 3 degrees of KA TKA knees and MA TKA knees. The lateral tilt of the joint line was smaller in KA TKA, accommodating 3 degrees more varus inclination than in MA TKA. The results indicated that 3 or more degrees of medial inclination of the joint surfaces are needed to keep parallel to the ground during the stance phase of gait, which supports the gait analysis data reported by Blakeney et al.³⁸

Summary

A growing amount of evidence favoring KA TKA over MA TKA is being accumulated. Articles not in favor of KA TKA are few. In current biomechanical studies, both MA TKA knees and native-aligned knees serve as controls, with few, if any, papers comparing KA to balanced gap techniques. One of the key findings has been that coronal joint line inclination of the tibia (MPTA <87 degrees) alone does not seem to increase KAM and medial contact stress, and overall varus limb alignment is at risk of increasing KAM.

Some surgeons perform rKA TKA in their clinical practice, limiting the LDFA (lateral distal femoral angle) and MTPA to parameters that maintain a neutral or nearly neutral HKA and limited varus in the coronal plane. However, the appropriate boundary condition for a varus tibial cut relative to the mechanical axis should be based on a comprehensive biomechanical perspective and not arbitrary alignment parameters. Further, although the femorotibial contact position and loads of TKA components in the sagittal plane indicated that KA TKA is much closer to the native knee than MA TKA, the anterior translation of the tibial component in the sagittal plane still evident in KA TKA knees when fully extended because of ACL deficiency suggests that there are still opportunities for improvement. Further studies are warranted to determine whether a bicruciate-retaining TKA design will provide a closer match to natural kinematics and whether an intact ACL will function properly in such TKA designs.

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Calipered Kinematically Aligned Total Knee Arthroplasty Closely Restores the Tibial Compartment Forces of the Native Knee

MAURY L. HULL, PHD

CHAPTER OUTLINE

Overview

In Vitro Tibial Compartment Forces During Passive Motion in the Calipered Kinematically Aligned Total Knee Arthroplasty and Native (i.e., healthy) Knee

Description of Custom Tibial Force Sensor and Methods

Results and Comparison With Native Knee

Intraoperative Tibial Compartment Forces During Passive Motion in the Calipered Kinematically Aligned Total Knee Arthroplasty

Description of Commercially Available Tibial Force Sensor and Methods

Results, Comparison With Native Knee, and Comparison With Mechanical Alignment

Overview

Tibial forces in the medial and lateral compartments following calipered kinematically aligned (KA) total knee arthroplasty (TKA) are of high interest for two reasons. One reason is that knowledge of the tibial compartment forces provides a quantitative indication of how well the goal of restoring biomechanical variables characterizing knee function to native has been achieved. A second is that differences in tibial forces between the medial and lateral compartments serve as an indicator of soft tissue “balancing.” This chapter summarizes the methods and results from two studies, one that measured in vitro tibial compartment forces of a calipered KA TKA during passive motion and another that measured intraoperative tibial compartment forces during passive motion. These results are compared with those of a third study, which measured in vitro tibial compartment forces in the native knee during passive motion. Based on these comparisons, the chapter demonstrates that patient-specific alignment of the limb, knee, and joint lines inherent to KA TKA, in conjunction with the verification checks used in calipered KA TKA, closely restore tibial compartment forces and the balance (i.e., difference) between tibial compartment forces to native, without ligament release.

In Vitro Tibial Compartment Forces During Passive Motion in the Calipered Kinematically Aligned Total Knee Arthroplasty and Native (i.e., healthy) Knee

[Video 12.1](#) describes and demonstrates methods used to measure tibial compartment forces during passive motion in vitro.

DESCRIPTION OF CUSTOM TIBIAL FORCE SENSOR AND METHODS

To measure tibial compartment forces in vitro, a unique custom tibial force sensor was developed.^{1,2} The sensor replaced the tibial component (i.e., baseplate and insert) and measured the tibial forces and their locations (i.e., centers of pressure) independently in the medial and lateral compartments over the full area of the articular surfaces. The root mean squared error (RMSE) of the custom tibial force sensor is 6.1 N or 1.3% of 450 N, which is full scale. The articular surfaces of the tibial force sensor were interchangeable to match those of a particular size tibial insert. Hence the substitution of the tibial force sensor in place of the tibial component did not alter the biomechanics of the tibiofemoral joint.

After calipered KA TKA, tibial compartment forces were measured over the range of passive motion (extension to 90 degrees of flexion) in 13 cadaveric knees.³ Small loads were applied to the tendons of the biceps femoris (15 N), the semimembranosus/semiotendinosus (26 N), and the quadriceps (80 N) to maintain the stability of the joint. The mean total tibial force caused by tension in the soft tissues was computed as the difference between the mean measured total tibial force (i.e., sum of medial+lateral) and the average contribution of the applied muscle forces to the total tibial force. The difference in tibial compartment forces was computed as the difference between the medial and lateral tibial forces. Thus, a positive difference indicated that the medial tibial force was greater than the lateral tibial force.

RESULTS AND COMPARISON WITH NATIVE KNEE

Although the mean medial tibial force was greater than the mean lateral tibial force from 0 degrees to 90 degrees flexion, the tibial force in each compartment ([Figs. 12.1A](#) and [12.1B](#))

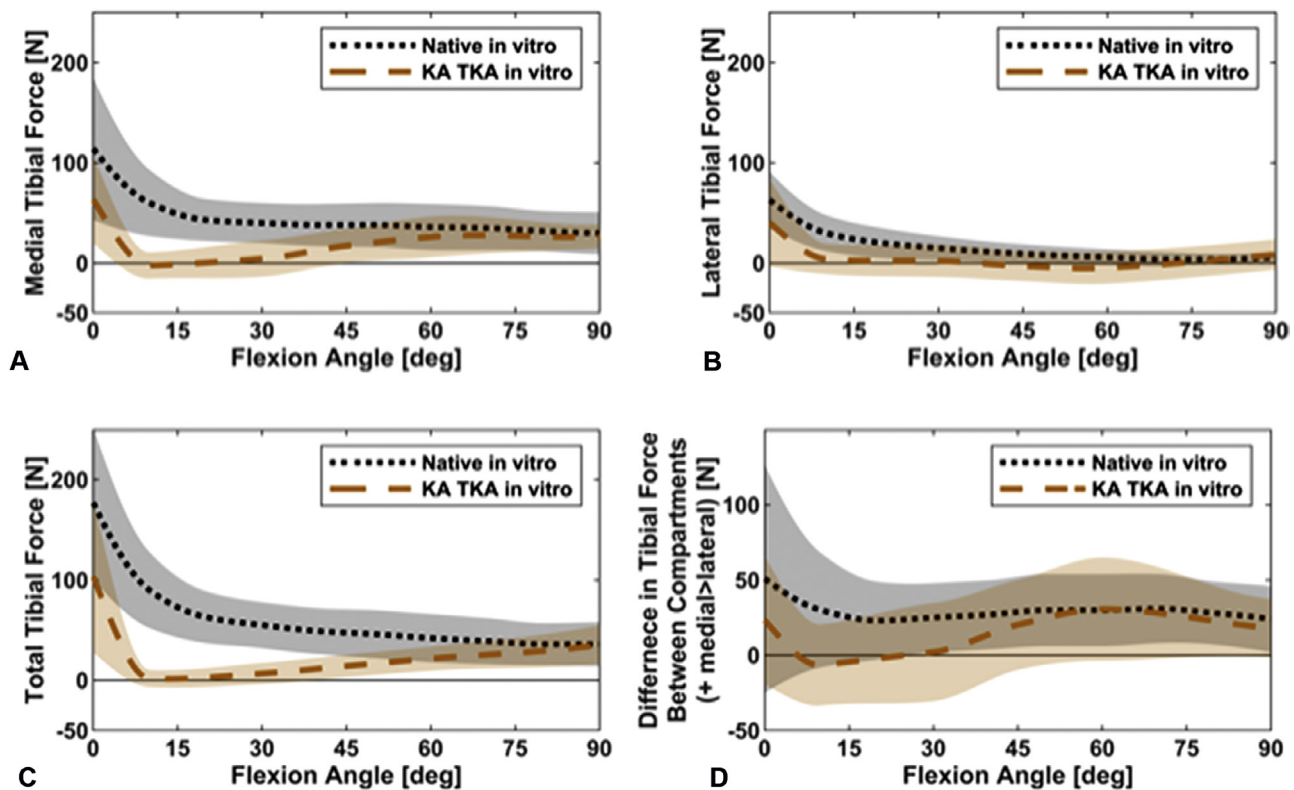


Figure 12.1 Plots illustrate, as a function of flexion angle, the in vitro tibial forces measured in each of the medial (A) and lateral (B) compartments, the total tibial force determined as the sum of the tibial forces in both compartments (C), and the difference in tibial forces between compartments (D) measured with the custom tibial force sensor after calipered kinematically aligned (KA) total knee arthroplasty (TKA) in vitro. Forces measured during passive motion in the native knee in vitro also are shown for comparison. The lines represent the mean, and the shaded regions represent ± 1 standard deviation. Note that the negative values of the medial tibial force and the total tibial force are not physiologic. However, negative values could occur in the data processing because the correction for the compressive component of the applied muscle force was estimated from a model.

showed similar patterns of decrease with flexion. Tibial compartment forces were greatest at extension, decreased rapidly to zero at about 5-degrees flexion, and remained near zero over the remainder of the flexion arc to 90-degrees flexion. The mean total tibial force (Fig. 12.1C) was greatest at 0-degrees flexion (mean total = 103 N), decreased to a minimum at 10-degrees flexion (mean total = 0 N), and then increased somewhat during flexion from 15-degrees to 90-degrees flexion (mean total = 36 N at 90-degrees flexion). The mean difference in tibial compartment forces (Fig. 12.1D) remained below 31 N (<7 lbs) from 0-degrees to 90-degrees flexion.

The mean tibial compartment forces and the mean total tibial forces after KA TKA in vitro are somewhat lower than those measured in the native knee in vitro⁴ (Fig. 12.1C). This likely occurred because the contribution of the soft tissue restraints was isolated in the present study and passive muscle forces were absent, whereas both effects were present in the study that measured tibial compartment forces in the native knee. In any case, the low mean tibial compartment forces and the low mean total tibial force indicate that calipered KA TKA reduces the risk of overly tight soft tissue restraints that might cause persistent pain, stiffness, and limited range of motion.^{5,6}

The mean differences in tibial forces between compartments closely match the differences of the native knee⁴ throughout flexion (Fig. 12.1D). This close match indicates that calipered KA TKA restores the tensions in the medial and lateral soft tissue restraints to native and the resulting balance in tibial compartment forces to native.

Intraoperative Tibial Compartment Forces During Passive Motion in the Calipered Kinematically Aligned Total Knee Arthroplasty

Video 12.2 describes and demonstrates methods used to measure tibial compartment forces during passive motion intraoperatively.

DESCRIPTION OF COMMERCIALLY AVAILABLE TIBIAL FORCE SENSOR AND METHODS

A commercially available tibial force sensor (VERASENSE, Orthosensor, Dania Beach, FL, USA) was used to intraoperatively measure tibial compartment forces and their locations (i.e., centers of pressure) independently in the medial and lateral compartments (Fig. 12.2). Again, only the tibial forces are of interest in this chapter. Unlike the custom tibial force sensor used in the cadaveric knees, the area of measurement in each compartment was limited to the triangle formed by three imbedded load cells. The RMSE for distributed loading within the triangular area is 17 N.⁷ Although this absolute error is almost three times greater than that of the custom tibial force sensor described above, the VERASENSE is still useful as long as mean values are computed over a reasonably large sample (i.e., >30 patients), because computing the mean negates the random error. By replacing the tibial insert with an exact match

Figure 12.2 Photograph of the proximal surface of the VERASENSE tibial force sensor (left) and diagram with the sensor substituted for a trial insert during total knee arthroplasty surgery (right). The sensor measures the tibial force and the location of the center of pressure in each compartment. The sensor is designed to be used intraoperatively and wirelessly broadcasts the tibial forces and locations of the centers of pressure to a receiving display and data-recording unit. One limitation of the design is that the sensing area in each compartment is limited to that of the triangles formed by the three load cells located at each of the vertices. (Used with the permission of OrthoSensor, Inc.)



in size and shape for a particular size insert, the VERASENSE enabled intraoperative measurement of tibial compartment forces without otherwise affecting the biomechanics of the tibiofemoral joint.

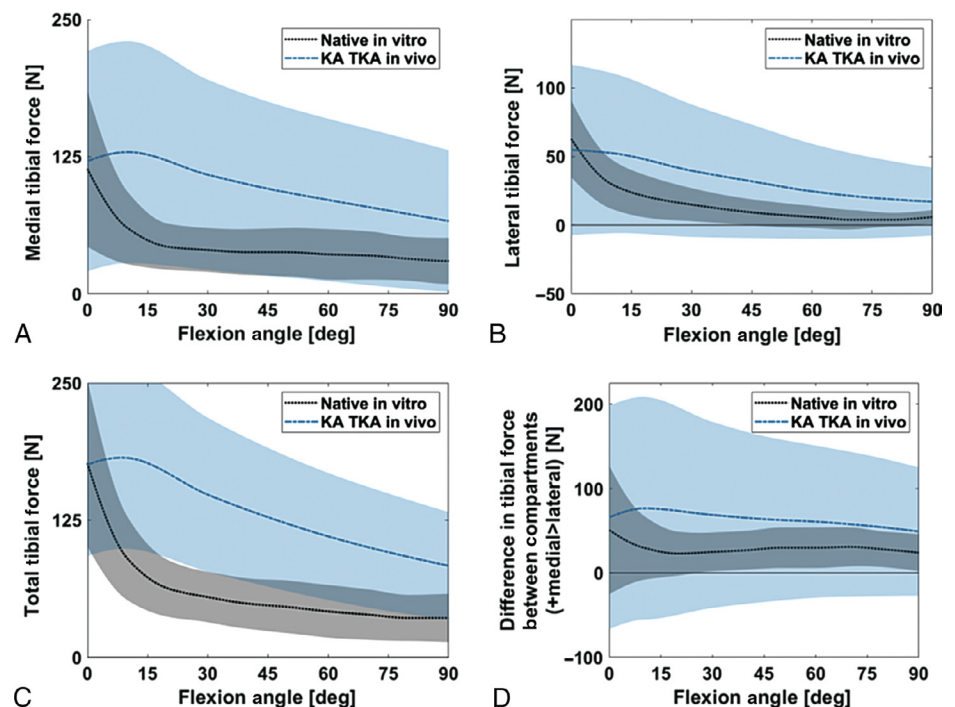
Tibial compartment forces were intraoperatively measured in 68 patients during passive motion while undergoing calipered KA TKA.⁸ The method of applying the passive motion minimized varus or valgus and internal or external rotational moments at the knee by placing the dorsal aspect of one hand under the heel and by placing the other hand on the posterior aspect of the thigh away from the popliteal fossa so that flexion was not limited. Because the surgeon and surgical team were blinded from the display showing the tibial compartment forces, these forces were not available for use when balancing the knee. The medial and lateral tibial forces from three cycles of passive motion were averaged at full extension and 10-degrees, 30-degrees, 45-degrees, 60-degrees, 75-degrees, and 90-degrees flexion. Both the total tibial force and the difference in tibial forces between compartments were determined at each flexion angle. The total tibial force was computed as the sum of

the medial and lateral tibial forces and the difference in tibial compartment forces was computed as the difference between the medial and lateral tibial forces. Thus, a positive difference indicated that the medial tibial force was greater than the lateral tibial force. At 6 months, all 68 patients filled out written questionnaires consisting of the Oxford Knee Score and Western Ontario McMaster Universities Osteoarthritis Index (WOMAC) score.

RESULTS, COMPARISON WITH NATIVE KNEE, AND COMPARISON WITH MECHANICAL ALIGNMENT

The mean tibial forces in each compartment varied with flexion, with the mean medial tibial force (Fig. 12.3A) being greater than the mean lateral tibial force (Fig. 12.3B) throughout flexion. The mean total tibial force (Fig. 12.3C) was greatest at 10-degrees flexion (mean total = 182 N) and steadily decreased to a minimum at 90-degrees flexion (mean total = 85 N). The mean difference in tibial compartment forces (Fig. 12.3D) ranged from

Figure 12.3 Plots illustrate, as a function of flexion angle, the intraoperative tibial forces measured in each of the medial (A) and lateral (B) compartments, the total tibial force determined as the sum of the tibial forces in each compartment (C), and the difference in tibial forces between compartments (D) measured with the VERASENSE device after calipered kinematically aligned (KA) total knee arthroplasty (TKA). Forces measured during passive motion in the native knee in vitro also are shown for comparison. The lines represent the mean and the shaded regions represent ± 1 standard deviation. (Used with the permission of OrthoSensor, Inc.)



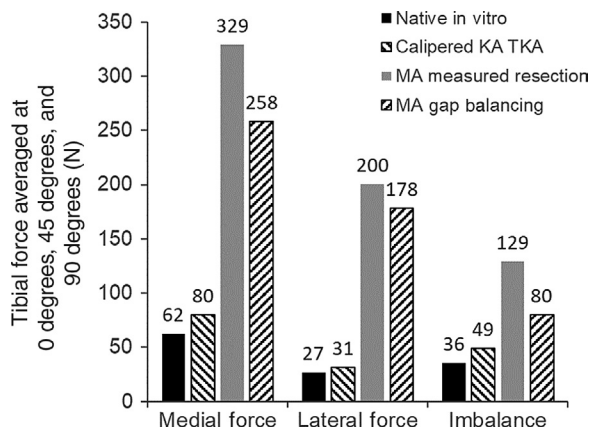


Figure 12.4 Bar chart comparing mean tibial forces measured intraoperatively using the VERASENSE in each compartment and averaged at 0-degrees, 45-degrees, and 90-degrees flexion for each patient and the difference in mean tibial forces between compartments (i.e., imbalance) for calipered kinematically aligned (KA) total knee arthroplasty (TKA) ($n = 68$), measured resection mechanically aligned (MA) TKA using surgical navigation ($n = 155$), gap balancing MA TKA ($n = 34$), and the native knee in vitro ($n = 8$). (Used with the permission of OrthoSensor, Inc.)

a maximum of 76 N (medial>lateral) at 12-degrees flexion to a minimum of 49 N (medial>lateral) at 90-degrees flexion.

To identify a target for a difference in tibial compartment forces that might be predictive of better patient reported outcomes scores indicating better satisfaction and function after calipered KA TKA, a logistic regression with a binary outcome computed the area under the curve (AUC) of the receiver operating characteristic (ROC) to determine whether the difference in tibial compartment forces at any flexion angle predicted either a better (≥ 34) or worse (≤ 33) 6-month Oxford Knee Score. The binary outcome was derived by combining the excellent (>41) with the good (41–34) and the fair (33–27) with the poor (<27) Kalairajah classifications.⁹ The value of this binary outcome is that a patient with a 6-month Oxford score of ≥ 34 has a significantly lower risk of revision within 2 years.¹⁰ Based on a rough classifying system, AUC can be interpreted as follows: 90 to 100 = excellent; 80 to 90 = good; 70 to 80 = fair; 60 to 70 = poor; and 50 to 60 = fail.¹¹ The low observed AUCs (from 0.56 to 0.58) at each flexion angle failed to identify a target for a difference in tibial compartment forces associated with a better (≥ 34) or worse (≤ 33) Oxford Knee Score.

Comparing the tibial compartment force results measured intraoperatively to those for the native knee measured in vitro, with the exception of full extension, the mean tibial forces in each compartment and the mean total tibial force after calipered KA TKA are somewhat greater but decrease with increasing flexion similar to the native knee (Fig. 12.3C).⁴ Considering that the tibial compartment forces for calipered KA TKA in

vitro compare closely to those of the native in vitro (Fig. 12.1), the greater intraoperative tibial compartment forces for calipered KA TKA are likely attributed to passive muscle tensions, which are greater in living subjects than knee specimens from deceased individuals, because of higher fluid volumes in living subjects.¹² The mean difference in tibial compartment forces measured intraoperatively tracks the mean differences in the native knee measured in vitro throughout flexion (Fig. 12.3D) with the greatest difference between the mean differences being less than 50 N.

Based on a study that measured tibial compartment forces intraoperatively using the VERASENSE in 189 patients undergoing mechanically aligned (MA) TKA,¹³ tibial compartment forces for KA TKA can be compared directly to those for MA TKA (Fig. 12.4). Averaged over 0-degrees, 45-degrees, and 90-degrees flexion within each patient, the mean medial tibial force was 3 to 4 times higher, the mean lateral tibial force was 5 to 6 times higher, and the mean difference in tibial forces between compartments was 1.5 to 3 times higher for MA TKA than for calipered KA TKA. Hence, MA TKA is unable to restore tibial compartment forces to native even after performing ligament releases, in contrast to KA TKA, which restores tibial compartment forces to native without ligament release.

Summary

When measured in vitro during passive motion, tibial compartment forces following calipered KA TKA track those of the native knee measured in vitro. Whether measured in vitro or intraoperatively, differences in tibial forces between compartments following calipered KA TKA track those of the native knee measured in vitro. These results indicate that calipered KA TKA achieves the two goals of (1) restoring these biomechanical variables to native while simultaneously (2) achieving soft tissue balance without ligament release. Thus, calipered KA TKA reduces the risk of high tibial forces that might lead to implant failure and, by inference, concomitant overly tight soft tissue restraints that might cause persistent pain, stiffness, and limited range of motion.^{5,6}

Acknowledgment

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Clinical Outcome, Postoperative Alignment, and Implant Survivorship After Kinematically Aligned Total Knee Arthroplasty

DRAGAN JEREMIC, MD

CHAPTER OUTLINE

Overview

Differences in Clinical Outcome Between Kinematically Aligned and Mechanically Aligned Total Knee Arthroplasty

Chronologic Review of the Author's Experience and International Randomized Controlled Trials That Summarize the Effectiveness of Kinematically Aligned Total Knee Arthroplasty

International Meta-Analyses Summarizing the Effectiveness of Kinematically Aligned Total Knee Arthroplasty

Differences in Postoperative Alignment Between Kinematically Aligned and Mechanically Aligned Total Knee Arthroplasty

Implant Survival, Risk of Tibial Component Migration, and Revision Surgery After Kinematically Aligned Total Knee Arthroplasty

Overview

This chapter reviews the clinical outcome, postoperative alignment, and implant survivorship after kinematically aligned (KA) total knee arthroplasty (TKA) based on results of international randomized controlled trials (RCTs), case-control studies, meta-analyses, and single-surgeon case series. The first section describes differences in patient-reported outcome scores and range of motion between patients treated with KA TKA and mechanical alignment (MA) TKA. Featured are a chronologic review of the findings of RCTs, a matched cohort of patients treated with calipered KA and MA performed with manual instruments and a medial pivot implant design published by the author of this chapter, and meta-analyses. Many studies used inclusion restrictions and postoperative correction restrictions in the KA cohort that biased the results against KA TKA and in favor of MA TKA. The second section discusses differences in KA and MA postoperative limb and joint line alignment and the accuracy of the calipered KA technique. The third section reports the mid- and long-term implant survival after KA TKA and discusses the differences in the rate of reoperations other than for infection between the KA and MA TKA. The contrary and unexpected finding of negligible long-term risk of tibial component failure from

a varus mechanism after KA TKA is highlighted. The explanation for the negligible risk is the lack of correlation between the degrees of varus alignment and component migration, low knee adduction moment during gait, and restoration of native tibial compartment forces after KA TKA, which MA TKA does not achieve. The educational objective is to provide compelling evidence that the KA target results in a better clinical outcome and that the calipered technique accurately restores the patient's prearthritic joint lines. Surgeons that perform KA TKA can expect a low risk of mid- and long-term implant failure and a negligible risk of varus failure of the tibial component that is lower than MA TKA.

Differences in Clinical Outcome Between Kinematically Aligned and Mechanically Aligned Total Knee Arthroplasty

Persistent patient dissatisfaction and residual symptoms after mechanically aligned MA TKA contrast with the generally favorable reports of high implant survival.^{1,2} These features of disappointment, unchanged by purported advances in implant design and more consistent neutral limb alignment from the use of intraoperative navigation and robotic technologies, show the intrinsic limitations of the MA technique.³⁻⁶ Modern views conclude that changing the native joint line, kinematics, and laxities, which is inherent to the MA technique, impede optimal clinical outcomes.⁷⁻⁹ For all modern arthroplasties except the knee, reconstruction of the patient's functional phenotypes, prearthritic joint surfaces, soft tissue envelopes, and joint laxities is recognized as the primary goal.⁷⁻¹² Over the past decade, improvements in the understanding of knee kinematics and the importance of restoring the flexion-extension axis¹³ encouraged the evaluation of other alignment techniques¹⁴ and the use of medial pivot or stabilized implant designs. These experiences brought insight and strategies for achieving higher function scores and satisfying even the highly active patient.^{7,8,15}

The calipered KA technique reduces the risk of patient disappointment after TKA. KA restores the patient's prearthritic joint lines regardless of preoperative knee deformity without ligament release and does so by reestablishing the tibial compartment forces, ligament lengths, and laxities of the native knee.^{14,16} KA is now a 15-year-old surgical technique that individualizes component placement, targeting anatomic surface landmarks within the knee, which is substantially different from the MA targets of

the center of the hip, knee, and ankle.¹⁷ The international orthopedic community is highly interested in KA because of the generally favorable results of the published RCTs, case-control studies, and meta-analyses, discussed further in this chapter, in which the differences between kinematically aligned and mechanically aligned total knee arthroplasty have been analyzed.

Chronologic Review of the Author's Experience and International Randomized Controlled Trials That Summarize the Effectiveness of Kinematically Aligned Total Knee Arthroplasty (Table 13.1)

In 2012, a US study by Dossett¹⁸ reported results of an RCT of 41 patients treated with KA performed with patient-specific instrumentation (PSI) and 41 patients treated with MA using measured resection and manual instrumentation and the same cruciate ligament-retaining (CR) fixed-bearing implants. There were no inclusion or postoperative correction restrictions. Follow-up was at 6 months. Ligaments were not released in the KA cohort. The KA cohort had significantly higher Knee Society Score (KSS), Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), and Oxford Knee Score (OKS). Radiologically, the hip-knee-ankle angle (HKA) was similar; however, the joint line was more oblique in the KA cohort. A 2-year follow-up article published in 2014 reported 8 degrees more flexion in the KA cohort, and a 3.2 and 4.9 odds ratio of having a pain-free knee based on the Oxford and WOMAC pain subsections, respectively, compared with the MA cohort.¹⁹

In 2016, a United Kingdom study by Waterson et al.²⁰ reported results of an RCT of 36 patients treated with KA performed with PSI and 35 patients treated with MA using measured resection and manual instrumentation with a CR fixed-bearing implant. Follow-up was from 6 weeks to 1 year. There were inclusion restrictions, as patients with varus and valgus deformities greater than ± 7 degrees were excluded, which biased the results in favor of MA TKA. The authors showed higher KSS outcomes in terms of early functional improvement and peak torque of the quadriceps in the KA cohort with no significant differences at 1-year.

In 2017, a German study by Callies et al.²¹ reported results of an RCT of 100 patients treated with KA performed with PSI and 100 patients treated with MA using measured resection and manual instrumentation with a CR fixed-bearing implant. Follow-up was at 1 year. There were inclusion restrictions, as patients were excluded when the preoperative varus and valgus deformities were greater than ± 10 degrees. There were correction restrictions as the postoperative distal lateral femoral angle was limited to 86 to 94 degrees and the medial proximal tibial was limited to 86 to 94 degrees in the KA cohort. Ligaments were not released in the KA cohort. The KA cohort had significantly higher KSS and WOMAC scores. Those few KA TKA patients with poor outcomes had deviations in joint line alignment between the postoperative radiographs and the initial plan, presumably caused by poor-fitting patient-specific guides.

In 2017, a New Zealand study by Young et al.²² reported results of an RCT of 49 patients treated with KA performed with PSI and 50 with MA using navigation with a CR fixed-bearing implant. Follow-up was at 2 years. The KA cohort showed a

trend toward a functional advantage over the MA cohort. There were inclusion and correction restrictions that biased the results in favor of MA TKA. Records of the PSI company showed the surgeon frequently reduced the correction by overriding the preoperative KA plan, which explains the use of ligamentous releases to balance the KA TKA. The mean Forgotten Joint Score (FJS) in the KA cohort of 69 was higher than the MA cohort score of 66, which is lower than other reports of KA and higher than those previously reported for MA.^{23,24} They concluded that functional outcomes were not different.

In 2017, a Japanese study by Matsumoto et al.²⁵ reported results of an RCT of 30 patients treated with KA and 30 with MA performed with navigation instrumentation with either a mobile-bearing or fixed-bearing CR implant design. There was an inclusion restriction, as only knees with varus deformities were treated. There was a correction restriction, as all tibial components in the KA cohort were placed at 3 degrees of varus to the MA. Follow-up was at 1 year. The postoperative knee flexion and the objective and functional activity components of the Knee Injury and Osteoarthritis Outcome Score (KOOS) were significantly better in the KA cohort.

In 2019, a Canadian study by Laende et al.²⁶ reported the results of an RCT of 24 patients treated with KA performed with PSI and 23 with MA performed with navigation instrumentation and a fixed-bearing CR implant design. There were no inclusion or correction restrictions. Follow-up was at 2 years. The primary outcome was tibial component migration, measured by radiostereometric analysis (RSA). KA TKA was associated with acceptable tibial component migration, indicating stable fixation. The postoperative alignment of the limb, varus alignment specifically, was not associated with tibial component migration. They concluded these results support continued investigation of implantation of tibial components outside the window of neutral mechanical alignment. There were no differences in the OKS; however the mean score of 31 and 30 at 2 years was uncharacteristically low in both the KA TKA and MA TKA cohorts.

In 2020, an Australian study by McEwan²⁷ reported results of an RCT of simultaneous bilateral TKA in 41 patients in which navigation performed KA and MA in opposite knees, with a CR implant. They excluded valgus knee deformities. There was a correction restriction, as the postoperative HKA angle limits of the KA cohort was limited from 6-degrees varus to 3-degrees valgus. Follow-up was at 2 years. Significantly more participants preferred their KA joint, although clinical outcomes were equivalent. Fewer releases were required using the KA technique. Participants were visually insensitive to modest HKA asymmetry.

In 2020, an Australian study by French²³ reported results of an RCT that determined differences in outcomes between 46 patients with a medial pivot design and 44 with a low-conforming CR design. All the arthroplasties were performed using KA principles with manual instruments. Follow-up was at 1 year. The authors concluded that the medial pivot KA TKA scored significantly better on the FJS and the quality-of-life subscale of the KOOS and KOOS-12 than for those who underwent a low-conforming CR KA TKA, which functions like an anterior cruciate ligament and partially meniscus-deficient knee.^{28,29} The mean FJS of those with the medial pivot KA TKA was 80 points, which was 16 points higher than the low-conforming CR KA TKA and comparable with total hip arthroplasty.

In 2020, a German study by the author of the present chapter reported results of a case-control trial of 24 consecutive KA TKA patients performed with the calipered technique and manual

TABLE 13.1 RCT Studies comparing KA TKA and MA TKA

Country, Author, Year, Study Design	Number of Knees	Surgical Instrumentation and Implant Type	Follow-up (Months)	Primary Outcome Measures	Differences Between KA TKA and MA TKA	Restrictions, Comments
United States, 2012, Dossett, ¹⁹ RCT	44 KA TKA; 44 MA TKA	KA with PSA vs. MA with manual measured resection. Implant: CR Vanguard fixed bearing, patella resurfaced, cemented.	6	OKS, WOMAC, KSS, VAS	All significantly different and in favor of KA TKA	Unrestricted inclusion criteria. Unrestricted postoperative alignment correction. Restored prearthritic joint lines. No bias. Almost exclusively male patients.
United States, 2014, Dossett, ²¹ RCT	44 KA TKA; 44 MA TKA	KA with PSI vs. MA with manual measured resection. Implant: CR Vanguard fixed bearing, patella resurfaced, cemented.	24	OKS, WOMAC, KSS	All significantly different and in favor of KA TKA	Unrestricted inclusion criteria. Unrestricted postoperative alignment correction. Restored prearthritic joint lines. No bias. Almost exclusively male patients.
United Kingdom, 2016, Waterson, ²³ RCT	36 KA TKA; 35 MA TKA	KA with PSI vs. MA with manual resection. Implant: CR Triathlon fixed bearing, patella resurfaced, cemented.	12	KOOS, KSS, UCLA, EQ-5D	No difference in outcome scores	Restricted inclusion criterion. Excluded knees with varus-valgus >10 degrees and flexion contracture >20 degrees. Unrestricted postoperative alignment correction. Restored prearthritic joint lines. Biased in favor of MA TKA.
New Zealand, 2017, Young, ²⁴ RCT	49 KA TKA; 50 MA TKA	KA with PSI vs. MA with navigation gap-balanced. Implant: CR Triathlon fixed bearing, patella selectively resurfaced, cemented.	24	OKS, WOMAC, KSS, VAS, EQ-5D	No difference in outcome scores	Restricted inclusion criterion. Excluded knees with varus/valgus deformity >15 degrees and fixed flexion contracture. Restricted postoperative alignment. Surgeon frequently changed preop plans from KA. Used ligament releases. Biased in favor of MA TKA.
Germany, 2017, Calliess, ²² RCT	100 KA TKA; 100; MA TKA	KA with PSI vs. MA manual gap balanced. Implant: CR Triathlon fixed bearing, patella selectively resurfaced, cemented.	12	KSS, WOMAC	All significantly different in favor of KA TKA	Restricted inclusion criteria. Excluded knees with varus/valgus deformity <10 degrees. Unrestricted postoperative alignment correction. Restored prearthritic joint lines. Biased in favor of MA TKA.
Japan, 2017, Matsumoto, ²⁵ RCT	30 KA TKA; 30 MA TKA	KA with navigation vs. MA with navigation gap balanced. Implant: CR Persona fixed bearing or CR Emotion mobile bearing.	15	KSS, knee flexion	All significantly different and in favor of KA TKA. Postoperative mean OKS 31—low in both cohorts.	Restricted inclusion criterion. Excluded valgus knees. Restricted postoperative alignment. Tibial cut in 3-degrees varus. Biased in favor of MA TKA. Unrestricted postoperative alignment correction. Restored prearthritic joint. No bias.

TABLE 13.1 RCT Studies comparing KA TKA and MA TKA (Continued)

Country, Author, Year, Study Design	Number of Knees	Surgical Instrumentation and Implant Type	Follow-up (Months)	Primary Outcome Measures	Differences Between KA TKA and MA TKA	Restrictions, Comments
Australia, 2020, McEwen, ²⁶ RCT	41 bilateral TKA—KA in one knee, MA in other, same implant	KA navigated unrestricted and MA navigated gap balanced. Implant: CR Triathlon fixed bearing, patella resurfaced, uncemented femoral component—other cemented.	24	OKS, KOOS, FJS, KOOS JR	More patients preferred the KA TKA Fewer ligament releases with KA. No difference in outcome scores.	Restricted inclusion criterion. Excluded valgus knees. Restricted postoperative alignment. HKA limited from 6-degrees varus to 3-degrees valgus. Biased in favor of MA TKA.
Australia, 2020, French, ²⁸ RCT	KA both knees—44 CR, 46 MBS	KA with manual instruments in all knees. Implants: Randomized to either Saiph knee MBS or Vanguard CR.	12	FJS, KOOS, OKS, WOMAC, UCLA and EQ-5D-5L	FJS and KOOS significantly different in favor of KA MBS over KA Vanguard CR. Means FJS of KA MBS (80) like total hip arthroplasty and 16 points higher than KA CR.	Unrestricted inclusion criteria. Unrestricted postoperative alignment correction. Restored prearthritic joint lines. No bias.

CR, Posterior cruciate ligament retaining; EQ-5D-5L, EuroQoL 5-dimension 5-level; FJS, Forgotten Joint Score; HKA, hip-knee-ankle angle; KOOS, Knee Injury and Osteoarthritis Outcome Score; KOOS JR, Knee Injury and Osteoarthritis Outcome Score for Joint Replacement; KSS, Knee Society Score; MBS, medial ball-in-socket; OKS, Oxford Knee Score; PSI, patient-specific instrumentation; VAS, Visual Analog Scale; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index; UCLA, University of California, Los Angeles Activity Score.

instruments and matched to 24 patients treated with MA-TKA.²⁴ Both knees received a medial pivot knee design. There were no inclusion or postoperative correction restrictions. Follow-up was at 1 year. The mean FJS of the KA medial pivot TKA of 77 points was similar to the 80-point score reported by French et al., and 26 points higher than the mean FJS of the MA medial pivot TKA.

The use of inclusion and postoperative correction restrictions in the KA cohort can bias the results in favor of MA TKA. The exclusion of treatment to those with severe knee deformities and valgus deformities biases the results because of the different frequency of use of ligament release, which adds morbidity and the risk of instability. Calipered KA does not use ligament releases to restore the prearthritic limb alignment. In contrast, MA uses more ligament releases to change the limb, as the deviation of the prearthritic alignment incrementally increases from a neutral HKA. In MA TKA, an increase in the number of ligament

releases to treat the valgus deformity lowers clinical outcome scores.³⁰ Postoperative restrictions that limit correction from the prearthritic limb and joint line alignment biases the results in favor of MA TKA, because treatment of the so-called “restricted version” of KA TKA (better termed “expanded” MA TKA) requires ligament releases.^{22,27}

International Meta-Analyses Summarizing the Effectiveness of Kinematically Aligned Total Knee Arthroplasty

Multiple meta-analysis used systematic reviews of RCTs and case-control studies to determine differences in a variety of primary and secondary outcomes between KA TKA and MA TKA.

TABLE 13.2 Reoperations in studies comparing KATKA and MA TKA

Country, Publication Date, and Author of Randomized Controlled Trial; Number of Each TKA Type	KA TKA Reoperations Excluding Infection	MA TKA Reoperations Excluding Infection
United States, 2014, Dossett ²¹ ; 44 KA TKA, 44 MA TKA	2 MUA, 2 excision lateral patella facet	1 excision lateral patella facet, 1 revision for tibiofemoral instability
New Zealand, 2017, Young ²⁴ ; 49 KA TKA, 50 MA TKA	2 MUA, 1 patella realignment	1 patella realignment
Germany, 2017, Calliess ²² ; 100 KA TKA, 100 MA TKA	2 revisions for tibiofemoral instability	1 revision for tibiofemoral instability
Canada, 2019, Laende ⁵⁷ ; 24 KA TKA, 23 MA TKA	1 exchange with a thicker insert	None
Australia, 2020, McEwen ²⁶ ; 41 bilateral TKA—KA in one knee and MA in the other	2 MUA, 1 arthroscopic popliteus release	2 MUA

KA, kinematic alignment; MA, mechanical alignment; MUA, manipulation under anesthesia; TKA, total knee arthroplasty.

A US meta-analysis concluded that functional outcome, as measured by the KSS, favored KA TKA over MA TKA and that KA did not adversely impact overall survivorship or complication rates at short-term follow-up.³¹ A United Kingdom meta-analysis concluded that the KA TKA had better clinical outcomes with no increase in patients with poor clinical results because of implant position, especially for those with varus placement of the tibial component.³² A Chinese meta-analysis showed the KA TKA provided better functional outcomes and better flexion following short-term follow-up.³³ An Australian meta-analysis showed no differences between techniques regarding radiological outcomes and complication rates and that KA TKA might produce better functional outcomes than MA and have shorter operation times.³⁴ A meta-analysis study consisting of only RCTs that performed KA with PSI found no difference in functional outcomes between KA TKA and MA TKA.³⁵

Differences in Postoperative Alignment Between Kinematically Aligned and Mechanically Aligned Total Knee Arthroplasty

The target for calipered KA TKA is to restore the patient's prearthritic limb and joint line alignment and not the MA target of a neutral HKA (Fig. 13.1). Although the targets are different, the mean postoperative HKA was not significantly different between KA and MA in the RCTs. There are differences in the varus-valgus orientation of the distal lateral femoral joint line and the proximal medial tibial joint line between KA and MA. The RCT by Dossett¹⁹ reported 2.1-degrees more valgus alignment of the femoral component and 2.2-degrees more varus alignment of the tibial component in the KA TKA. The RCT of simultaneous bilateral TKA by McEwan²⁷ reported 1.5-degrees more valgus alignment of the femoral component and 2.3-degrees more varus alignment of the tibial component in the KA TKA. These differences in joint line obliquity between KA and MA techniques benefit the weight-bearing biomechanics of the KA TKA, as

the joint line of the tibial component is oriented more parallel to the floor than in MA TKA.^{25,36,37} At the same time, the overall limb alignment is comparable.

The calipered KA technique is highly reproducible at restoring the patient's prearthritic alignment. The varus-valgus orientation of the distal femoral resection is set so the thicknesses of the distal femoral resections, as measured with a caliper to within 0 ± 0.5 mm, match the condyles of the femoral component after compensating for cartilage wear and kerf of the saw blade. An accuracy analysis showed a mean difference between the femoral component and the target of the patient's prearthritic distal joint lines of less than 1 mm and 1 degree.^{17,38} The varus-valgus orientation of the tibial resections is set so that the thicknesses of the medial and lateral tibial condyles measured at the base of the tibial spines are equal. The varus-valgus angle of the tibial resection is adjusted, working in 1- to 2-degree increments, until there is negligible medial and lateral lift-off of the femur from a spacer block and trial insert during a varus-valgus laxity assessment with the knee in full extension. An accuracy analysis showed the proportion of patients with a proximal medial tibial angle of the tibial component within the target of the normal left to right symmetry of the normal contralateral knee was 97%.³⁸ The accuracy of the calipered technique exceeds that of navigation instrumentation, which deviated by ± 1 mm or more from the target thickness in 40% of medial and lateral tibial resections.³⁹

Implant Survival, Risk of Tibial Component Migration, and Revision Surgery After Kinematically Aligned Total Knee Arthroplasty

The MA mindset of overriding the restoration of the patient's prearthritic joint line and targeting a neutral HKA is considered a requirement for high implant survivorship and a low risk of varus tibial component failure from medial overload. This dogma led to the postoperative categorizing of alignment in ranges as a varus outlier, valgus outlier, or neutral as a predictor

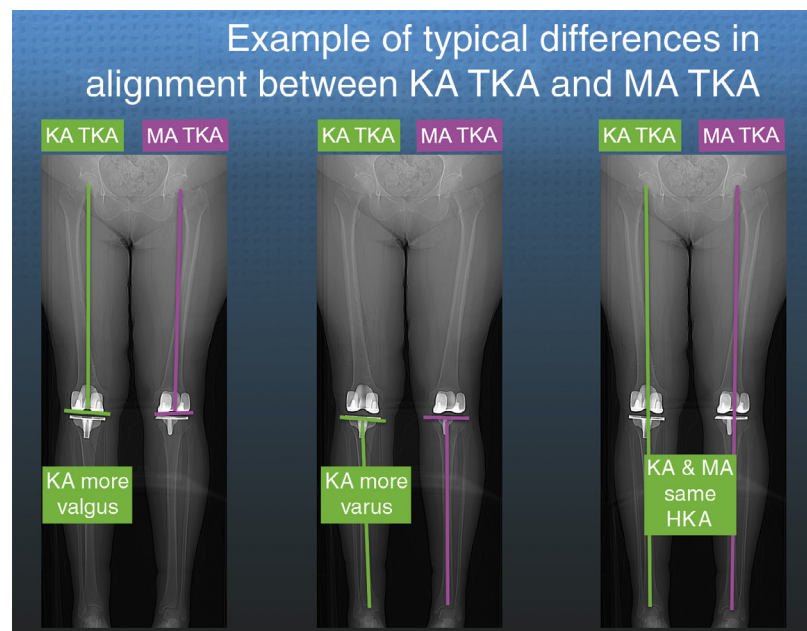


Figure 13.1 Composite of anterior-posterior scannograms shows the representative differences in the distal lateral femoral angle (left), proximal tibial angle (middle), and hip-knee-ankle angle (HKA) (right) between kinematically aligned (KA) total knee arthroplasty (TKA) (green) and mechanically aligned (MA) TKA (magenta). The KA femoral component is more valgus and the KA tibial component is more varus than the MA TKA, and the HKA the same. At 4 years' follow-up, the Forgotten Joint Score (100 best, 0 worst) was 78 for the KA TKA and 24 for the MA TKA.

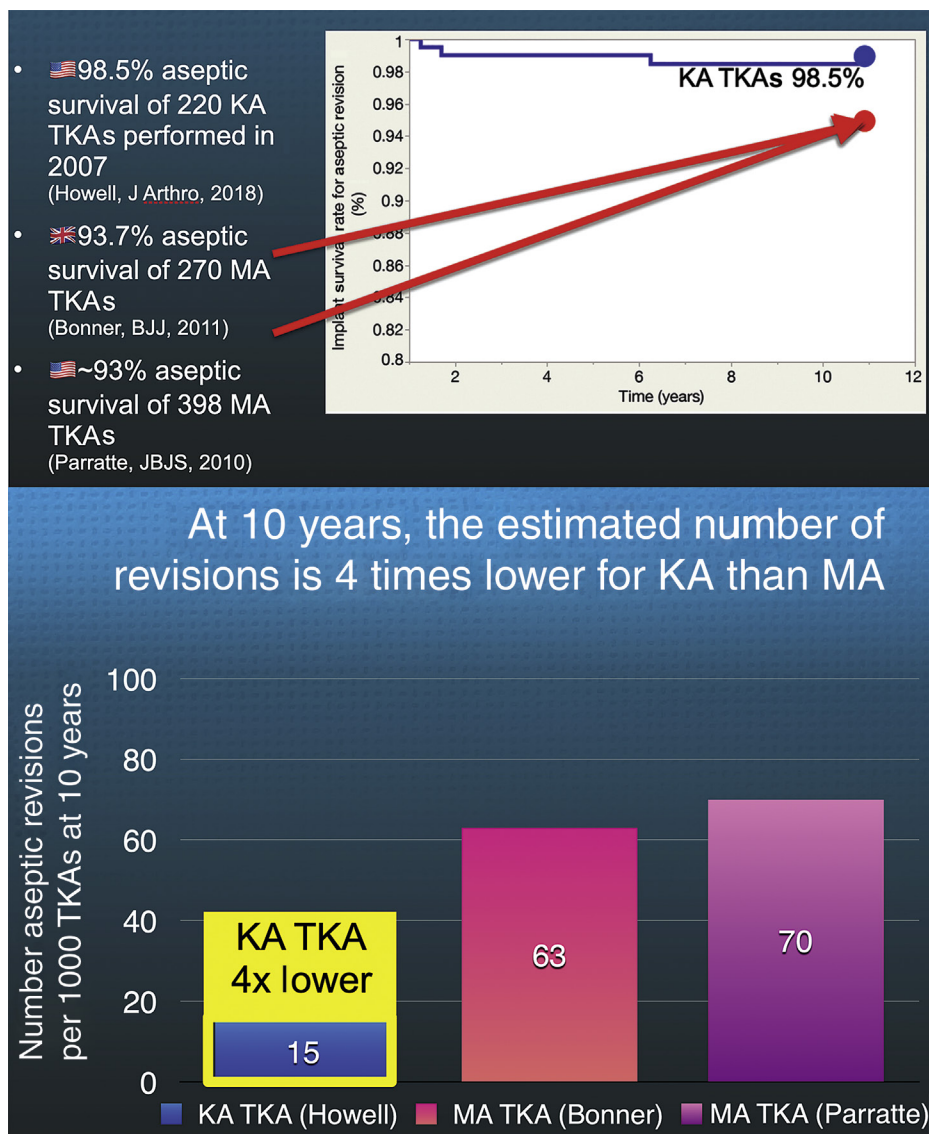
of the risk of implant failure. Modern studies report the relationship between implant survival of a primary TKA and the MA categories of postoperative alignment is much weaker than described in several previous reports, and it does not apply to KA TKA and unicompartmental knee arthroplasty (UKA).^{40–42}

In 2020, a midterm registry study reported differences in the implant survivorship, revision rate, and causes of revision between 416 KA TKAs performed with PSI and Triathlon CR prosthesis (Stryker, Mahwah, New Jersey) and the same TKA delivered with all other systems recorded in the Australian and New Zealand Joint Replacement Registries.⁴² The mean age of the patients with KA was 67 ± 8.2 years, compared with 68 ± 9.0 years for the other group. There was no difference in gender distribution. The cumulative percent revision rate at 7 years was 3.1% for KA TKA and 3.0% for the other TKAs (hazard ratio = 1.0; 95% confidence interval 0.6–1.8). The most common reasons for reoperation in the KA TKA group were patellofemoral instability, patella erosion, and arthrofibrosis, but not tibial component failure.⁴²

These results are comparable to those of a 10-year single-surgeon case series that reported implant survivorship, revision rates, complications, and patient-reported outcome scores after

220 consecutive KA TKAs performed with PSI.⁴⁰ There were no exclusions based on the severity of preoperative knee deformity and no postoperative restrictions from full correction of the patient's prearthritic joint line and limb alignment. The aseptic implant survival at 10 years was 98.5%, with only one tibial loosening. A poor-functioning PSI tibial guide caused posterior overload by setting the CR tibial component in less posterior slope than the patient's prearthritic knee. The tibial component failed from posterior subsidence, which is different from the mechanism of medial compartment overload and varus tibial loosening that occurs after MA TKA. Patella complications occurred in 2% and were associated with excessive flexion of the femoral component from 13 degrees to 25 degrees from the sagittal anatomic axis of the femur. In each, a poor fit of the PSI femoral guide resulted in unintended flexion. Regardless of whether the postoperative limb alignment and tibial component were in the varus outlier, valgus outlier, or in the neutral range according to MA criterion, the implant, survival, and outcome scores were not different. The implant survival after KA TKA is comparable, if not lower, than those of other single-surgeon case series of MA TKA^{43,44} (Fig. 13.2).

Figure 13.2 Composite shows the differences in 10-year implant survival after kinematically aligned (KA) total knee arthroplasty (TKA) and mechanically aligned (MA) TKA reported by three single-surgeon case series (upper image), and that KA TKA could have a four times lower number of aseptic revisions/1000 patients at 10 years than MA TKA (lower image).



There are several explanations for the low risk and negligible rate of varus tibial loosening after KA TKA and the higher rate after MA TKA.⁴⁵ First, an RSA analysis showed no association between the degrees of postoperative varus alignment and component migration 2 years after KA TKA.²⁶ This is contrary to current thinking and an opposite finding from an RSA study that reported mechanically out-of-range postoperative alignment, especially mechanical varus, caused higher tibial component migration after MA TKA.⁴⁶ Second, the postoperative joint line after KA TKA is more parallel in orientation to the floor during single- and double-leg standing and weight-bearing than the MA TKA, which lowers the knee adduction moment during weight-bearing when compared with MA.³⁷ A lower knee adduction moment lowers the forces in the medial tibial compartment and the risk of medial compartment overload. Third, calipered KA TKA restores the native tibial compartment forces without ligament release regardless of the category of postoperative limb, knee, and tibial component alignment according to MA criteria (Fig. 13.3).⁴⁷ In contrast, MA TKA does not achieve soft tissue balance of native tibial compartment forces in a high percentage of patients, even after ligament release.^{47,48} These explanations

agree with the 0.4% aseptic tibial component failure from posterior subsidence of the tibial baseplate or posterior rim wear of the insert, and no cases of varus failure, out of a review of 3212 KA TKAs followed-up for 11 years, of which 2725 TKAs had a 2-year minimum follow-up (Chapter 17).⁴⁵

Excluding cases of infection, the rates of major complications including revisions consisting of removal or exchange of components for stiffness, component failure, and tibiofemoral instability are not significantly different between the KA and MA techniques in short-term follow-up of RCTs (Table 13.2). Although patellofemoral complications occurred, the incidence was low and comparable to MA TKA. KA restores the prearthritic Q-angle in those patients with constitutional varus, whereas MA increases the Q-angle and the risk of patellofemoral instability. Biomechanical studies show that the patella tracks more physiologically after KA than MA with femoral components designed for use in MA.^{49,50} Fewer than 0.4% of patients reported patellofemoral instability in a series of 3212 consecutive patients operated on with PSI KA and calipered measured KA using a variety of implant designs. The case-match portion of the study associated greater than 6 degrees of flexion from the

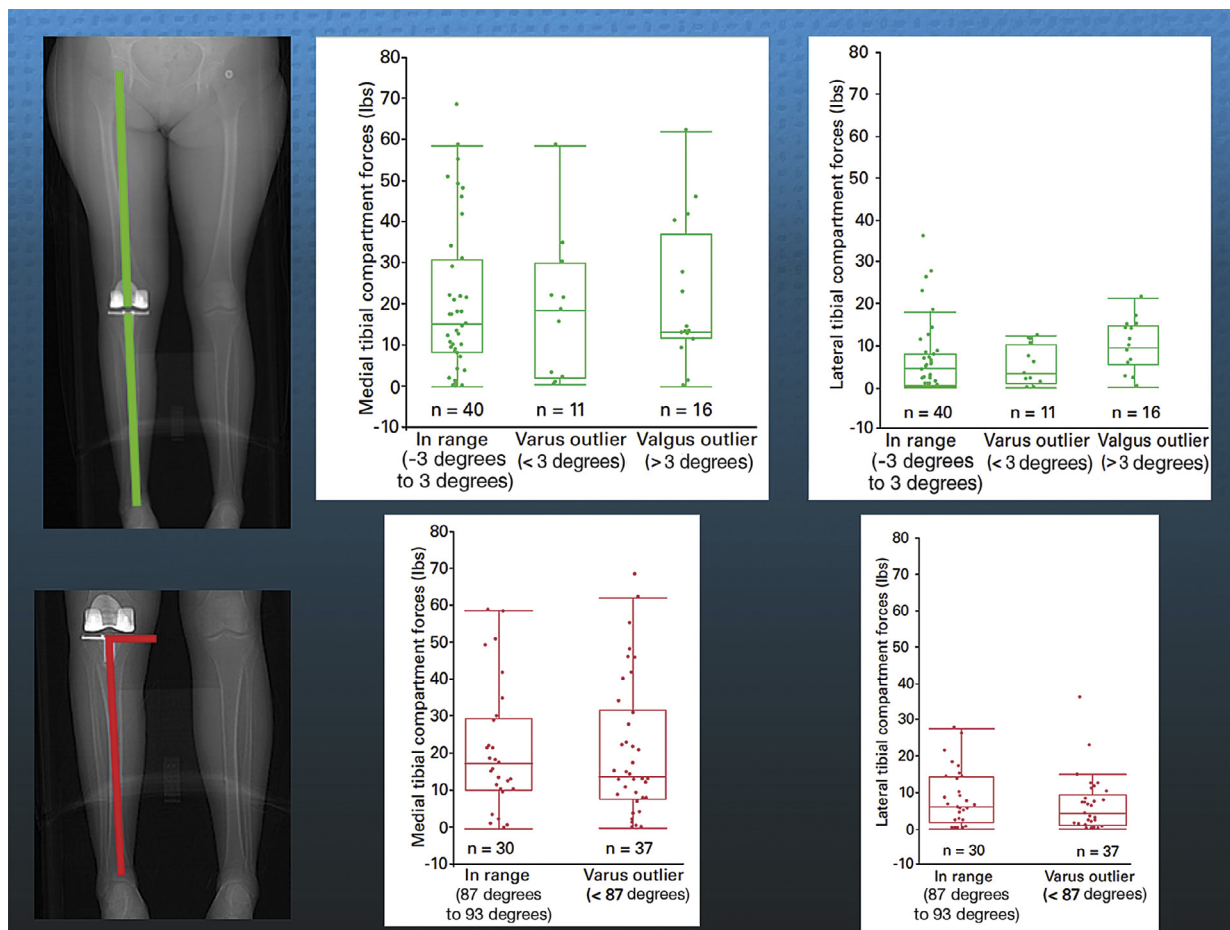


Figure 13.3 Composite of quantile plots for the hip-knee-ankle angle (green) and the proximal medial tibial angle (red) show the mean medial and lateral tibial compartment forces averaged at 0 degrees, 45 degrees, and 90 degrees of flexion after calipered kinematically aligned total knee arthroplasty are not significantly different between patients assigned to a varus outlier, valgus outlier, and neutral category, according to mechanical alignment criteria. Hence, the medial force of the varus outlier group showed no evidence of medial overload and was comparable to the native knee. (From 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? *Bone Joint J.* 2017;99-B(10):1319–1328; Verstraete MA, Meere PA, Salvatore 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;58:195–202.)

anatomic axis of the distal femur and the use of a dome-shaped patella component instead of an anatomic design as risk factors for patellofemoral instability.⁴⁹ Careful surgical execution and the use of verification checks that limit flexion of the femoral component and an anatomic patella component lowers the risk of this infrequent complication (Chapter 18).⁵¹

Summary

This chapter analyzed the clinical outcome, postoperative alignment, and implant survivorship after KA TKA based on the results of international RCTs, case-control studies, meta-analyses, and single-surgeon case series. Patient-reported outcome scores and range of motion after KA TKA were better than after MA TKA. The use of inclusion and postoperative correction restrictions in the KA cohort biased the results in favor of MA TKA. Radiologically, there were no differences in the limb alignment and HKA between KA and MA. There were

significant differences in joint line obliquity because KA restored the patient's prearthritic limb and joint line. The difference in the alignment targets explains the better results for KA TKA. The ± 0.5 mm accuracy of the calipered KA technique exceeds that of navigation instrumentation, which deviated by ± 1 mm or more from the target thickness in 40% of medial and lateral tibial resections. A patient with a KA TKA can expect a negligible risk of tibial component failure from varus overload. This risk is contrary to current thinking and an opposite finding from an RSA study that reported postoperative mechanically out-of-range alignment, especially mechanical varus, caused higher tibial component migration after MA TKA. KA TKA restores a low knee adduction moment during gait and postoperative tibial compartment forces comparable to those of the native knee without ligament release that MA TKA does not achieve after ligament release. Surgeons that use calipered KA and a medial ball-in-socket design can restore a mean FJS comparable to total hip arthroplasty.

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Managing Severe Deformities With Calipered Kinematic Alignment

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CHAPTER OUTLINE

Overview

Calipered Kinetically Aligned Total Knee Arthroplasty (Linked) Technique Principles and Application to Treating Severe Deformities

Surgical Technique

The Femur

Linked Technique for Proximal Tibial Osteotomy

Case 1: Kinetically Aligned Total Knee Arthroplasty for Severe Varus Deformity

Case 2: Kinetically Aligned Total Knee Arthroplasty for Severe Valgus Deformity

Case 3: Kinetically Aligned Total Knee Arthroplasty for Severe Posttraumatic Extraarticular Deformity

Case 4: Approach to the Treatment of Long-standing Extraarticular Deformities That Are at a Distance From the Joint

Case 5: Posttraumatic Deformity Assisted by Patient-Specific Instruments Combined With Linked Kinematic Alignment Total Knee Arthroplasty

Case 6: Posttraumatic Deformity

Overview

Currently, there is lack of consensus about the universal definition of severe deformity for the arthritic knee. Some consider a deviation of more than 10 degrees for a varus knee as a significant deformity. Others consider a severe deformity as more than 15 degrees for the varus knee and more than 20 degrees for a valgus knee.^{1,2} These angles are relative to a hip-knee-ankle (HKA) angle of 180 degrees, which has been believed traditionally to be neutral for every patient, but has recently been proven to be different and highly variable in the population.³ Only recently has a universal classification system been proposed for varus knees that considers the amount of deformity and its origin of location, and whether it is metaphyseal or diaphyseal.⁴

Whatever the numerical definition will be, there is consensus among orthopedic surgeons that total knee arthroplasty (TKA) for severely deformed knees poses a challenge. We believe that this challenge has been aggravated for many years by an incorrect approach to TKA that tries to reproduce a neutral alignment, thereby creating a bucket of iatrogenic difficulties, each of which had to be solved. We will propose a different approach for treating complex knees without the creation of nonanatomic complexity, by applying the kinematic alignment (KA) technique.

The etiology of severe deformities has been considered for many years as the result of either long-standing neglected arthritis

that deteriorated to a point of extensive bone loss and secondary ligament insufficiency, or of congenital pathologic states such as Blount's disease or rickets. Both of the latter are rare in the general arthroplasty practice in developed countries, although they may still be found in less developed parts of the world.⁵

Today, the etiology of those deformities as seen from the perspective of constitutional alignment^{6,7} might best be categorized into two separate groups that will be further discussed in this chapter:

1. Severe constitutional varus or valgus (single-level or multi-level) coupled with cartilage wear and occasionally bone loss to create severe deformity.
2. Posttraumatic extra/intraarticular deformities.

Today, the most common treatment workflows for cases with severe deformity include extensive soft tissue releases to attain balance and neutral mechanical alignment (MA), in addition to the use of stems, augments, and constrained or hinged implants.⁸⁻¹² The addition of constrained or stemmed implants increases the cost burden two- to threefold. Extensive releases, reduction osteotomies, and even epicondylar transfers have been described as means to achieve stability.^{13,14} Failure to manage these cases using the aforementioned techniques and restoring mechanically neutral alignment is widely believed to lead to premature loosening and failure. Several methods have been described to address severe deformities using these techniques, with the main emphasis being on short-term survivorship with minimal attention toward functional outcomes.¹⁵

During the last decade, a better understanding and definition of the phenotypic presentation of constitutional alignment, coupled with a pronounced paradigm shift toward a more natural and anatomic reconstruction of the knee joint, have been gaining traction.¹⁶ At the same time, a changing population demographic skewing toward younger patients with higher expectations for clinical function of their artificial joints has challenged the surgical community to strive for better clinical results. These trends have encouraged alternative solutions and the exploration and optimization of kinematic knee alignment philosophies, even in the context of considerable deformity.

The concept of KA has been extensively studied and is a hot topic of debate in the field of total knee arthroplasty.¹⁷⁻²⁰ In KA, the goals of the reconstruction are to restore the native tibial-femoral articular surfaces to their original alignment relative to the long bone anatomic axes, restore the native prearthritic limb alignment, and restore the native soft tissue laxities of the knee.²¹

Unlike traditional mechanical alignment techniques, which focus on making the tibia orthogonal to the floor, KA techniques focus on placing the femoral component to match the native three-dimensional (3D) position of the distal femur as the primary goal of the reconstruction process. Next, by compensating for tibial wear (cartilage and bone) and placing the tibial component in its prearthritic anatomic position, there

is no need for ligament releases or other soft tissue interventions to restore normal motion around the knee's native rotational axes. The result is a well-balanced and more natural-feeling knee, with multiple studies showing favorable patient-related outcome measurements.²²

With respect to restoring native soft tissue laxity, we note that MA TKA for severe deformity has traditionally emphasized the need for ligamentous release to balance the knee perpendicular to the mechanical axis of the entire limb. The goal is to create “balanced gaps” where the same tension is created between the medial and lateral ligaments both in full extension to 90 degrees of flexion, even though in a normal knee there is more laxity in flexion on the lateral side.²³ We believe there is a price to be paid for every ligament release or soft tissue manipulation, reflected in the way patients perceive their new knee as not natural.

From our perspective, one of the primary benefits of KA TKA is, therefore, its inherent ability to address severe deformity using the same general principles as are used for common minor deformity, with only a few specific considerations.

The aim of this chapter, therefore, is to briefly summarize the following:

- The caliper-based KA TKA technique applied to severe deformities.
- The application of KA TKA in six examples, including severe varus deformity, severe valgus deformity, and intra- and extraarticular posttraumatic deformities.
- Special considerations relative to applying KA TKA to severe deformity.

Calipered Kinematically Aligned Total Knee Arthroplasty (Linked) Technique Principles and Application to Treating Severe Deformities

The key step of KA reconstruction is to replicate the distal femur's 3D position, as it is the primary driver of knee kinematics, not the tibia. In this context, it has been noted that there is seldom much bone loss from the femur, whereas most of the intraarticular deformity originates from the proximal tibia.²⁴ Therefore, once the femoral component is reconstructed as close as possible to its prearthritic state (within 0.5–1 mm), all that is necessary is to match the tibial tray position to that of the reconstructed femur. This can be done through the principles of a “linked technique” (described herein) or according to the basics of KA as discussed in previous chapters.

SURGICAL TECHNIQUE

Exposure and Soft Tissue Management

A skin incision is performed in the standard fashion, slightly medialized to midline, followed by medial parapatellar capsulotomy. In our practice, the medial parapatellar approach is used both for varus and valgus deformities, with one exception, known preexisting chronic patellar subluxation with valgus deformity, where a lateral parapatellar approach is used. The joint is exposed and the fat pad is excised. Patellar tracking is examined to verify the proper patellar tracking that should be recreated at the end of surgery. The patella is subluxed to the lateral gutter but not everted. Extensive osteophyctomy is done. No release of deep or superficial medial collateral

ligament (MCL) is done. Anterior cruciate ligament (ACL) is excised if present and posterior cruciate ligament (PCL) is retained. Suprapatellar synovectomy is performed, and the anterior femoral cortex is exposed with a periosteal elevator to be able to place the anterior reference extramedullary device for the distal cut—setting up the flexion-extension plane of the distal cut. Because no release of MCL is done, a mobile window retractor approach is used and attention is given not to tension the soft tissue too much. We treat flexion contractures at the end of bony cuts after initial full trial is done with posterior femoral osteophyte removal and posterior capsular release, followed by aplastic deformation if required. For valgus knees we apply the same no-release philosophy and avoid releasing posterior-lateral structures, as well as popliteus and lateral collateral ligament (LCL). The only structure that may be released at the end of trial reduction is the ITB, which is rarely required. We do not resurface the patella routinely. For patellar maltracking, we follow a simple algorithm that we apply to all our KA TKA cases:

1. If tracking was proper after initial arthrotomy, it should be tracking the same at the trial phase; if not, varus-valgus (V-V) balance and tibial rotation should be reassessed, as they may influence the patellar tracking. Specifically, this is important if the valgus knee has been undercorrected in error (most probably originating from insufficient varus on the tibial side or too much valgus from the femoral side).
2. If slight lateral tracking is present, we do lateral patellar facetectomy.
3. If there is still maltracking, a patellar resurfacing might be considered.
4. Lateral retinacular release will be used as a last resort: of our 1000 KA TKA cases so far, it has only been required once (for chronic patellar subluxations).

THE FEMUR

Step 1: Distal Cut

After exposure of the knee through a standard medial parapatellar arthrotomy for both severe varus and severe valgus knees, we assess cartilage wear on the distal aspect of the femur. From the eroded condyle we remove any partially worn cartilage to reference bare subchondral bone with our distal femoral cutting blocks. The flexion-extension axis of the femoral component is set parallel to the anterior surface of the distal femur and perpendicular to the distal articular surface (Fig. 14.1). The V-V angulation and proximal distal position of the femoral component are set using a distal referencing guide that compensates 2 mm when there is cartilage wear on the distal medial femoral condyle in the varus knee, and 2 mm when there is cartilage wear on the distal lateral femoral condyle in the valgus knee. The anterior-posterior (AP) translation and internal-external rotation of the femoral component are set as described in previous chapters, by placing a posterior referencing guide in contact with the posterior femoral condyles and in 0 degrees of relative rotation (Fig. 14.2).

We assess cartilage thickness with a scalpel blade at the most posterior aspect of the posterior condyles; this requires deep flexion for proper assessment. We aim for the same cartilage thickness at both posterior condyles. If one is eroded, it is compensated for by applying a 1- or 2-mm shim between the posterior lateral condyle and the sizer.

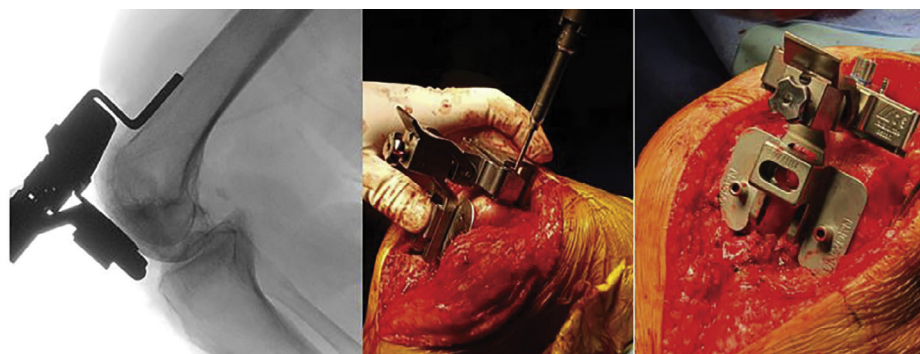


Figure 14.1 Photos demonstrate distal cut referencing the anterior cortex and distal surface compensating for cartilage loss (worn-unworn).

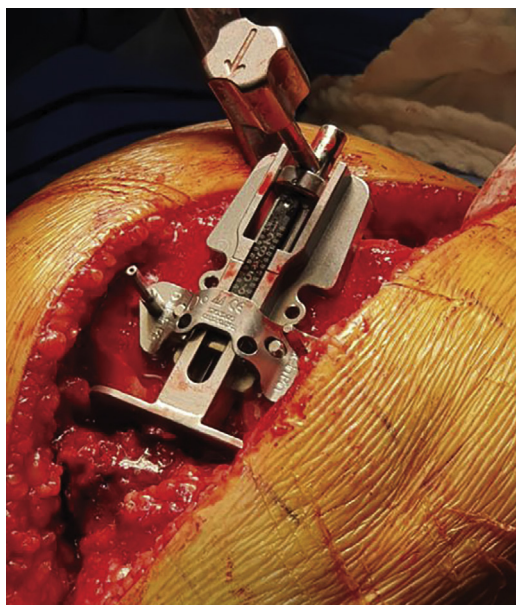


Figure 14.2 Photo shows correct position of anterior-posterior sizer set with 0-degree rotation to individually recreate the posterior condylar axis.

The positioning of the posterior referencing guide rarely requires correction, because complete cartilage loss is uncommon on the posterior medial femoral condyles in varus osteoarthritic knees, although it may be found quite often in valgus knees, as they commonly present a flexion disease with posterior erosion pattern. Correction for bone erosion is rarely needed at 0 and 90 degrees of flexion, even in the most arthritic knees.

Step 2: Sizing the Femur, Referencing Its Native Posterior Condylar Axis and Placement of the 4:1 Resection Guide

After the distal cut is completed and quality assurance with the caliper is completed (accounting for 2-mm worn cartilage and 1-mm saw kerf), an AP sizer is positioned to set the component rotation and select the component size. Next, the 4:1 cutting guide is applied to complete the preparation for the femoral cuts. The caliper is used to measure bone resected from the posterior condyles to confirm the appropriate femoral rotation ([Fig. 14.3](#)).

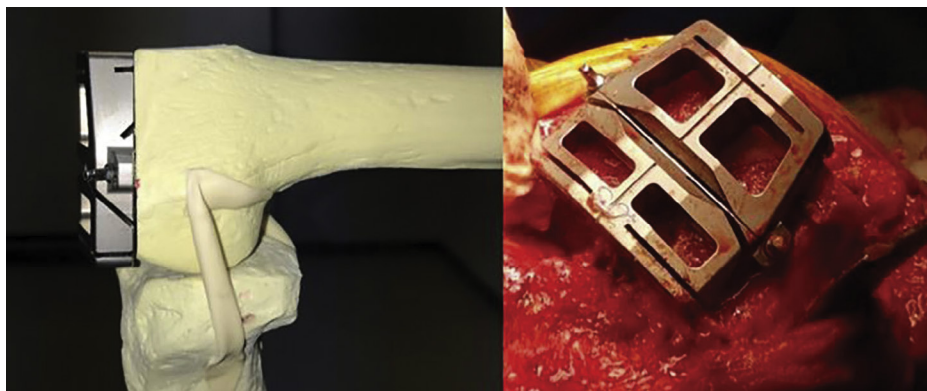
Step 3: Preliminary Trial and Knee Balancing With Shims

Once the femoral preparation is completed and calipers used to ensure the bone cuts were appropriate, a femoral component trial is positioned in situ. The knee is then taken through a range of motion (ROM), and any cartilage and bone loss on the eroded side is compensated for by using a semiflexible shim available in increments of 1 mm, for balancing the knee ([Fig. 14.4](#)).

The knee is then tested for stability through a full ROM, with the patella reduced in the trochlea to avoid tethering. The implant should recreate a negligible V-V opening and lack of rotational movement in full extension, and a physiologic and individualized progressive laxity on the medial and the lateral side with increasing flexion. At 90 degrees, the lateral side should open significantly more than on the medial side ([Video 14.1](#)).

This initial trial with a reduced patella gives valuable information to the surgeon about the balance, soft tissue behavior, and tracking of the patella, before the tibial cut.

Figure 14.3 A 4:1 cutting block placement.



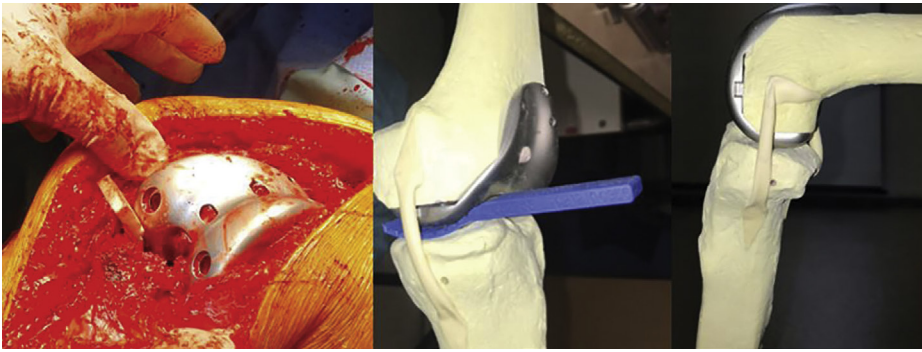


Figure 14.4 Pictures show femoral first trial method with shim compensation at the eroded compartment to achieve in situ balance.

At this step, and before the tibial cut, it is mandatory to check for intimate contact between the femoral trial to the tibial plateau, both medially and laterally at the points of contact. If interference with the eminence or base of the tibial spines is present, or the spines force the femoral component into a nonanatomic position, we recommend resecting them using a saw.

For severe deformities, especially those that present significant tibial bone loss (mainly posterior-medial) it is not uncommon that a thick shim, or even a few shims, are required to balance the knee to achieve the goals of KA: negligible V-V laxity in extension and lateral opening in flexion to varus stress.

Step 4: Linkage and Tibial Osteotomy

The proximal tibia cut can be done independently as described in previous chapters or by a linked method to the femoral component at the end of the preliminary trial step. The idea of this technique is that the femur is prepared for compensating for cartilage loss. Once preparation is complete, a femoral component is positioned, the proximal tibial cutting jig is coupled to the femoral component, and the cut is guided by the already positioned femoral component trial, linking the coronal plane cut of the tibial surface to the distal femur when appropriately balanced in extension and flexion.

LINKED TECHNIQUE FOR PROXIMAL TIBIAL OSTEOTOMY

After completing a satisfactory preliminary trial, the knee is flexed to 90 degrees with the shim in place. Two drill holes are made in the distal holes for the pegs in the femoral component (Fig. 14.5). A device that links the rotational plane of these two

holes to the proximal tibial cutting block is applied in 90 degrees of flexion with the shim still in place (Fig. 14.6). Once the linkage is completed, the tibial cutting jig is pinned in place and the link device is removed.

At this stage, the V-V obliquity of the tibial cut is set, leaving only the resection height (usually 10 mm from the highest tibial-plateau articulating point) and posterior slope to adjust (Fig. 14.7).

The gaps are subsequently rechecked (Fig. 14.8), either with trial components or spacer blocks. As the knee has been already balanced and rectangular space has been created in extension, additional balance is rarely required; however, if required, it will be done by tibial recut (either additional height resection of 2 mm or 2-degrees V-V recut guides) and not by soft tissue release.

Case examples that demonstrate how the principles of the technique are applicable to reconstructing severe deformities follow.

Case 1: Kinematically Aligned Total Knee Arthroplasty for Severe Varus Deformity

A 72-year-old female, 22-years status post left proximal tibial plateau fracture treated with screw fixation, presented with varus deformity and severe disabling left knee pain that had failed conservative treatment. Her ROM was 5 to 100 degrees of flexion, with 23 degrees of varus deformity (Fig. 14.9). The patient underwent KA TKA with the addition of a tibial stem to support the proximal medial tibial bone after the removal of

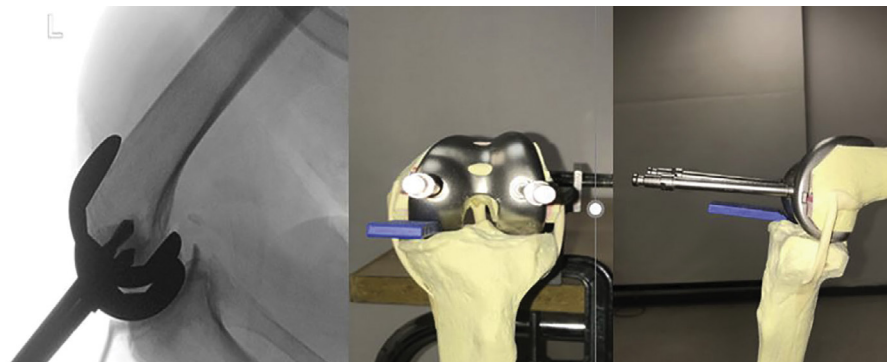


Figure 14.5 The knee is flexed to 90 degrees with the compensating shim in place. Two drill holes are made into the distal holes for the pegs in the femoral component.

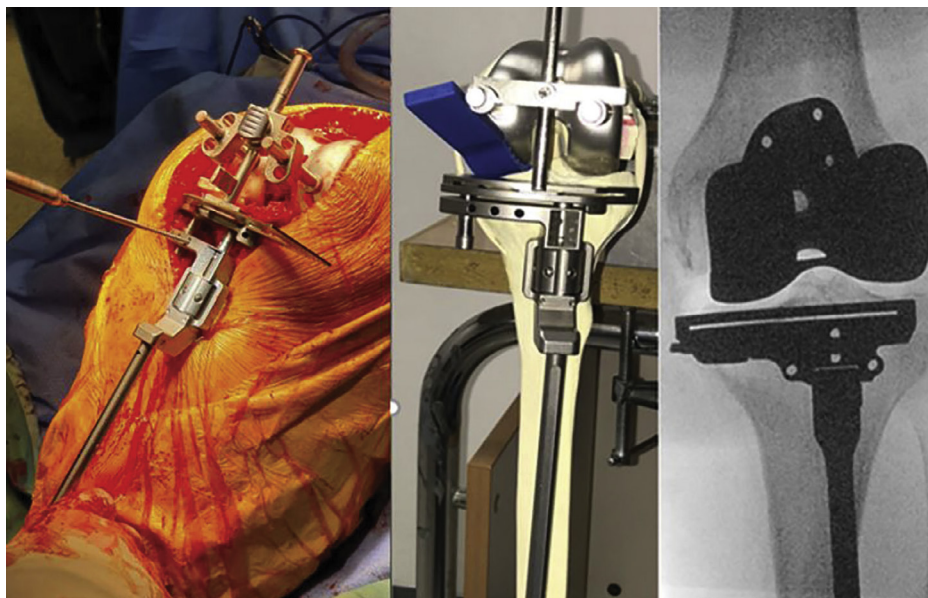


Figure 14.6 Photos demonstrate the linkage device that connects the tibial cutting jig to the femoral component and automatically restores the prearthritic alignment of the tibia.

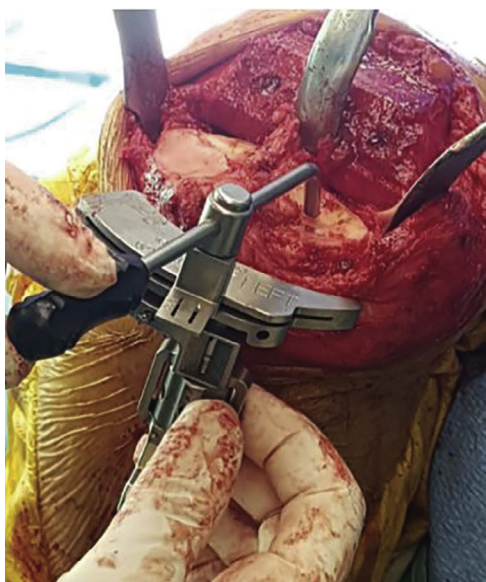


Figure 14.7 Recheck of resection height and posterior slope before tibial proximal bone cut.

the previously placed hardware. Furthermore, an intraoperative evaluation of the wear pattern of the medial femoral condyle revealed bone loss, and the decision was taken to compensate for this with a 1-mm shim to restore the native 3D position of the femur. Caliper measurements of a 5-mm distal medial femoral condylar resection and an 8-mm distal lateral femoral condylar resection confirmed that the correct planned resection was performed but that a 1-mm shim would be required medially. When evaluating the cartilage of the posterior femoral condyle, we noted an uncommon wear pattern requiring compensation with a 2-mm shim to restore anatomic rotation and AP component placement. Following resection, a caliper was used to confirm a 5-mm posterior medial and 7-mm posterior lateral cut.

At this point, the femoral trial was seated, and the knee was taken through full ROM. Significant medial opening to valgus stress was noticed, and a 9-mm shim was needed to recreate the desired balance with no opening to stress in extension on either the medial or the lateral side and, in flexion, a slight medial opening to valgus stress and slightly bigger lateral opening to varus stress laterally. The Link device (Medacta International) was then applied according to the technique described

Figure 14.8 Pictures show gap evaluation with spacer block in full extension and 90 degrees of flexion.

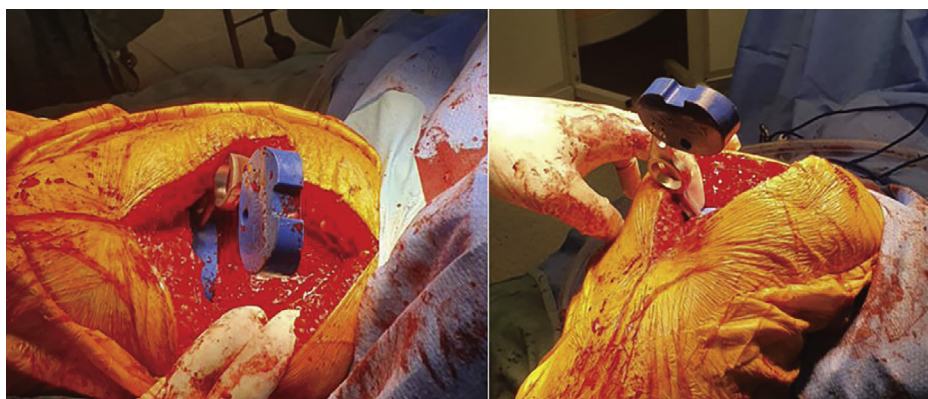




Figure 14.9 Preoperative X-rays: severe osteoarthritis with pronounced medial compartment wear.

previously, the tibial cutting block pinned to the tibia, and the tibial cut performed.

The knee balance was rechecked with trial components and found to be satisfactory.

At 1-year follow-up, the patient reported high satisfaction (OKS Oxford knee score: 41, FKS functional knee score: 68), her ROM was 0 to 115 degrees, and she ambulated freely without assistive devices.

The case demonstrates how KA TKA and the use of the linked tibial cutting technique can address severe varus deformity with bone loss. An alignment correction of more than 20 degrees was achieved by restoring her native femoral anatomy and using it to define the placement of the tibial tray while respecting her native soft tissue envelope (Fig. 14.10A). Comparison with the healthy contralateral knee on a standing radiograph shows that the valgus alignment was corrected and that it approximates that of the native knee. A common belief is that KA TKA will always end up with varus angulation at the tibial side—this case emphasized that this belief is wrong and irrelevant. KA TKA will recreate the tibia to its correct position as dictated by the soft tissue envelope and will restore individual alignment.

Similar principles can be demonstrated in a patient with a history of a lateral tibial plateau fracture and KA TKA resulting in restoration of native alignment (Fig. 14.10B).

Case 2: Kinematically Aligned Total Knee Arthroplasty for Severe Valgus Deformity

A 66-year-old male presented with severe bilateral valgus knees because of end-stage osteoarthritis (Fig. 14.11) after having failed conservative treatment. He was more painful on the right side.

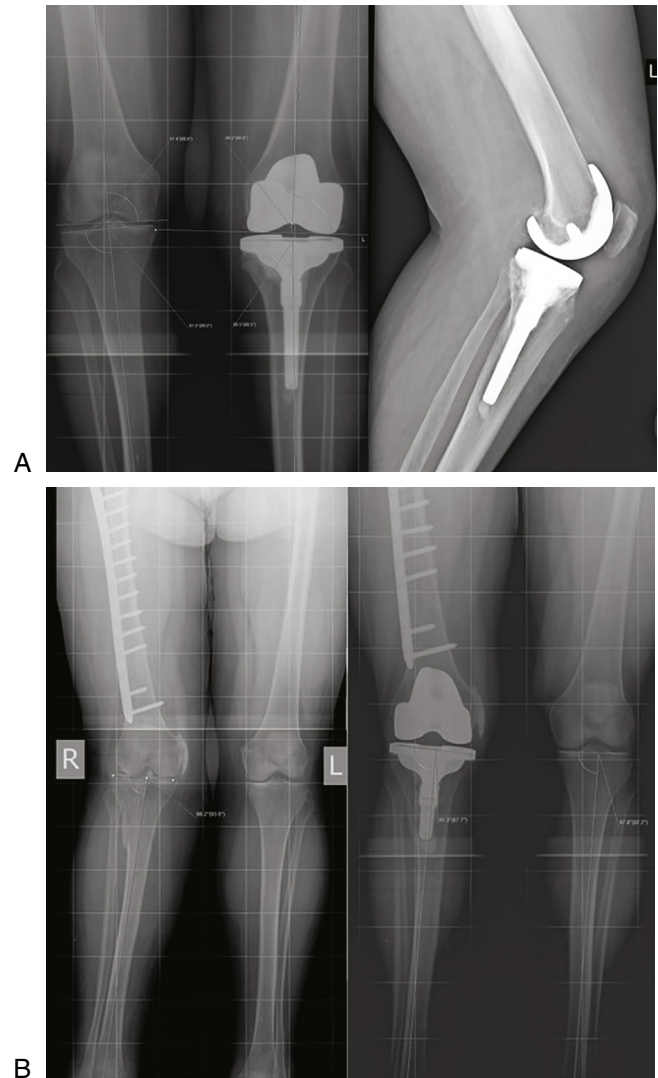


Figure 14.10 (A) Postoperative X-rays showing symmetrical restoration of alignment to the contralateral limb. (B) Preoperative X-rays showing posttraumatic valgus deformity caused by lateral plateau fracture; postoperative X-rays reveal kinematically aligned total knee arthroplasty with symmetrical restoration of limb alignment and joint line obliquity.

The patient was operated using a KA technique (Fig. 14.12). Postoperative X-rays of the right knee are shown in Fig. 14.13.

Two months later, his left knee was operated using the same KA technique. The distal femoral resection was performed using a cutting block with a 2-mm lateral build-up, and calipers were used to confirm an 8-mm distal medial resection and a 6-mm distal lateral resection from the femoral condyles.

The intraoperative femoral sizing allowed compensation for the posterior lateral cartilage loss. This was done by using a 2-mm blue shim placed between the posterolateral femoral condyle with the femoral sizing guide set to 0 degrees of rotation. Unlike varus knees, valgus knees often present with posterior-lateral cartilage wear (Fig. 14.14).

After completion of femoral preparation and the use of calipers to ensure appropriate bone cuts, the femoral component was applied for the preliminary trial (Fig. 14.15).



Figure 14.11 Clinical image and X-ray showing severe bilateral valgus deformity.

The Link device is applied to link the femoral trial to the tibial cutting jig. The knee is balanced in extension with shims inserted in the lateral joint space until there is negligible V-V laxity. The knee is then flexed to 90 degrees.

Two blue shims were used to compensate for a 5-mm gap attributed to bone and cartilage loss from the posterolateral femur and proximal lateral tibial plateau (Fig. 14.16). The ability to place shims for compensation of the tibial erosion after positioning the femoral component allows the surgeon to test the knee through a full ROM and check if the balance of the knee

has been restored to a perfect rectangular space in extension, while restoring the native nonrectangular and patient-specific gap in flexion.

A postoperative standing AP view is shown in Fig. 14.17, demonstrating bilateral symmetrical recreation of constitutional valgus alignment (originated by pronounced femoral valgus angle of this specific patient morphotype).

At follow-up of 2 years, the patient reported high satisfaction with full ROM and high mobility (OXS: 42, FJS: 72).

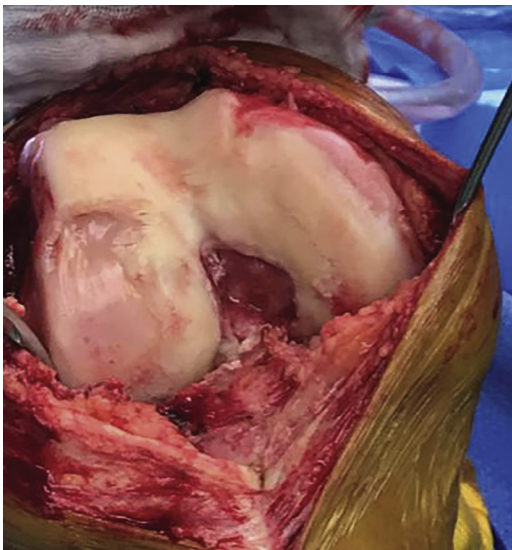


Figure 14.12 Intraoperative findings typical of lateral compartment wear in valgus disease.



Figure 14.13 Postoperative right knee X-ray showing restoration of constitutional native valgus alignment.

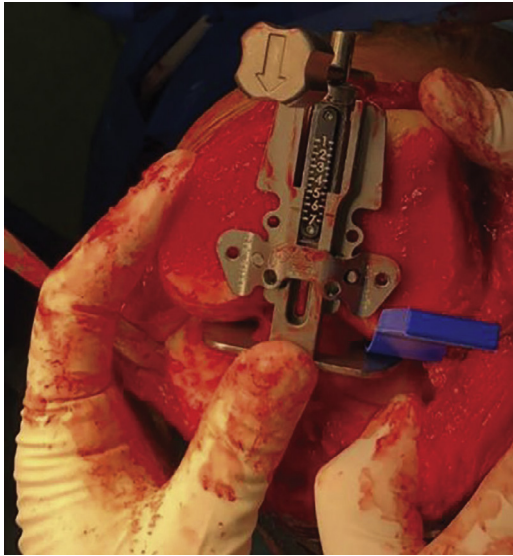


Figure 14.14 Intraoperative findings typical for valgus knees, with additional wear of the posterior lateral condyle that needs to be compensated for by using a 2-mm shim.

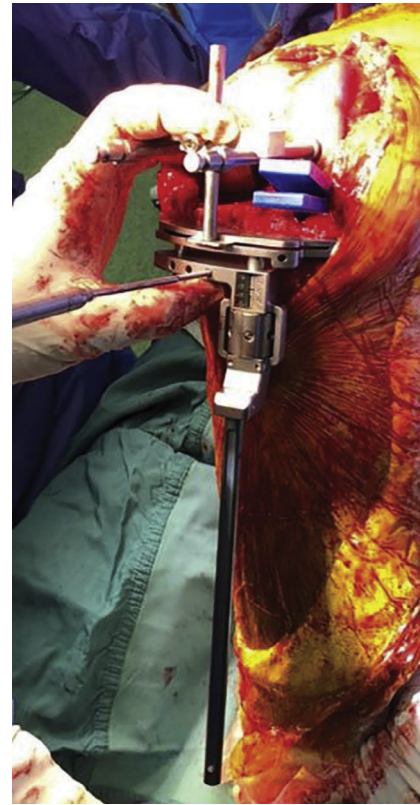


Figure 14.16 Linkage of femoral tibial articulation cuts through shim compensation in the lateral joint space because of lateral tibial erosion attributed to valgus deformity.

Case 3: Kinematically Aligned Total Knee Arthroplasty for Severe Posttraumatic Extraarticular Deformity

A 67-year-old-male with a history of remote severe traumatic war injury of his lower extremities was treated with cast immobilization and no hardware (Fig. 14.18). The left knee showed relative preservation of overall axial alignment of the joint line relative to the floor, while there was significant deformity of the right knee.

The patient underwent a left TKA using KA in 2016 (Fig. 14.19) with the assistance of patient-specific instrumentation guides (PSIs) to restore neutral alignment. Normal postoperative course with satisfactory clinical outcome was reported by the patient at follow-up.

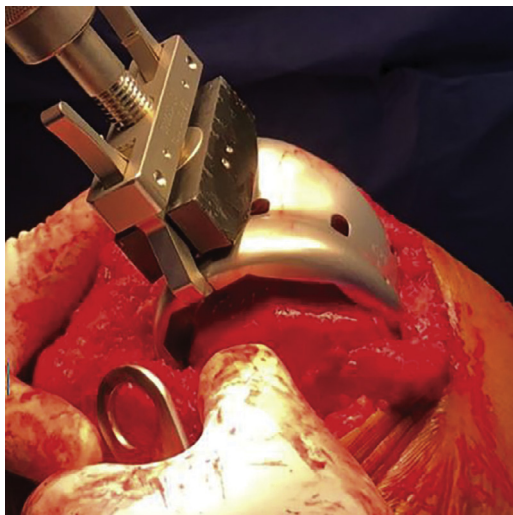


Figure 14.15 Positioning of femoral trial for femoral trial first evaluation.

In 2018, the patient was evaluated for right total knee replacement (Fig. 14.20) and, owing to the complexity of the deformity, a 3D computed tomography (CT) reconstruction was requested.

The right knee was operated using the KA technique in 2018 with the goal of maintaining the joint line and correcting coronal



Figure 14.17 Postop X-rays showing symmetrical anatomic knee angle restoration of constitutional valgus alignment.



Figure 14.18 X-rays showing severe posttraumatic malalignment with end-stage arthritis.

deformity in such a way as to respect the soft tissue envelope and without performing any soft tissue releases (Fig. 14.21).

At 1-year follow-up, the patient reported satisfactory clinical results with subjective preference toward the right knee that was kinematically aligned (OKS left: 34, OKS right: 36).



Figure 14.19 X-ray showing good mechanical alignment restoration of left knee.

Case 4: Approach to the Treatment of Long-standing Extraarticular Deformities That Are at a Distance From the Joint

A 59-year-old female presented 27 years following a proximal femur fracture treated in traction. She complained of a painful left knee that has failed conservative treatment (Fig. 14.22).

The patient underwent a simple KA TKA (Fig. 14.23) in which the proximal femoral deformity was largely ignored. The patient had early satisfactory clinical outcomes despite being

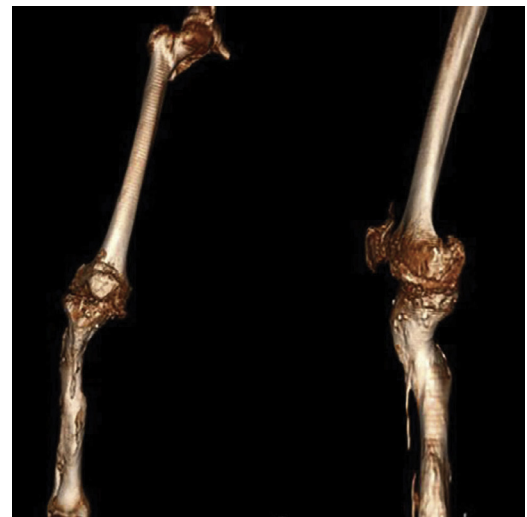


Figure 14.20 Computed tomography reconstruction of patient's right knee.



Figure 14.21 Postoperative standing X-ray showing left knee that was operated using kinematic alignment technique without release. Notice that the joint lines are not symmetric or parallel to the floor because of both knees having extraarticular acquired deformities. Any attempt to correct these angular deformities within the soft tissue envelope of the ligamentous structures of the knee would have led to an unbalanced knee requiring asymmetric soft tissue releases. In our practice, these very stable knees have excellent clinical outcomes and no tendency toward early failure.



Figure 14.23 Postoperative long-standing X-ray—the extraarticular femoral deformity was ignored while native restoration of the knee joint was performed with kinematically aligned total knee arthroplasty. The overall joint-line obliquity angle in a few degrees of valgus is very similar to the contralateral unoperated side.



Figure 14.22 EOS (low-dose full body medical imaging system) and computer tomography coronal view of knee joint showing medial compartment arthritis and a valgus joint line obliquity angle.

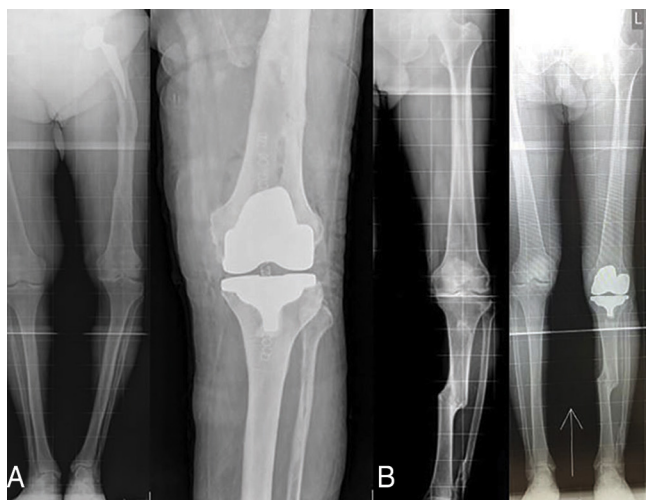


Figure 14.24 (A) Kinematically aligned (KA) total knee arthroplasty (TKA) for proximal extraarticular deformity of the femur and (B) KA TKA for midshaft tibial deformity.

very active (OKS: 42, FJS: 72). Before surgery, a discussion with the patient was had regarding the possibility of second-stage corrective femoral osteotomy; however, following her successful TKA, the patient has declined that operation.

The same reconstruction principles may be shown in the cases shown in Figs. 14.24A and 14.24B with a presentation of longstanding extraarticular deformity (either proximal femoral or distal tibial) that is distinct from the joint. In both cases, the deformity was largely ignored and the TKA was implanted to replicate native anatomy while adjusting for wear, replicating the joint line and respecting the soft tissue envelope. No releases were required.

Case 5: Posttraumatic Deformity Assisted by Patient-Specific Instruments Combined With Linked Kinematic Alignment Total Knee Arthroplasty

A 30-year-old male presented 6 years after a gunshot wound to his left knee. He had had multiple operations, the last of which, an osteochondral allograft (Fig. 14.25A) and a protective closing wedge tibial osteotomy (Fig. 14.25B), were done in 2017. He presented with a failed allograft with extensive posttraumatic cartilage wear, inability to bear weight, a stable medial collateral ligament, and a stiff knee with ROM from 10 to 85 degrees of flexion.

We chose to reconstruct his left knee by using the right knee as a reference point. A CT scan was used. The right knee was noted to have a constitutional varus with a 176-degree HKA, 7 degrees of tibial varus, and 3 degrees of femoral valgus. The left knee, in contrast, had a 168-degree HKA, thanks to 16 degrees of varus on the previously osteotomized tibia and 4 degrees of valgus on the femur.

The plan was to address bone loss with augments and to use stems to stabilize the components. Owing to the interferences with the lateral cortex, we had to limit tibial varus and perform what has been described as a restricted KA TKA,

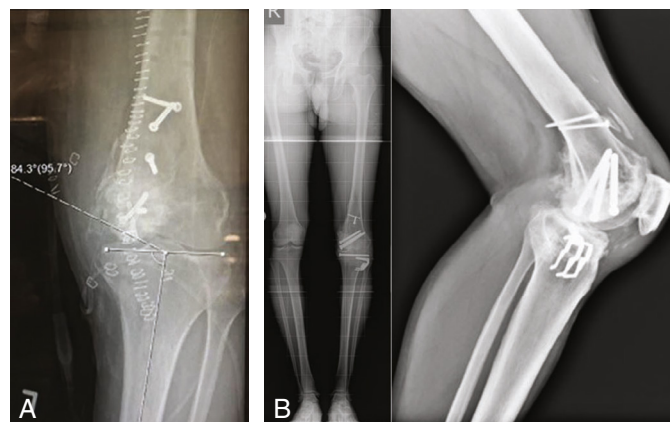


Figure 14.25 (A) X-ray demonstrating the left knee joint after allograft implantation and before a lateral closing wedge protective osteotomy. (B) X-rays showing posttraumatic state of left knee joint.

while matching the pretraumatic native alignment as best as possible (Figs. 14.26A and 14.26B).

An ultracongruent tibial articulation was chosen rather than a constrained implant, to minimize bone loss.

Femoral resections were made with the assistance of a patient-specific guide to restore the femoral valgus. A trial femur with trial augments was seated and the knee taken through a ROM. This was followed by using the linked tibial resection technique discussed in this chapter (Fig. 14.27).

Postop X-rays (Fig. 14.28) demonstrate planned re-creation of alignment with close to native joint-line obliquity restoration.

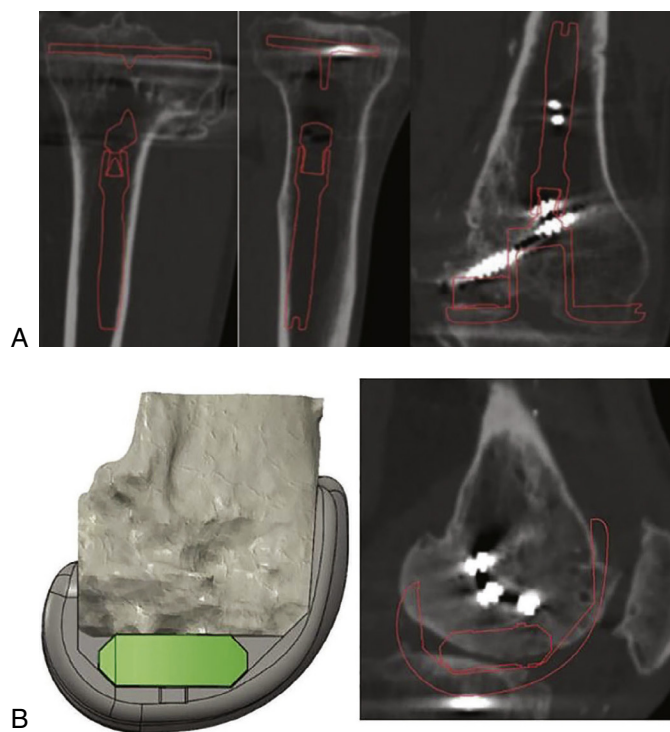


Figure 14.26 (Case 5) (A) Planned stem to support the prosthetic construct because of bone deficiencies. Notice that unless one restricts the tibial joint line angle, the stem size selected would interfere with the medial cortex. (B) Planned femoral augmentation to compensate for bone loss and restore alignment.

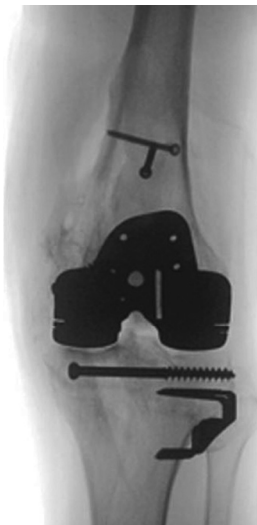


Figure 14.27 Intraoperative fluoroscopy demonstrates the recreation of the planned restoration of femoral valgus, which was a correction from 16 degrees of femoral varus.

The patient exhibited a fast recovery with high satisfaction, and a ROM of 5–120 degrees of flexion at 6-month follow-up (OKS: 39, FJS: 65). [Video 14.2](#) shows the patient at their 2-month postoperative visit in the physiotherapy clinic.

Case 6: Posttraumatic Deformity

A 49-year-old woman presented with end-stage osteoarthritis and varus deformity of the right knee. She had suffered as distal femoral fracture in 1992, which had subsequently been treated with multiple operations, including a closing wedge high tibial osteotomy in 2017. X-rays revealed end-stage arthritis ([Fig. 14.29](#)) with a biplanar distal femoral deformity leading to 15 degrees of femoral varus, 7 degrees of tibial valgus, and valgus joint-line orientation angle because of her high tibial osteotomy.

The patient was consulted about various surgical options and decided to undergo a KA TKA with minor restrictions and, possibly, a secondary corrective extraarticular femoral osteotomy at a future date if either the function or the alignment achieved through KA TKA was insufficient.



Figure 14.28 Postoperative X-rays showing the execution of the planned alignment and restoration of the native joint line obliquity.



Figure 14.29 X-rays demonstrating severe multiplanar, combined, iatrogenic, and posttraumatic deformity of both the femur and tibia.

Basic steps of the procedure were as follows:

- Owing to extensive adhesions and contractions found at the time of surgery, a tibial tubercle osteotomy was performed for exposure. Intraoperative limb alignment assessment was done with fluoroscopy ([Fig. 14.30](#)).
- An evaluation of the wear pattern of the distal femur found a worn medial femoral condyle and an unworn lateral femoral condyle ([Fig. 14.31](#)).
- Distal femoral resection was performed with an anterior cortex referencing guide followed by caliper checks (6-mm distal medial and 8-mm distal lateral; [Fig. 14.32](#)).
- To help correct the extraarticular varus deformity, the cartilage on the lateral femoral condyle was also removed before seating the distal femoral cutting block. The effect was to decrease varus while using worn-medial and unworn-lateral block ([Fig. 14.33](#)).
- A second manual correction to the existing anatomy was performed by not compensating for posterolateral wear



Figure 14.30 An intraoperative picture of a guidewire positioned at the femoral head down to the center of the talus was taken to demonstrate limb alignment.

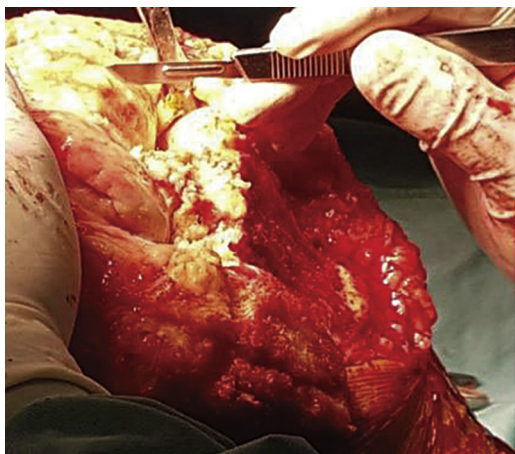


Figure 14.31 Comparison of femoral condylar cartilage wear confirms no cartilage present on the distal medial condyle.

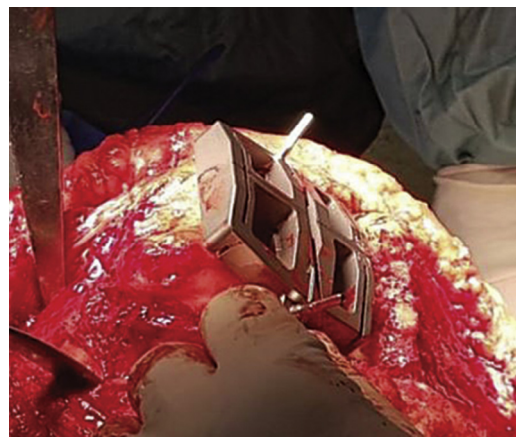


Figure 14.34 Placement of the "4:1" cutting block and posterior osteotomy caliper check (7 mm for each posterior cut).

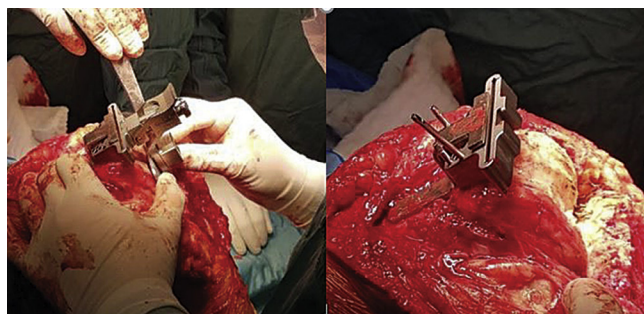


Figure 14.32 Distal femoral jig positioned for distal femoral resection.

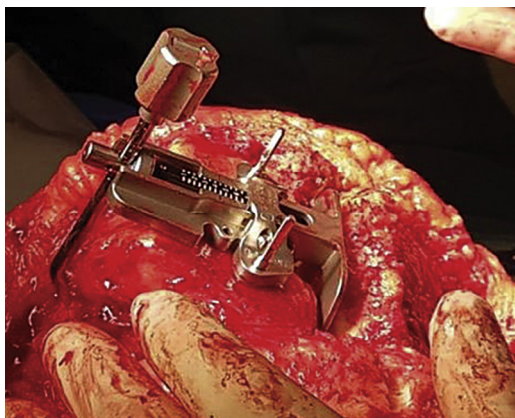


Figure 14.33 Sizing the femur with 0 degrees of rotation relative to the posterior femoral condyles.



Figure 14.35 Initial femoral trial first application.

when setting femoral rotation. Doing so will compensate for decreasing overall valgus by resecting the lateral femoral cartilage (Figs. 14.34–14.37).

Notice that the lateral 2-mm spoon was applied as a third adjustment to help create slightly less valgus on the tibial side (Figs. 14.38 and 14.39).

At 6-month follow-up, the patient reported high satisfaction (OKS: 40, FJS: 68) and ROM –5 to 115 degrees (Video 14.3, 5 months later).



Figure 14.36 Initial evaluation of overall limb alignment under the minor restrictions that were applied.

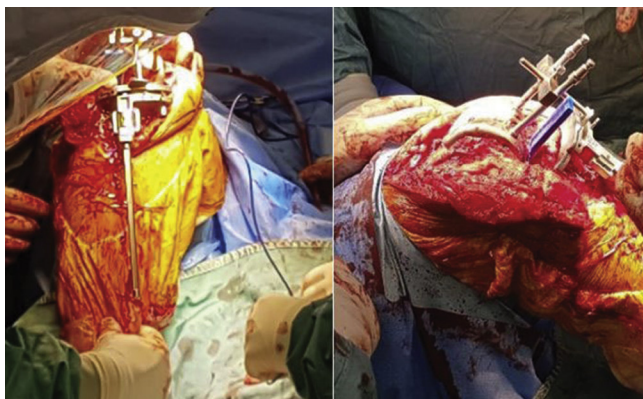


Figure 14.37 Linking the tibia to the femur with shim compensation.



Figure 14.38 Intraoperative fluoroscopy confirms desired alignment and balanced restoration of the articular surfaces without any attempt to restore overall alignment through any extraarticular osteotomy and with only minor, balanced adjustments in the implant positioning.

Summary

The common principle we apply to all severe deformities originates from the understanding and belief that restoring the patient's overall alignment to its prearthritic state without manipulating the soft tissue envelope will result in a more natural joint.

We do not differentiate between long-standing extraarticular deformities and severe deformities because of arthritis, insofar as we aim to restore the articular joint, its corresponding soft tissue envelope, and surrounding muscular structures to the state that is “normal” for the individual patient. This is true even if the joint, as a “unit,” is not in its traditional anatomic position, as is true for complex, multiplanar posttraumatic extraarticular deformities. We treat these the same as common minor arthritic deformity: our KA TKA goal is the same.

The main concern is related to the lack of long-term survivorship of prosthetic constructs positioned with the pronounced angulations typically found with severe deformities.

This concern has been slowly but repeatedly addressed during the last decade as more evidence to support the neglect of old dogmatic MA assumptions is becoming evident.^{25–28}

Unlike in MA TKA, for example, severe deformity does not require extensive releases of soft tissue. We can achieve



Figure 14.39 Postoperative X-rays confirm that joint resurfacing has been achieved.

the desired physiologic correction of the HKA toward pre-disease individual alignment and restore the patient's natural joint-line obliquity. It is our experience that reconstructing the knee using KA principles in severe deformity improves patient pain and motion without creating the sensation of a nonnatural knee that we typically used to see when applying MA principles.

There is a delicate balance between the unknown long-term survivorship of this new technique and the better functionality and superior satisfaction achieved in this unique patient group. We recommend consulting the patient and letting them make an informed decision. Choosing to perform MA TKA in these patients also has clear and well-documented risks.

Acknowledgment

The authors of this chapter would like to acknowledge Dr. Steven Howell for his enormous contribution for the KA field, not only as the pioneer and leading researcher of the philosophy and technique, but also for his long and continuing effort to provide the “backup,” both surgically and scientifically, that supports our vital mission to better treat our patients. We can see already how his endless efforts will lead to a paradigm shift toward KA in knee arthroplasty. Without both his initial and more recent evidence, we would not have come to a point of enlightenment and would not have changed our practice for the daily benefit of our patients.

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Kinematic Alignment Technique for Unicompartamental Knee Arthroplasty

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CHAPTER OUTLINE

Overview

Definition

Rationale

Expected Benefits and Evidence

Surgical Technique

Overview

The kinematic alignment (KA) technique for unicompartamental knee arthroplasty (UKA) has been successfully performed for decades and presents potential clinical benefits. The discussion and videos in this chapter assist the surgeon in understanding how to perform KA UKA with the calipered technique. The first section defines the KA UKA technique; the second section provides the rationale; the third lists the potential benefits of this technique and summarizes the evidence; the final section briefly describes the surgical technique for medial KA UKA. Our objective is to encourage surgeons to use the KA UKA technique because it is a simple, safe method with a more physiologic outcome. It presents multiple potential advantages over the traditional MA technique, and further investigations are needed to better define its clinical impact and the limits for alignment of components.

Definition

See [Video 15.1](#) Discussion on the definition of the kinematic alignment technique for unicompartamental knee arthroplasty.

Traditional techniques for partial or total knee arthroplasty (TKA) recommend positioning components in a systematic orientation, thereby neglecting the anatomic variation of the individual knee. The standard for decades has been to frontally align the components perpendicular to the femoral and tibial mechanical axes, and to produce an identical tibial slope for all patients; this is known as the mechanical alignment (MA) technique for TKA¹ and UKA.² Although MA prosthetic knees altered the knee anatomy and physiologic soft tissue balance, the technique was thought to improve the reproducibility of the implantation. Nevertheless, function and perception of these MA prosthetic knees have been disappointing,^{3,4} despite great advancements in implant design and surgical precision.^{5,6} This has led to the development of more personalized and physiologic techniques of implantation, which respect the individual knee anatomy and soft tissue balance, known as kinematic alignment (KA; [Fig. 15.1](#)).^{1,7}

Similar to the KA TKA, the goal of the KA UKA is to coalign UKA components with the kinematic axes that dictate native motion of the tibia around the femur.^{8,9} Components are therefore aligned parallel and perpendicular to the cylindrical axis and longitudinal tibial axis, respectively ([Fig. 15.2](#)). In simplistic terms, the KA technique for UKA aims to produce a “true resurfacing,” restoring the native joint line level and orientation in the implanted knee compartment ([Fig. 15.3](#)). In the case of medial UKA, the individual medial and posterior slopes of the medial tibia plateau and the frontal and axial orientation of the medial femoral condyle are therefore restored ([Fig. 15.3](#)). The KA technique for UKA was popularized decades ago under the name ‘Cartier Angle’ technique.^{10,11} Philippe Cartier developed this technique in the 1970s and was influenced by works from Christophe Levigne and Michel Bonnin (Lyon School), who first described the proximal tibia metaphyseal-epiphyseal axis.¹²

The KA and MA techniques differ at almost every step of the procedure (see the Surgical Technique section further in this chapter), with different goals for aligning UKA components.⁸ It is therefore important when assessing UKA component performance to consider the technique of alignment by distinguishing between KA and MA positioning of components ([Fig. 15.4](#)).⁸ The terminology describing the alignment technique is derived from the reference landmark used to align UKA components: the KA and MA techniques respectively align the UKA components on the kinematic axes of the knee and the mechanical axis of long bones ([Figs. 15.4](#) and [15.5](#)).

Rationale

See [Video 15.1](#) Discussion on the rationale for the kinematic alignment technique for unicompartamental knee alignment.

KA is a personalized, physiologic technique that intends to restore the unique individual knee's soft tissue balance and kinematics, and to optimize the bone loading and dynamic interaction between components ([Figs. 15.1, 15.2, 15.4, and 15.5](#)). This is in contrast to the MA technique for UKA, whereby posterior and frontal tibial slopes usually alter the medial knee compartment anatomy, balance, and biomechanics,^{8,9} making the MA technique less physiologic.

By respecting the individual anatomy of the knee compartment, namely the joint line height and orientation of articular surfaces, the KA technique is biomechanically sound. The components are aligned on the knee's native kinematic axes that dictate the physiologic motion of the tibia around the femur. Restoration of the natural medial collateral ligament tension and knee kinematics is enabled. In addition, the tibial component is positioned perpendicular to the subchondral trabeculae, the orientation of which are dictated by

Figure 15.1 This figure illustrates the multiple knee arthroplasty options for treating osteoarthritic varus knees. The kinematic alignment (KA) techniques for unicompartamental (UKA) and total (TKA) knee arthroplasty are the only options that aim to restore the patient's pre-arthritic anatomy and soft-tissue balance; they are de facto personalized and physiological methods to implant knee prosthetic components. AA, Anatomical alignment; aMA, adjusted mechanical alignment; MA, mechanical alignment; rKA, restricted kinematic alignment.

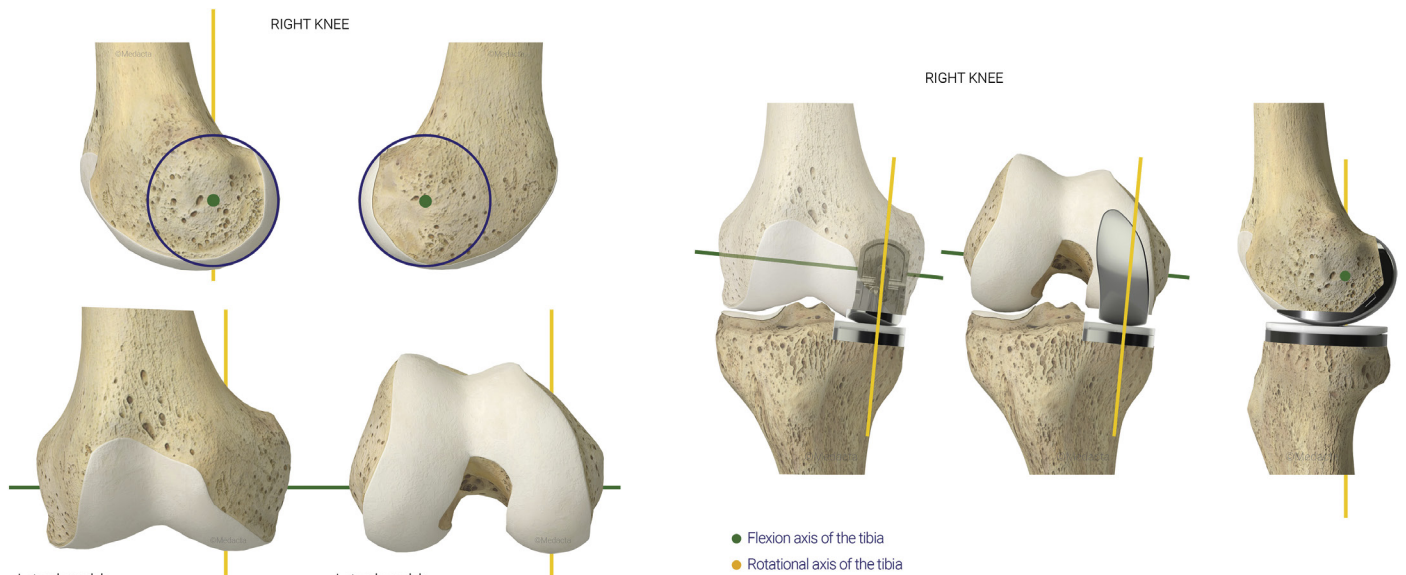
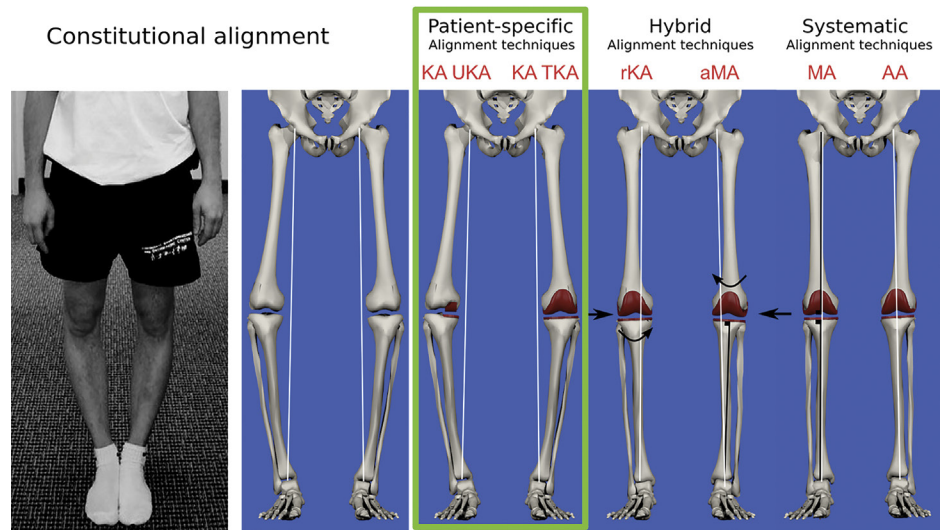
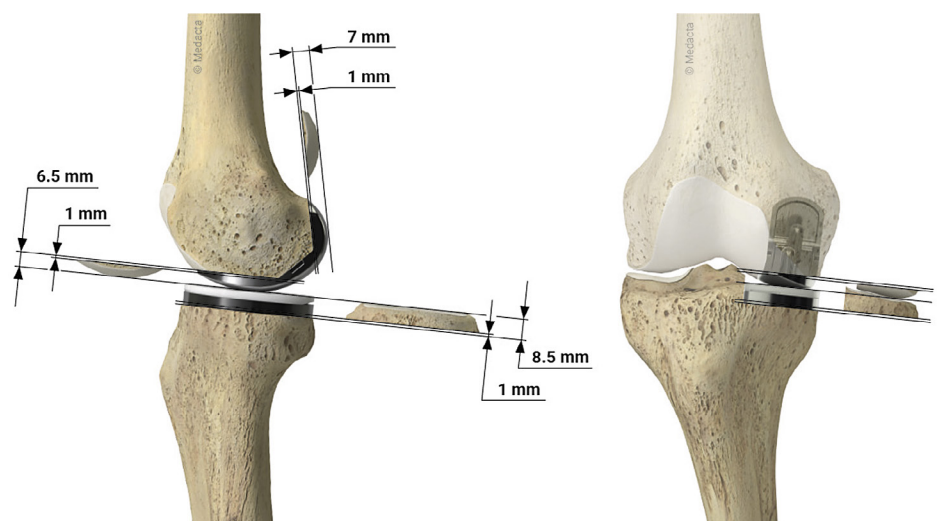


Figure 15.2 This figure illustrated the “academic definition” of a kinematically aligned medial unicompartamental knee arthroplasty. Implants are aligned parallel to the cylindrical axis (or flexion axis of the tibia—green line) and perpendicular to the longitudinal tibial axis (or rotational axis of the tibia—yellow line). These knee kinematic axes dictate the movement of the tibia around the femur.

Figure 15.3 This figure illustrates the “simple definition” of a kinematically aligned medial unicompartamental knee arthroplasty. Implants aim for a “true resurfacing” of the medial knee compartment. Implant thickness equals the sum of the bone cut thickness, the 1-mm saw kerf, and the 2 mm of cartilage loss. By doing so, the physiologic knee soft tissue balance and kinematics are likely to be restored, and optimal clinical outcomes generated.



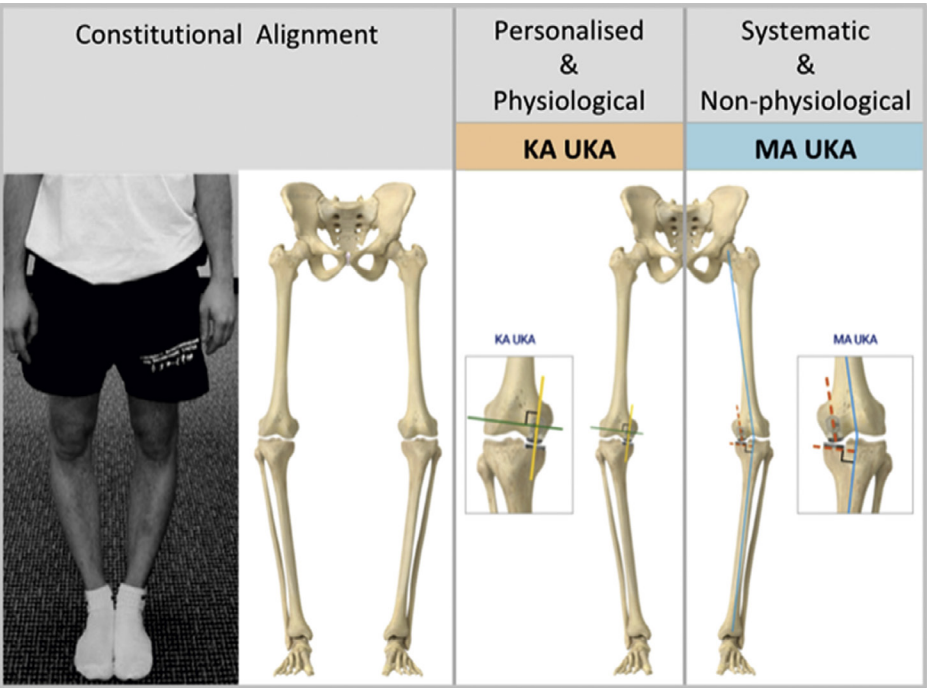


Figure 15.4 This figure illustrates the two main options for aligning medial unicompartmental knee arthroplasty (UKA) components. The personalized and physiologic kinematic alignment (KA) technique aims to position components on the knee kinematic axes that dictate movement of the tibia around the femur. The systematic mechanical alignment (MA) technique refers to the long-bone mechanical axis to orientate the components, which is not physiologic. *Green line: cylindrical axis, yellow line: longitudinal tibial axis, blue line: mechanical axis of femur (upper line) and tibia (lower line).*

Wolff’s law, adapted to mechanical loads,¹³ and parallel to the ground during gait.¹⁴ The more physiologic the loading of the tibial bone, the more the shear stress at the bone-implant fixation interface is reduced, thereby potentially benefiting the implant’s life span.

Similarly to KA TKA, respecting knee anatomy when implanting UKA components adequately restores the native knee’s soft tissue balance and kinematics, thereby producing optimal clinical outcomes.^{1,8,15} This approach is echoed by many studies that have reported on the deleterious effect of altering the medial tibia plateau anatomy when implanting medial UKA.^{16–19}

Expected Benefits and Evidence

See [Video 15.1](#) Discussion on the expected benefits of and the evidence on kinematic alignment unicompartmental knee arthroplasty.

Although both KA and MA techniques for UKA aim to restore the constitutional standing lower limb and knee alignment, the KA technique is likely to better replicate the natural dynamic limb/knee frontal alignment (particularly during knee flexion), as the individual tibial slope is not altered. As a consequence, KA enables more physiologic knee biomechanics through decreased alteration of anatomy and soft tissue balance.

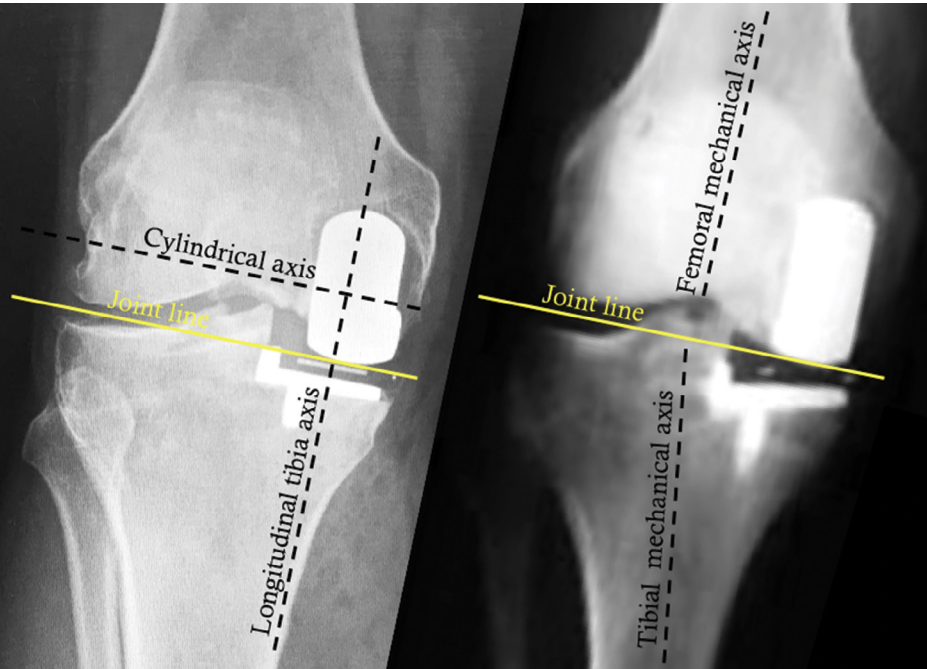


Figure 15.5 This composite of radiographs illustrates the frontal radiographic appearance of kinematically aligned (left image) and mechanically aligned (right image) aligned medial unicompartmental knee arthroplasty (UKA). When kinematically aligned, the UKA components are positioned on the kinematic axes that dictate the motion of the tibia around the femur. When mechanically aligned, the UKA components are positioned alongside the tibial and femoral mechanical axes. Note the mechanical alignment technique has resulted in a tibial implant that may concentrate excessive load on the medial cortex, and result in a slight eccentric loading of the polyethylene liner by the femoral component.

The KA UKA technique presents multiple theoretical benefits over the MA technique; however, some of these have yet to be demonstrated scientifically. This relative absence of evidence is rooted in the fact that alignment of UKA components has been poorly debated thus far, and no study on UKA has ever focused on comparing the value of alignment philosophies.⁸ However, there are several aspects of KA principles that are theoretically beneficial to UKA.

First, the KA technique preserves tibial bone stock and loads the supporting tibial bone more physiologically (toward the metaphysis)^{20–22} than MA techniques. This reduces the risk of stress and excessive tibial cortex loading, thus potentially preventing complications such as tibia plateau fracture and residual pain from bone remodeling that some authors have identified in UKA.^{20–22} Second, by restoring the native tibial plateau's posterior slope, the KA technique potentially generates a more physiologic soft tissue balance by preventing mismatch between flexion and extension (more precisely 90-degrees and 10-degrees knee flexion) gap laxities. This may reduce complications such as residual pain and stiffness, and clinically detrimental poor prosthetic knee kinematics.²³ Third, the KA technique enables components to remain perpendicular relative to one another throughout the knee's range of motion, therefore creating optimal dynamic component interaction that may reduce complications related to liner edge loading (dislocation for mobile liner, accelerated polyethylene wear for fixed liner). Fourth, it has been shown that the Oxford® UKA components better fit the supportive bone (less compromise regarding implant overhang and bone undercoverage) when kinematically aligned.⁹ Again, this could be clinically beneficial by lowering the risk of residual pain and optimizing implant life span. Finally, it is biomechanically sound to perform KA UKA that places the tibial component perpendicularly aligned to the subchondral trabeculae¹³ and orientated parallel to the ground in weight-bearing positions¹⁴ (reduction of shear stress on implant fixation). By reducing shear stress on implant fixation and reproducing the physiologic metaphyseal bone loading, the KA technique could benefit long-term UKA outcomes.

Many studies have reported good outcomes for KA UKA over the long term, demonstrating acceptable implant life span, excellent functional performance, restored joint perception, and high patient satisfaction after KA-UKA.^{10,12,24–27} By simulating KA medial Oxford® UKA on 40 unselected osteoarthritic knee models, Rivière et al.⁹ found that the orientation of components was always within the acceptable range of alignment, as recommended by the Oxford Group, and that the shape-fit between KA components and supportive bone was improved compared with the MA technique. Three radiostereometric studies found KA component fixation to be reliable, with low component migration up to 2 years postoperatively and that up to 6 degrees of varus orientation for the tibial component is acceptable.^{28–30} Conversely, many studies have reported on the deleterious effect of altering the medial tibia plateau anatomy when implanting UKA.^{16–19} A recent systematic review found nine studies having indirectly compared KA and MA UKA.⁸ Those studies included 593 KA UKAs with follow-up between 3.2 and 12 years. The findings reported high Knee Society Score (KSS) (from 87 to 95), in addition to satisfaction scores of 88% for KA UKA patients. There were low revision rates reported for KA UKA for tibial plateau fracture (0%, no case), unexplained pain (0.8%), tibial component loosening (2%), and any causes of aseptic failures (5.6%). The prosthetic lower limb and tibial

implant alignments were found to be in varus (mean of 3 degrees to 5 degrees), while the postoperative joint line and tibial component were found to be parallel to the floor when standing. The authors concluded KA UKA had good mid- to long-term safety and efficacy but could not determine if one technique was superior to the other. The authors highlighted the need for research specifically focused on comparing the outcomes of KA and MA techniques for UKA.

Surgical Technique

See [Video 15.1](#) Discussion on the surgical steps for performing medial calipered kinematic alignment unicompartmental arthroplasty with the Oxford®.

See [Video 15.2](#) Illustrating the execution of a medial calipered kinematic alignment unicompartmental arthroplasty with the Oxford® components.

Similar to KA TKA, the KA technique for UKA is a measured resection technique that can simply and reliably be performed with manual instrumentation and a caliper-based check of the bone cut thickness. Technological assistance allowing three-dimensional planning (e.g., personalized surgical instrumentation³¹ and robotics) may also be of interest, but is unlikely to be a gamechanger, as the KA technique relies on easily accessible intraarticular anatomic landmarks. KA UKA does not need to establish extraarticular landmarks to identify the long bones' mechanical axes, and the surgeon has the intraoperative ability to quality assure alignment by checking and potentially correcting bone cuts.³¹ The KA and MA surgical techniques differ at every step of the preparation, with the exception of the axial and sagittal rotations of the tibial and femoral components, respectively ([Table 15.1](#)).

It is likely that most UKA designs currently available on the market (fixed or mobile bearing, metal-backed or full polyethylene tibial components, resurfacing or inset femoral components) are suitable for the KA technique; however, only a few of them use instrumentation that allow it. The first author is currently performing KA UKA with the Oxford® (Zimmer-Biomet), using the “Phase 3” manual instrumentation. The Phase 3 was preferred to the Microplasty® instrumentation, as the latter constrains the operator to MA positioning of components. The author has manually performed 80 KA Oxford® medial UKAs over the last 2 years. Of these, one patient had an anterior knee debridement that successfully treated some residual anterior knee pain; no other significant complications or revisions have been recorded (National Joint Registry data). The median Oxford Knee Score and patient satisfaction score at 1-year follow-up were 44 and 98%, respectively (unpublished data). Please refer to [Videos 15.1](#) and [15.2](#), illustrating the KA technique for implanting a medial Oxford®. In these videos you will see a “tibia first” technique, followed by a measured resection of the posterior condyle that sets the flexion gap, followed by distal femoral reaming to balance the flexion and extension (more precisely 90-degree and 10-degree knee flexion) gaps.

Tibial cut ([Fig. 15.6](#)): The tibial cut can easily be performed free-hand by following a K-wire positioned in the joint space, and the anteroposterior axis of the medial condyle's flexion facet.³² These landmarks indicate the native medial tibial plateau's constitutional posterior and medial slopes, respectively ([Fig. 15.6](#)). Once executed, the tibial cut is visually checked to assess the posterior slope (it should parallel the patient's prearthritic slope), the mediolateral width and anteroposterior

TABLE
15.1

The different implant positioning targets between mechanical and kinematic alignment techniques for implanting medial unicompartmental knee arthroplasty

		Mechanical Alignment Technique	Kinematic Alignment Technique
Femoral component	Flexion	Same	
	Frontal cut	Perpendicular to femoral mechanical axis	Parallel to tibial cut
	Posterior cut	Parallel to tibial mechanical alignment cut	Parallel to tibial cut
Tibial component	Axial rotation	Same (Parallel to the lateral wall of the medial femoral condyle)	
	Frontal orientation	Perpendicular to the mechanical axis of tibia	Perpendicular to the antero-posterior axis of the medial condyle's flexion facet
	Sagittal slope	Systematic slope, of which the number varies between 2 degrees and 7 degrees, depending on company and implant design	Parallel to the medial plateau slope

The two techniques differ significantly because only the flexion of the femoral component and the axial rotation of the tibial component are following the same targets.

depth (use of tibial trial for contralateral knee), and the thickness of the resected segment (caliper measurement—in this case the minimum thickness of the Oxford® tibial implant is 6 mm and the resected bone, accounting for lost cartilage and saw kerf, should be at least 6 mm thick). A bone recut may be performed if the initial cut does not meet expectations—this is unusual. For the majority of medial UKAs, the tibial cut is oriented in slight varus, the degree of which varies between individuals to match their anatomy. By following these steps, the tibial component will be aligned parallel and perpendicular to the cylindrical axis of the femur and the tibial longitudinal axes, respectively. By adding the thickness of the bone resected from the proximal tibia, 1 mm for the saw kerf, and approximately 2 mm for cartilage loss in case of antero-medial exposed tibial subchondral bone, the surgeon can adequately determine the thickness of the polyethylene liner needed to restore the prearthritic height of the medial plateau's articular surface.

Femoral cut (Fig. 15.7): The posterior femoral cut is first performed using the measured-resection jig. The axial and frontal rotations of the femoral component are set by following the flexion facet's antero-posterior axis and the medial wall (after

osteophyte removal) of the medial femoral condyle, respectively (Fig. 15.7). A K-wire may be inserted alongside the medial wall, between the medial collateral ligament and the bone, to ease the assessment of the condylar frontal orientation. For the majority of medial UKAs, the femoral component is oriented in slight valgus (Fig. 15.7). Once performed, the adequacy of the thickness of the posterior femoral cut is checked with a caliper. The sum of the resected posterior condylar bone thickness, the 1 mm of bone removed from the saw kerf, and the estimated cartilage loss (if any) must equal the thickness of the implant's posterior condyle. In medial arthritis, with an intact anterior cruciate ligament, the posterior condylar cartilage is generally preserved. Using the Oxford knee technique, the last step is straightforward and consists of balancing the “90-degree” and “10-degree” flexion gaps by way of slight distal femoral reaming. As the femoral component has a resurfacing design of 3.2 to 4.3 mm thickness, and the cartilage is around 2 mm thick, the reaming of the distal femur should only remove 1 or 2 mm of subchondral bone. By following these steps, the femoral component will be aligned parallel and perpendicular to the cylindrical femoral and tibial longitudinal axes, respectively.

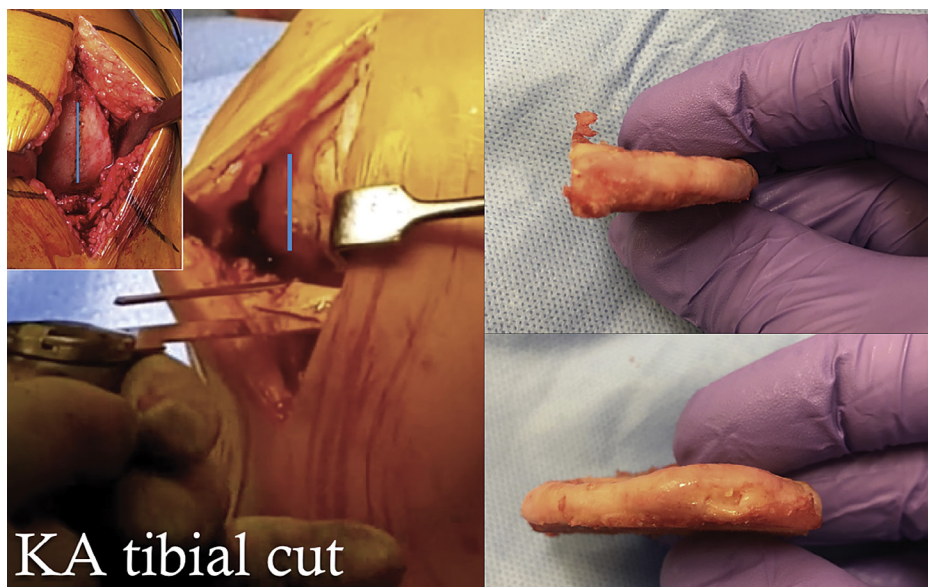
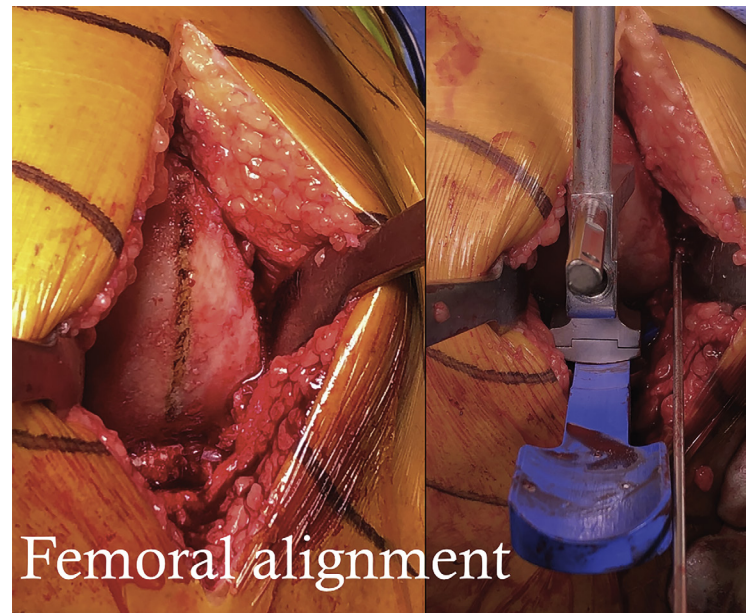


Figure 15.6 This composite of images shows the anatomic landmarks that are used for kinematically aligning the tibial component when performing medial kinematically aligned (KA) unicompartmental knee arthroplasty. The *left* images show the antero-posterior axis of the condyle's flexion facet (*blue lines*) and a K-wire inserted in the joint line on both anterior and posterior lips of the medial plateau. They will respectively serve to adjust the frontal rotation (varus-valgus) and posterior slope of the tibial component. The *right* images show the resulting tibial cut which intends to restore the medial (*above image*) and posterior (*below image*) tibial slopes.

Figure 15.7 This composite of intra-operative photographs shows the anatomic landmarks that are used for kinematically aligning the femoral component when performing medial kinematically aligned unicompartmental knee arthroplasty. The *left image* shows the antero-posterior axis of the condyle's flexion facet that has been drawn with electro-cautery; this line serves to adjust the axial rotation and the medio-lateral position of the femoral component. The *right image* shows the femoral jig aligned with the flexion facet's axis, and a K-wire that is positioned alongside the medial wall of the condyle, indicating its frontal orientation.



Through quality assurance at each step of the surgery (carefully checking bone cuts with a caliper), the decision regarding the final liner's appropriate size may safely rely on the measured thickness of the tibial cut. When selecting the liner, ensuring there is a residual 1- to 2-mm medial laxity when performing the valgus stress test at any degree of knee flexion is of paramount importance. It is possible to undersize the final liner by 1 or 2 mm if one wants to protect the lateral knee compartment by undercorrecting the limb's native constitutional varus alignment.

Summary

The KA technique is a simple, physiologic, and safe method for implanting UKA, and presents multiple potential advantages over the traditional MA technique. Components can be

reproducibly implanted with manual instrumentation. The literature supports its good mid- to long-term clinical safety and efficacy. However, the current literature does not allow a direct comparison of outcomes between KA and MA techniques. Further investigations are needed to better determine the clinical impact of KA in UKA and if there are limits for the safe alignment of components.

Acknowledgments

We thank Cedric Maillot for creating [Video 15.2](#), Illustrating the procedure to implant a medial Oxford KA UKA; Ciara Harman for perfecting the manuscript; and Medacta for providing the images illustrating the kinematic alignment of the MOTO® UKA.

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Postoperative Management

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CHAPTER OUTLINE

Overview

Immediate Postoperative Management

Long-Term Management

Overview

Similar to the preoperative evaluation, postoperative management of the kinematically aligned (KA) patient does not stray from traditional management. Outpatient surgery, physical therapy, and office and radiographic evaluations will certainly vary among surgeons. This chapter presents some framework for optimal care of the KA total knee arthroplasty (TKA) patient.

Given the short-term data and lack of long-term data, patients should be followed closely, and data collection with regards to clinical outcomes and radiographic results is imperative.

Immediate Postoperative Management

Postoperative care of the TKA patient is in a current state of evolution. Advancements in anesthesia and multimodal pain control have made outpatient TKA a common pathway.¹ TKA technique has not been identified as a factor for choosing inpatient or outpatient pathways for patients. There are no aspects of the surgical technique that would increase patient risk in the outpatient surgery setting. Given the fact that KA involves fewer soft tissue releases than other techniques, there may be an advantage to calipered KA, with less postoperative pain, which may facilitate outpatient management. However, this has not yet been proven. If a physician is comfortable with outpatient TKA using mechanical alignment (MA) techniques, there should be no issues transitioning to the KA technique and still using an outpatient pathway.

Physical therapy has long been a staple in postoperative protocols for TKA. With the advent of bundled payments and cost reductions, many traditional postoperative care modalities are being scrutinized for their necessity. A recent study determined that unsupervised home programs were not inferior to formal outpatient postoperative physical therapy.² Many of the authors in this book use a home therapy program after KA TKA, supplemented when necessary with formal therapy in patients who are having trouble with their recovery. Again, a surgeon utilizing a postoperative protocol that includes formal outpatient physical therapy would not need to change once they transition to utilizing a KA technique.

The need for radiographs and the number of follow-up visits after TKA are both elements of the postoperative protocol

that are difficult to standardize. Immediate postoperative short-film X-rays after KA TKA will often appear startling when compared with traditional MA TKA radiographs. This is largely because radiology technicians are taught to align the cassette with the long axis of the tibia and frequently are not able to obtain a true anterior-posterior (AP) view of the knee. The rotation effectively increases the projected slope of the tibia on the two-dimensional plate, whereas placing the tibia parallel to the cassette makes the joint line appear artificially in varus relative to the “floor” when the image is viewed on a screen. Therefore, immediate postoperative X-rays of the knee are of little value. Full-length, standing cassette radiographs are preferred for evaluating and confirming restoration of patient’s pre-arthritis alignment (Figs. 16.1 and 16.2). Full-length hip-knee-ankle images are often more easily obtained 6 weeks to 3 months postop. However, a standing short cassette AP and lateral knee can be used to check the joint line inclination angle and posterior tibial slope on the tibial side, and femoral joint line angle, posterior offset, and rotation of the femoral component. When assessing for rotation, only a computed tomography (CT) scan can reliably assess a true rotational measurement.

The importance given to physical examination findings or those of a physical therapist treating the patient are also surgeon dependent. Given fewer soft tissue releases, postoperative stiffness should be encountered less with KA TKA. Most KA surgeons note that their patients regain range of motion (ROM), particularly flexion, faster than their historical MA patients. However, some patients simply have a longer recovery. Swelling, ecchymoses, pain, arthritic joints elsewhere, and morbid obesity are just some of the factors that can delay recovery in KA patients, as in any other TKA procedure. It has been our experience that if the knee is allowed to heal and the swelling allowed to decrease, KA knees very seldom stay stiff past 3 months. Manipulations, if deemed necessary by the surgeon and patient, are generally performed from 6 weeks to 3 months. Some KA surgeons will wait as long as a year before a manipulation. See Chapter 17 for a more in-depth discussion of stiffness following KA.

The postoperative protocol any one surgeon chooses to follow may vary. A goal for all KA TKAs is a restoration of patient’s pre-arthritis joint lines alignment, which can be confirmed with a long standing radiograph. A CT scan can also assist with confirmation of rotational alignment of the components but adds exposure and cost. Clinical outcomes are best collected using standardized patient-reported outcome measures. The Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) and the Forgotten Knee Score are probably the most sensitive measures to functional outcome improvements seen with KA, of the measures available. As we move into a value-based model for health-care delivery, reducing any extraneous unnecessary costs such as outpatient formal physical therapy, extraneous radiographs, and frequent office visits will be imperative.

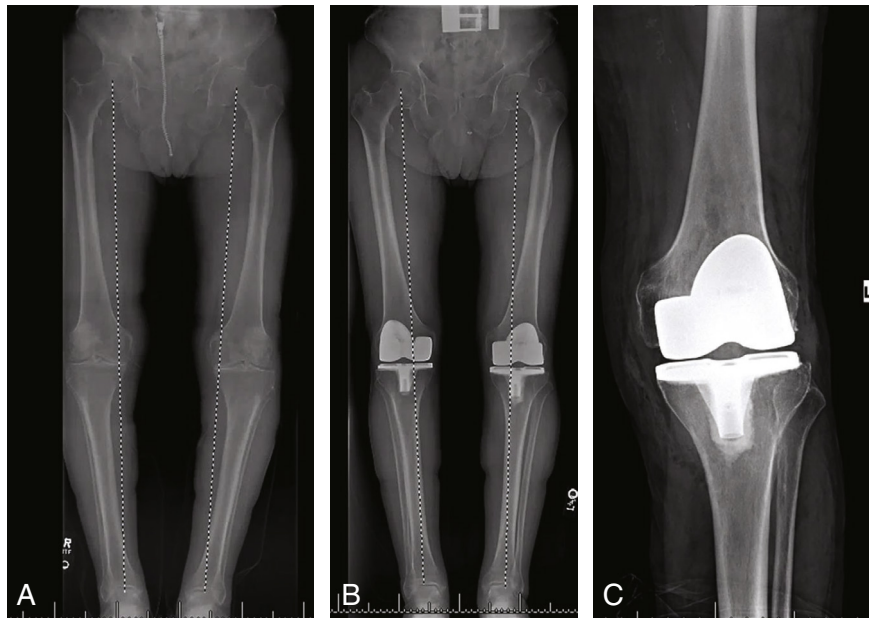


Figure 16.1 (A–C) demonstrate preoperative long standing anterior-posterior radiographs compared with postoperative films. Note the varus alignment in the preoperative film, which still remains in the postoperative film but to a lesser extent. As with all KA knees, note that the joint line orientation angle of the tibia is maintained parallel to the floor and the axis of the tibia is in 4 to 5 degrees of varus relative to the floor. The last radiograph shows the postoperative short cassette X-ray, which appears malaligned by conventional comparison as the tibia is artificially imaged as orthogonal to the bottom of the cassette, a reference point that our eye interprets as being parallel to the floor.

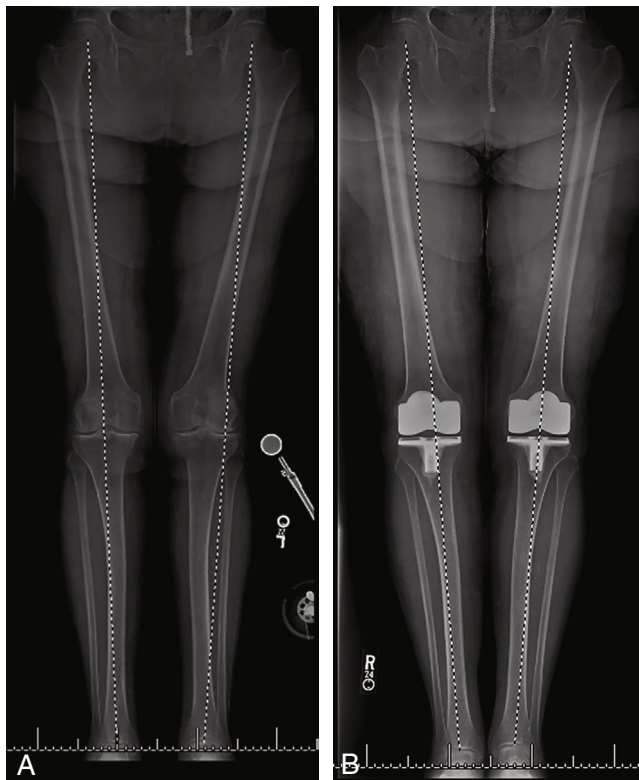


Figure 16.2 (A–B) demonstrate a neutral wear pattern on the left with a valgus deformity on the right. Postoperative alignment shows a neutral alignment for both knees and the joint line orientation angle retained parallel to the floor.

Long-Term Management

Given the paucity of long-term follow-up data for the KA technique, gathering long-term outcome and survivorship data is important. At this point in time, yearly patient-reported outcomes should be collected from all KA TKA patients and maintained in a suitable registry. Radiographic follow-up protocols may be more controversial. Particular attention should be paid to the potential for tibial component aseptic loosening at the 2- to 5-year mark and posterior insert wear at longer-term follow-up, generally past 9 years. Yearly radiographs may therefore be excessive, but until substantial long-term survivorship data is compiled, close yearly follow-up is recommended.

Summary

Many surgeons may be changing from a technique based on MA principles to the calipered KA technique. There is no reason to change any of their postoperative protocols. If collecting outcome data is currently not a part of their current postoperative protocol, however, changing to KA would be a good time to start collecting patient-reported outcome measures. As surgeons become more comfortable with the KA technique and can document improvement in patient outcomes, less postoperative touch points may be needed.

Future research should include study of the advantages of the KA technique as it pertains to outpatient surgery and whether there is a consistent requirement for structured physical therapy. Finally, data collection on outcomes and long-term survivorship of TKAs should continue.

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Reducing the Risk and Methods of Managing Stiffness After Calipered Kinematically Aligned Total Knee Arthroplasty

STEPHEN M. HOWELL, MD

CHAPTER OUTLINE

Overview

Incidence of Stiffness After Calipered Kinematically Aligned Total Knee Replacement Declines With Use of Intraoperative Verification Checks

Calipered Kinematically Aligned Total Knee Replacement Restores Native Tibial Compartment Forces, Which Reduces the Risks of Stiffness and Loss of Motion

Calipered Kinematically Aligned Total Knee Replacement Restores the Native Ligament Lengths That Determine Knee Laxities, Which Reduces the Risks of Stiffness and Loss of Motion

Seven Intraoperative Verification Checks That Restore Native Tibial Compartment Forces and Laxities to the Kinematically Aligned Total Knee Replacement

Methods for Managing Stiffness and the Timing of Manipulation Under Anesthesia After Calipered Kinematically Aligned Total Knee Replacement

Option 1: Self-Administered Stretching Exercises
Option 2: Early and Late Manipulation Under Anesthesia

Overview

This chapter contains a discussion and videos to assist the surgeon in reducing the risk and managing stiffness management after calipered kinematically aligned (KA) total knee arthroplasty (TKA). The treatment of over 5300 primary TKAs from 2006 to 2020 with the anatomic target of restoring the patient's prearthritic femoral and tibial joint lines regardless of knee deformity, without ligament release with posterior cruciate ligament (PCL)-retaining implants (CR), provides the background. The first section reports the 10-year incidence of treatment of stiffness with manipulation under anesthesia (MUA), which declined in 2018 with the initiation of intraoperative verification checks and self-administered flexion/extension stretching exercises after hospital discharge. The second and third sections review that results of in vitro and in vivo studies that show the biomechanical targets for balancing a calipered KA TKA are the restoration of the native medial and lateral tibial compartment forces and prearthritic ligament lengths that determine knee laxities. The fourth section describes seven intraoperative verification checks that restore the native medial and lateral tibial compartment forces and most laxities. The final section uses instructional case studies to discuss the options for managing

motion loss from stiffness with self-administered flexion/extension stretching exercises and manipulation under anesthesia. The educational objective is to encourage surgeons to use a caliper and verification checks when performing KA with manual, patient-specific, navigational, and robotic instrumentation, to reduce the risks of stiffness and motion loss.

Incidence of Stiffness After Calipered Kinematically Aligned Total Knee Replacement Declines With Use of Intraoperative Verification Checks

Video 17.1 discusses the decline in the incidence of manipulation under anesthesia beginning in 2018.

From 2010 to 2019, over 4500 consecutive, primary TKAs were performed with calipered KA and CR implant designs (Fig. 17.1). The anatomic target for setting the femoral and tibial components was to restore the patient's prearthritic joint lines regardless of the degree of knee deformity and without ligament release. During this time, 114 MUAs were performed. Between 2010 and 2017, the rate of MUA fluctuated between 2% and 4% per year, which is lower than the 5% to 7% rate reported for MA TKA.^{1,2}

In 2018, two practice changes were made. One change was the intraoperative use of a verification worksheet to record caliper measurements and corrections based on a decision tree. All corrections to balance the TKA were on the tibial side and included fine-tuning the varus-valgus (V-V) and posterior slope of the tibial resection and adjusting the thickness of the insert. The second change was instructing the patient to self-administer flexion/extension stretching exercises instead of prescribing outpatient or at-home physical therapy. From 2018 to 2019, the incidence of MUA dropped to 1% per year. Hence, intraoperative checks consisting of caliper measurements of bone resections, use of a verification worksheet, and home-based, self-administered exercises were associated with a lower risk of stiffness.

Calipered Kinematically Aligned Total Knee Replacement Restores Native Tibial Compartment Forces, Which Reduces the Risks of Stiffness and Loss of Motion

Video 17.2 discusses studies showing calipered kinematically aligned total knee replacement restoring native tibial compartment forces.

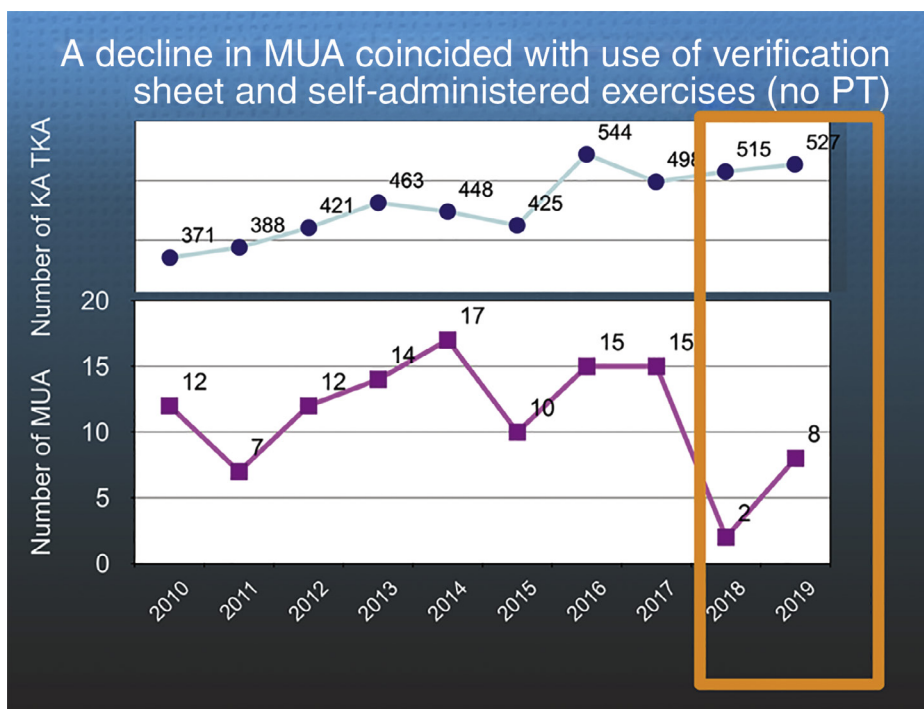


Figure 17.1 The line graph shows the yearly incidence of calipered kinematically aligned total knee replacement and manipulation under anesthesia for loss of motion and stiffness over 10 years. In 2018, the decline in the incidence of manipulation coincided with the use of intraoperative verifications, a decision tree, and self-administered flexion/extension stretching exercises after hospital discharge. KA, kinematic alignment; MUA, manipulation under anesthesia; PT, physical therapy; TKA, total knee replacement.

The first biomechanical target for balancing a TKA is the restoration of the medial and lateral tibial compartment forces to those of the native knee. To balance the TKA, the surgeon must have an understanding of the mean and variability of the medial and lateral compartment forces of the native knee. A cadaveric study of normal knees measured the medial and lateral tibial compartment forces at 0, 45, and 90 degrees of flexion. The mean medial force was 14 ± 5 lbs and the mean lateral force was 6 ± 2 lbs.³ The mean forces are ideal physiologic targets for TKA, as forces as little as two times higher cause stiffness as measured by intraoperative loss of flexion and extension and anterior tibial subluxation.⁴

In vivo and in vitro studies showed that calipered KA TKA with a CR implant design performed without ligament release restored medial and lateral tibial compartment forces comparable to those of the native knee.^{5,6} An in vivo study of 67 osteoarthritic knees treated with KA TKA reported a medial force of 21 ± 17 lbs and lateral force of 7 ± 8 lbs in the tibial compartment, which were comparable to the medial force of 14 lbs and lateral force of 6 lbs reported for the native knee, respectively.⁶

In contrast to calipered KA TKA, there are no reports of MA TKA being able to restore the native tibial compartment forces, even after ligament release (Fig. 17.2).^{7,8} One cause for uncorrectable tibial compartment forces higher than the native knee is that MA changes the patient's prearthritic distal femoral and proximal tibial joint lines more than ± 1.5 degrees in 85% and 70% of patients, respectively.⁹⁻¹¹ Placing a component either outside or inside the boundary of the patient's prearthritic joint line by removing less or more bone and cartilage than the thicknesses of the femoral and tibial components causes higher or lower compartment forces, overtensioning or slackening of ligaments, and knee stiffness or instability, respectively. Because MA causes obligatory deviations from the patient's prearthritic femoral and tibial joint lines, most knees have distal and posterior femoral resections within a compartment whose thicknesses deviate differently from the target thickness of the distal and posterior condyles of the femoral component, which cause

a wide range of complex collateral ligament imbalances that are uncorrectable with ligament releases.^{9,12} The inability of MA TKA to restore the native tibial compartment forces release was reported by three surgeons that used either measured resection or gap-balancing techniques checked with navigation and performed with release of healthy ligaments. The tibial force after MA TKA after ligament release were three to four times higher in the medial compartment and five to six times higher in the lateral tibial compartment than those reported for the native knee and calipered KA TKA.^{3,8,13}

Although the intraoperative use of tibiofemoral force sensors allows surgeons to measure forces very precisely, the level of precision is not called for to achieve a good/excellent result after calipered KA TKA. This is mostly because the soft tissue balance and contact forces appropriate for any knee are not known and vary widely. Thus, when the goal is to restore normal function, the use of this generation of force sensors may simply add expense and time without improving the surgeon's ability to achieve an individual patient's normal soft tissue tension and loads.⁶

Calipered Kinematically Aligned Total Knee Replacement Restores the Native Ligament Lengths That Determine Knee Laxities, Which Reduces the Risks of Stiffness and Loss of Motion

Video 17.3 discusses studies that show calipered kinematically aligned total knee replacement restores native ligament lengths and laxities.

The second biomechanical target for balancing a TKA is the restoration of the lengths of the patient's PCL, and collateral and retinacular ligaments, which are the primary restraints of the knee laxities. To balance the TKA, the surgeon must have an understanding of the mean and variability of the V-V and

Can intraoperative sensors determine the “target” ligament balance? early outcomes in total knee arthroplasty

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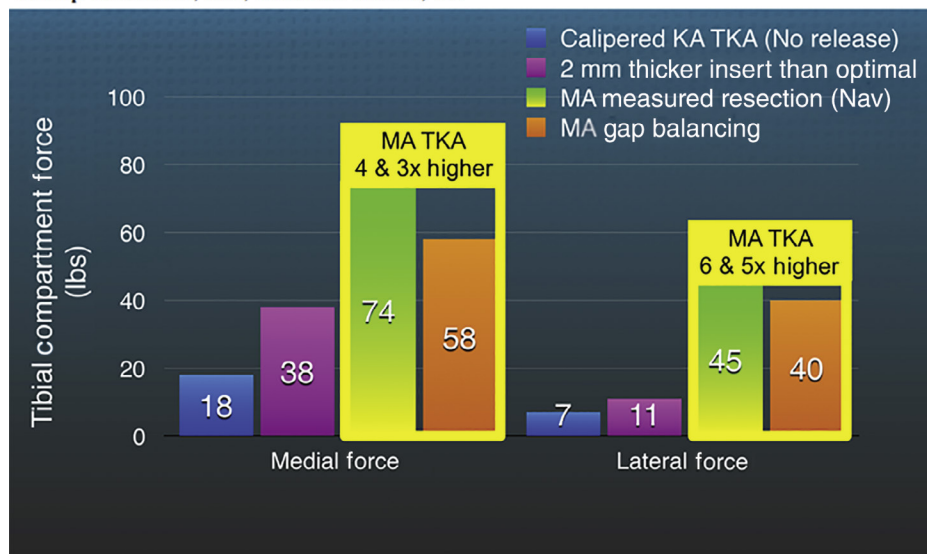


Figure 17.2 The column graph compares the medial and lateral tibial compartment forces after calipered kinematic alignment (KA) total knee arthroplasty (TKA) and with an optimal insert and with an insert 2-mm thicker insert than optimal with those reported for mechanical alignment (MA) TKA performed with the measured resection and gap-balancing methods. The compartment forces of the calipered KA TKA and an optimal insert and a 2-mm thicker insert without ligament release were comparable and two times higher than the native knee, respectively. In contrast, the compartment forces of the MA TKA after ligament release were three to six times higher than those of the calipered KA TKA with an optimal insert and without ligament release. (From: KA, Kinematic alignment; MA, mechanical alignment; TKA, total knee arthroplasty. 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 S.* 2019;32(10):1008–1014. 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(5):1200–1207. 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 Arthroplasty.* 2016;31(10):2181–2187.)

internal and external (I-E) rotation of the native knee in full extension and at 90-degrees of flexion where intraoperative verification checks are made.^{14,15}

The V-V laxity of the native knee is negligible in full extension and greater at 90 degrees of flexion. In full extension, the space is rectangular and tight with a 0.4 ± 0.3 mm opening in the medial compartment and a 0.7 ± 0.3 mm opening in the lateral compartment under a ± 5 Nm V-V load. When the native knee is flexed to 90 degrees, the space becomes trapezoidal and looser lateral than medial, and the lateral compartment opens 3.2 ± 1 mm and the medial compartment opens 1.4 ± 0.6 mm.^{14–16} In full extension, where the V-V verification checks are made with spacer block and trial components, the medial and lateral openings are generally 1 mm (or less) in most native knees. In 90 degrees of flexion the lateral opening can range from 1 to 5 mm and the medial opening can range from 0.2 to 2.6 mm in most native knees. Those surgeons that perform arthroscopy are aware of this variability, as it explains the variation in the ease and difficulty of performing medial and lateral meniscectomies between compartments and between patients.

The I-E rotational laxity of the tibia in the native knee is minimal in full extension and greater at 90 degrees of flexion. In full extension, the space is rectangular and has 4.6 ± 1.4 degrees of internal rotation and -4.4 ± 1.7 degrees of external rotation under a ± 3 Nm I-E load. When the native knee is flexed to 90 degrees, the space becomes trapezoidal and has 14.6 ± 5.5 degrees of internal rotation and -14.5 ± 3.8 degrees of external rotation.^{14–16} In 90 degrees of flexion where the verification check is made with

a spacer block, the surgeon should notice that I-E rotating the handle of the block causes a pivot to occur about the center of the medial compartment, indicating restoration of a trapezoidal flexion space. In 90 degrees of flexion where the verification check is made with trial components, the surgeon should verify that the I-E rotation with trial components matches those of the knee during an examination at the time of exposure. Because each knee has a specific I-E laxity, the internal rotation should range from 5 degrees to 25 degrees and the external rotation should range from -8 degrees to -23 degrees.

These patient-specific differences in V-V and I-E laxity and shape between the extension and flexion space do not support the concept of the gap-balancing, which is a common and ill-conceived MA technique.^{14,15} Because native ligaments are not tight in flexion, there is no role for the use of tensiometers, as they adversely overtighten the flexion space. When gap balancing “equalizes” the medial and lateral gaps in the flexion space to those of the extension space, the laxity of the lateral flexion gap is tightened more than the medial flexion gap, which distorts the trapezoidal shape to rectangular and over-constrains I-E rotation of the tibia on the femur.¹⁷ The clinical effects of gap balancing are tibial compartment forces higher than the native knee, which cause stiffness, loss of motion, and pain.^{4,6,8}

In vitro studies of calipered KA TKA performed in normal knees with a CR implant and without the use of ligament releases restored V-V and I-E laxities to those of the native knee. The CR implant did not, however, restore anterior laxity at 30 degrees of flexion because the low-conforming insert

functioned like an ACL and partial meniscal deficient knee, allowing more anterior laxity than the native knee.^{5,18} One implant design that provides anterior stability is the medial ball-in-socket implant. The medial ball-in-socket restores more normal kinematics and medial anterior-posterior stability during walking than a CR, posterior stabilized (PS), or ultra-congruent (UC) implant design.^{19,20} It follows that when a patient wants the TKA to function and feel like the prearthritic knee, the ligament lengths and laxities of the extension and flexion space should match those of the native knee and ligament releases should not be performed.

Seven Intraoperative Verification Checks That Restore Native Tibial Compartment Forces and Laxities to the Kinematically Aligned Total Knee Replacement

Video 17.4 discusses studies that show the intraoperative use of verification checks.

We recommend performing a series of seven verification checks to achieve the anatomic and biomechanical targets of restoring the prearthritic joint lines, tibial compartment forces, ligament lengths, and laxities to those specific for the patient's pre-arthritis knee.

The first two verification checks rely on assessments made with a spacer block to determine whether the tibial resection restored the ligament lengths and the V-V laxity of the extension space and the I-E laxity of the flexion space (Fig. 17.3).

1. Place the knee in 90 degrees of flexion, insert and I-E rotate the tightest-fitting spacer block. The surgeon should notice that the I-E rotation of the handle of the spacer block causes a pivot to occur about the center of the medial compartment, indicating restoration of a trap-ezoidal flexion space.

2. Place the knee in extension and insert a spacer block. The surgeon should notice negligible V-V laxity indicating the restoration of the native tight rectangular extension space. When a compartment is tighter than the other, refer to the decision tree for balancing the KA TKA. When the medial side opens 1 to 2 mm, perform a varus recut of 1 degree. When the lateral side opens 1 to 2 mm, perform a valgus recut of 1 degree.
3. The next five verification checks use trial components to provide a final assessment of whether the KA TKA restores the native tibial compartment forces, ligament lengths, and laxities.⁶
4. Place the knee in maximum extension and verify that there are 3 to 5 degrees of hyperextension like the native knee. Adjust the insert thickness to set the degree of hyperextension. When the extension is limited, insert a thinner insert.
5. Apply a V-V load to the tibia and verify the V-V laxity is negligible. When one tibial compartment opens 1 to 2 mm, fine-tune the V-V plane 1 or 2 degrees until the V-V laxity is negligible like the native knee.^{14,15}
6. Place the knee in 15 to 30 degrees of flexion and apply a V-V load to the tibia. Verify that the medial side does not open more than 1 mm and the lateral side opens 2 to 3 mm.
7. Place the knee in 90 degrees of flexion and verify there is ± 15 degrees of I-E rotation, which restores the native laxity of the flexion space.^{14,15}
8. With the knee in 90 degrees of flexion, use an offset caliper and measure the distance between the anterior tibia and the distal medial femoral condyle. Compare this offset to the one taken at the time of exposure. When the offset is greater and the I-E rotation is more than ± 15 degrees, add more posterior slope. When the offset is less, add a thicker insert or set the tibial component in less posterior slope.

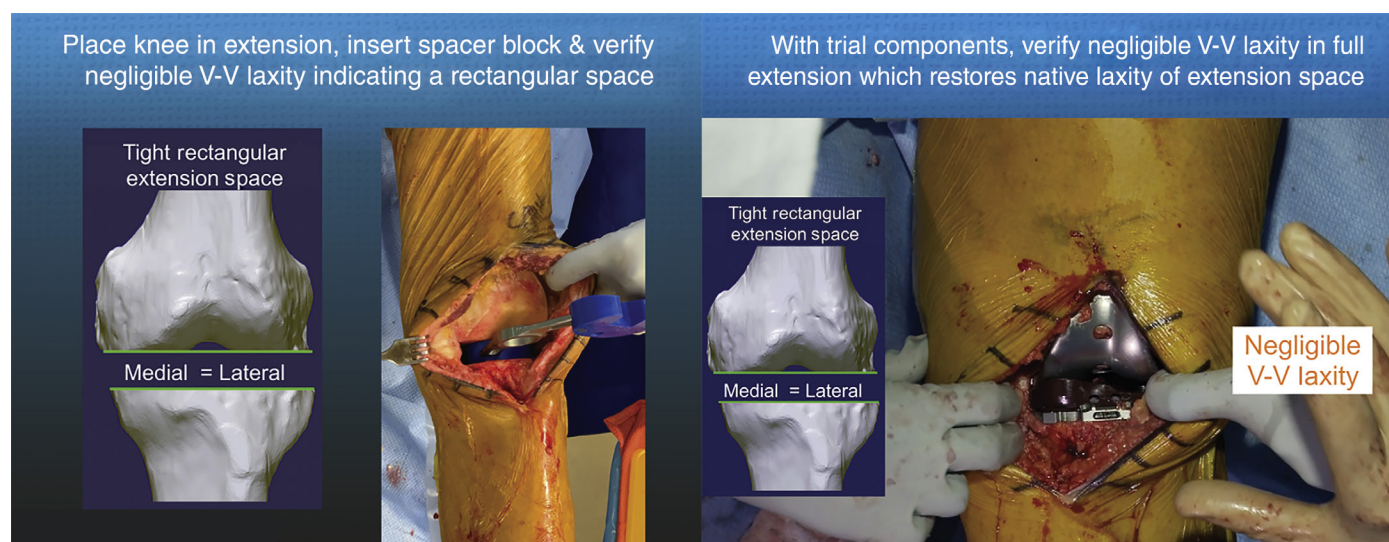


Figure 17.3 The composite consisting of schematics and intraoperative images show the intraoperative verification steps that use a spacer block (left) and trial components (right) to restore the native extension space. The surgeon should notice negligible varus-valgus (V-V) laxity indicating the restoration of the native tight rectangular extension space. (From 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):1678–1684; 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):1589–1601.)

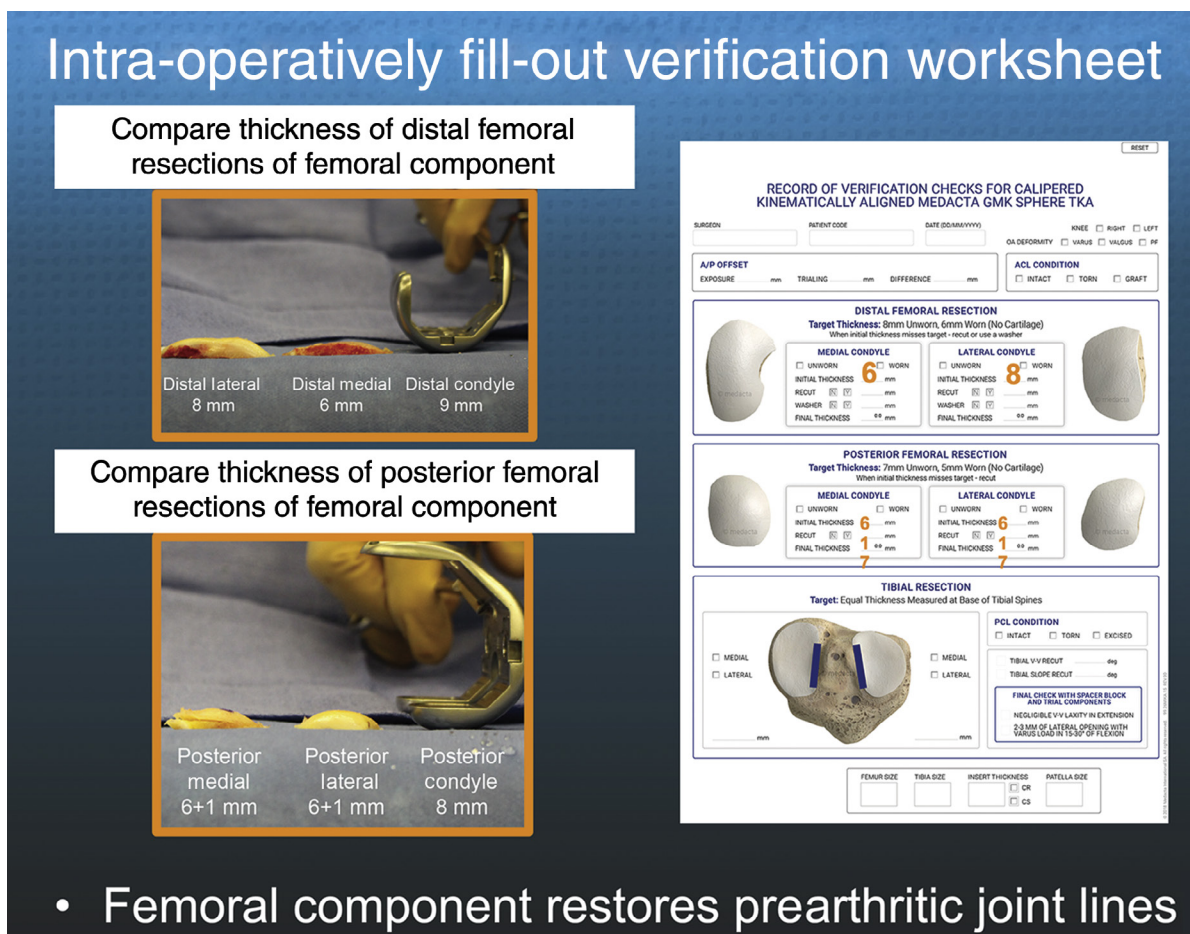


Figure 17.4 The composite images shows the thicknesses of the distal and posterior femoral bone resections compared to the thicknesses of the condyles of the femoral component (*left*) and the caliper measurements of the bone resections recorded intraoperatively on the verification sheet (*right*). The femoral component is kinematically aligned when the femoral resections match the thicknesses of the condyles of the femoral component within ± 0.5 mm after compensating around 1 mm from the loss of bone from the kerf of the saw blade and 2 mm for cartilage loss.

Methods for Managing Stiffness and the Timing of Manipulation Under Anesthesia After Calipered Kinematically Aligned Total Knee Replacement

Video 17.5 shows the management and outcomes of patients treated for loss of motion caused by stiffness.

When a patient presents with stiffness after calipered KA TKA, review the verification worksheet and operative note, and determine whether the measurements of the distal and posterior femoral resections restored the prearthritic joint lines (**Fig. 17.4**). When the femoral component was kinematically aligned as intended, the options of self-administered stretching exercises followed by MUA, when necessary, often restore motion.

OPTION 1: SELF-ADMINISTERED STRETCHING EXERCISES

The first management option to improve motion is for the physician to show the patient how to perform self-administered flexion and extension stretching exercises. The self-administered approach is often more effective than formal physical

therapy, which patients often find is too forceful and painful.²¹ The most common type of stiffness after calipered KA TKA is the complaint of loss of flexion, which is easier to treat than loss of extension, which is quite rare.

OPTION 2: EARLY AND LATE MANIPULATION UNDER ANESTHESIA

When the self-administered flexion and extension stretching exercises fail to resolve the loss of motion, consider a manipulation of the knee under general anesthesia with an injection of cortisone and a local anesthetic. The 10-year experience of the senior author suggests that MUA as late as a year or more after calipered KA TKA can be as effective as an earlier manipulation within 6 weeks of the surgery. Unlike the treatment of stiffness following MA TKA, which is often associated with a femoral component that deviated from the native to pre-arthritis joint line resulting in poor outcomes, our experience of manipulating the KA TKA generally restores better motion and function.¹ The video discusses the management of three patients and shows the effectiveness of late manipulation for stiffness after calipered KA TKA and the difficulty in regaining motion when the femoral component deviated from the prearthritic joint line.

Summary

The educational objective of this chapter is to encourage the surgeon who performs calipered KA TKA to reduce the risk of postoperative stiffness by using the seven verification checks. The incidence of MUA following KA TKA should be about 1% to 2% with the use of intraoperative verification checks, and self-administered flexion and extension stretching exercises.

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Restoring the patient’s pre-arthritis joint lines, tibial compartment forces, ligament lengths, and laxities to those specific for the treated knee reduces the risk of stiffness and motion loss. When motion loss occurs after calipered KA TKA, the use of self-administered flexion and extension exercises and, if necessary, an early or late MUA are effective as long as the femoral component restored the prearthritic distal and posterior femoral joint lines.

Reducing the Risk and Management of Early and Late Tibial Component Failure After Calipered Kinematically Aligned Total Knee Arthroplasty

STEPHEN M. HOWELL, MD

CHAPTER OUTLINE

Outline

Incidence and Causes of Early and Late Tibial Component Failure After Calipered Kinematically Aligned Total Knee Arthroplasty With Posterior Cruciate Ligament–Retaining Implants

Verification Checks Restore the Native Slope and Laxities of the Flexion Space and Reduce the Risk of Early Tibial Component Failure

Medial Stabilized Implant Restores Anterior-Posterior Stability and Higher Function Than Anterior Cruciate Ligament–Deficient and Partial Meniscal–Deficient Designs

Revision of Just the Tibial Implant Often Manages the Tibial Component Failure After Kinematically Aligned Total Knee Arthroplasty

Outline

The discussion and videos in this chapter assist the surgeon in (1) reducing the risk of aseptic loosening of the tibial component and (2) managing both early and late tibial component failure from insert wear after calipered kinematically aligned (KA) total knee arthroplasty (TKA). The chapter draws from the author's experience treating of over 5300 primary KA TKAs from 2006 to 2020 without restrictions on preoperative alignment, without limits on the postoperative correction to the patient's pre-arthritis femoral and tibial joint lines, and with the use of posterior cruciate ligament–retaining implants (CR), to provide the background. The first section discusses the incidence and early and late causes of tibial component failure. The second describes the use of verification checks that restore the native posterior slope and native laxities (except anterior laxity) of the trapezoidal flexion space, which reduces the risk of early failure from posterior subsidence or rim wear of the insert. The third section proposes the use of a medial stabilized ball-in-socket implant with a flat lateral compartment as a strategy for reducing the risk of late posterior rim wear of the insert (>9 years). The case studies in the final section showcase options for managing early tibial component failure, which is a revision of the tibial component and restoration of the native posterior slope. For late failure, management includes an exchange with a thicker insert or one with a medial constraint when available. The objective is to encourage those surgeons who perform

calipered KA TKA to restore the native posterior slope when using the CR insert and consider the use of a medial stabilized implant with a flat lateral compartment.

Incidence and Causes of Early and Late Tibial Component Failure After Calipered Kinematically Aligned Total Knee Arthroplasty With Posterior Cruciate Ligament–Retaining Implants

Video 18.1 discusses the incidence, time of onset, and early and late causes of tibial component failure.

A case-match study from 2006 to 2015, clinical observations, and results from in vivo contact kinematic studies provide information for understanding the early and late causes of tibial component failure after calipered KA TKA. Early tibial component failure in this series presented at an average of 28 months, following surgery for an incidence of 0.3%. The cohort consisted of 8 patients out of 2725 consecutive primary KA TKAs.¹ The setting of the slope of the tibial component was more posterior than native in seven patients. Not restoring the native posterior slope caused early posterior subsidence of the tibial baseplate or posterior rim wear of the insert within the first 2 to 5 years of the index surgery. In those patients with early tibial component failure, the mean posterior slope was 11 degrees, whereas the mean in the control cohort was 7 degrees (**Fig. 18.1**).¹ Posterior slope greater than the native slope slackened the flexion space. Laxity in the flexion space that is more slack than native promotes excessive anterior tibial component translation and excessive posterior rollback of the femoral component on the tibial component that causes posterior overload. This combination of abnormal motions manifested as posterior and not varus subsidence of the baseplate or wear of posterior rim of the polyethylene insert. Hence a strategy for reducing the risk of early failure with a CR insert is to restore the native posterior slope.

In 2016, we introduced the use of three verification checks to restore the native posterior slope, soft tissue laxities, and tibiofemoral compartment forces of the trapezoidal flexion space when using a CR insert. The verification checks were designed to reduce the risk of both early and late failure from posterior tibial component subsidence and rim wear.^{2–4} Following the introduction of the verification checks (2017–2020), we noted that late tibial component failure (>9 years) was no longer related to subsidence of the tibial base plate but rather

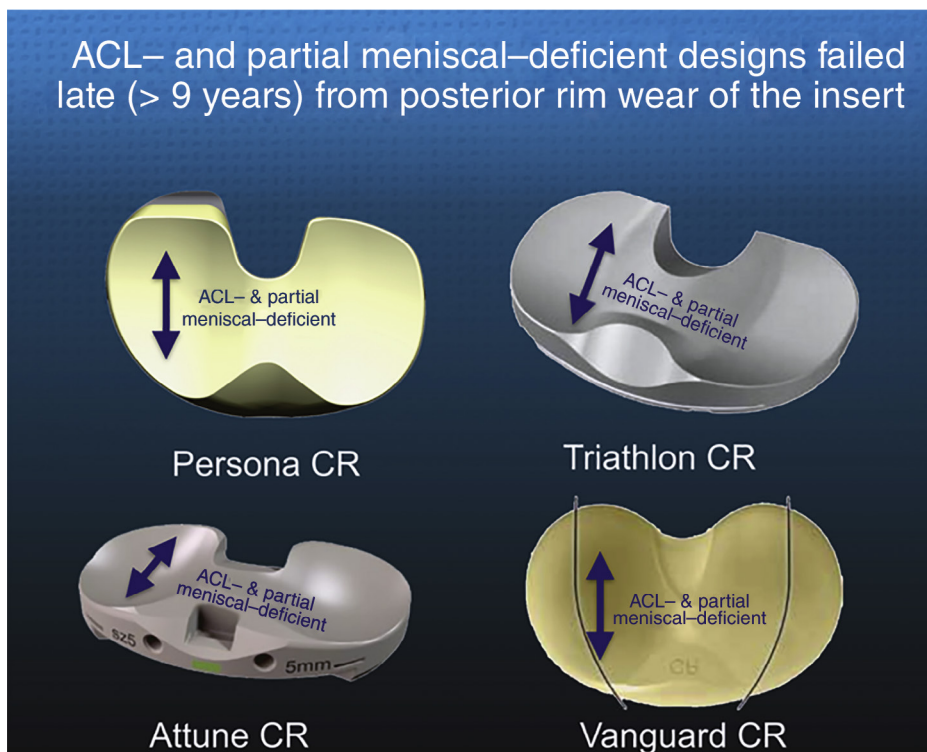


Figure 18.1 Composite shows schematics of various low-constraint anterior cruciate ligament (ACL)-deficient and partial meniscal-deficient cruciate-retaining (CR) insert designs that do not restore native anterior stability when placed with kinematically aligned and mechanically aligned techniques. These designs enable excessive anterior tibial translation and posterior femoral rollback, which increases the risk of posterior rim contact of the insert that can occur between 30 and 90 degrees of knee flexion during activities of daily living. (From Roth JD, Howell SM, Hull ML. Analysis of differences in laxities and neutral positions from native after kinematically aligned TKA using cruciate retaining implants. *J Orthop Res.* 2019;37(2):358–369; Schutz P, Taylor WR, Postolka B, et al. Kinematic evaluation of the GMK sphere implant during gait activities: a dynamic videofluoroscopy study. *J Orthop Res.* 2019;37(11):2337–2347; Nicolet-Petersen S, Saiz A, Shelton T, Howell SM, Hull ML. Small differences in tibial contact locations following kinematically aligned TKA from the native contralateral knee. *Knee Surg Sports Traumatol Arthrosc.* 2019;1–12.)

to wear of the posterior rim of the insert. We concluded that a KA TKA with a low-constraint CR and posterior stabilized (PS) implant design has anterior tibial instability similar to a partial meniscal and anterior cruciate ligament (ACL)-deficient knee (Fig. 18.1).^{2,5} The ACL-deficient functioning insert representative of nearly all modern TKA CR and PS designs enables excessive anterior translation of the tibial component and excessive posterior rollback of the femoral component during flexion. This abnormal motion increases the risk of overload of the posterior rim of the insert in mid-flexion during activities of daily living, leading to wear.⁶

Verification Checks Restore the Native Slope and Laxities of the Flexion Space and Reduce the Risk of Early Tibial Component Failure

Video 18.2 shows the intraoperative verification checks for restoring the native slope and laxities of the trapezoidal flexion space.

The introduction of three verification checks in 2016 reduced the risk of early tibial compartment failure by restoring the native posterior slope, the native laxities (except anterior laxity) of the trapezoidal flexion space, and native compartment forces with a CR implant.^{2–4,7} In this section we will review the checks in more detail.

The first verification check examines the degree of the posterior slope of the tibial resection and determines whether the plane of the resection is parallel to the posterior slope of the medial articular surface after compensating for wear of the

native tibia.⁷ With the knee fully extended and trial components in place, an insert thickness is chosen so that the knee has negligible varus and valgus laxity, like the native knee. The second verification check, performed with the knee in 90 degrees of flexion and with the thigh suspended until the foot is off the operating table, determines whether the passive internal-external (I-E) rotation of the tibia on the femur is ± 15 degrees, like the native knee.^{2,8} The third verification check, performed with the knee in 90 degrees of flexion and the leg resting on the operating table, determines whether the anterior-posterior (A-P) offset of the tibia from the distal medial condyle of the femoral component matches that of the knee at the time of exposure, which is considered to be the native offset.^{4,9}

In those knees with unfulfilled verification checks, the decision trees for the CR and CS inserts provide guidelines for fine-tuning the slope (Fig. 18.2) by recutting or bone-grafting the tibial resection. With the TKA at 90 degrees of flexion, if the anterior edge of the insert lifts off the trial tibial baseplate, the I-E rotation is less than ± 15 degrees, and the A-P offset is greater than at exposure, then it is likely that the setting of the slope for the tibial component is less than the native slope. This scenario requires a recut of the tibia to increase the posterior slope of the tibial resection in 1- to 2-degree increments until all three verification checks are fulfilled. Conversely, if the A-P offset is less than at exposure, then the setting of the slope for the tibial component is likely greater than the native slope. This scenario requires a recut of the tibial plateau to reduce the posterior slope in 1- to 2-degree increments until the three verification checks are fulfilled. When the TKA is well balanced in extension, loose in flexion, and the PCL is damaged, use a

Figure 18.2 Six-step decision-trees are shown for balancing a calipered kinematically aligned total knee arthroplasty with use of cruciate ligament-retaining (CR) and substituting (CS) insert. Fine-tuning the varus-valgus and posterior slope of the plane of the tibial resection and adjusting the insert thickness restores the native laxities except anterior of the rectangular extension and trapezoidal flexion spaces, and the native tibial compartment forces without ligament releases. A-P, Anterior-posterior; PCL, posterior cruciate ligament; TKA, total knee arthroplasty. (From Roth JD, Howell SM, Hull ML. Analysis of differences in laxities and neutral positions from native after kinematically aligned TKA using cruciate retaining implants. *J Orthop Res.* 2019;37(2):358–369; 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):1589–1601; 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(5):1200–1207; 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.)

Decision tree for balancing a calipered kinematically aligned 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 1–2 mm more bone.	Increase posterior slope until exposure A-P offset is restored at 90 degrees 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 a Cruciate Stabilized insert.	Remove medial osteophytes. Reassess. Recut tibia in 1–2 degrees more varus. Insert 1 mm thicker insert.	Remove lateral osteophytes. Reassess. Recut tibia in 1–2 degrees more valgus. Insert 1 mm thicker insert.
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 1–2 mm more bone.	Confirm complete resection of the PCL. Increase posterior slope until natural A-P offset is restored at 90 degrees 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 degrees more varus. Insert 1 mm thicker insert.	Remove lateral osteophytes. Reassess. Recut tibia in 1–2 degrees more valgus. Insert 1 mm thicker insert.

PCL-substituting (CS) insert instead of a CR insert, or switch to a PS implant design.

Medial Stabilized Implant Restores Anterior-Posterior Stability and Higher Function Than Anterior Cruciate Ligament-Deficient and Partial Meniscal-Deficient Designs

Video 18.3 discusses the biomechanical strategy for the use of a medial stabilized implant to reduce the risk of late failure from posterior rim wear of the insert.

A promising strategy for promoting A-P stability and high function, and reducing the risk of late tibial component failure from posterior rim wear of the insert, is the use of a medial stabilized (MS) implant design with an insert comprised of a medial ball-in-socket geometry, a lateral flat surface without a posterior rim, and an anatomic baseplate that covers the posterior tibia (Fig. 18.3).^{5,6,10–12}

In the medial compartment, the design of the CR and CS inserts should be socket-like to promote A-P stability, like the native knee.⁵ The conformity of the CR concavity can be slightly less than the 1:1 ball-in-socket conformity of the CS design, to minimize the risk of kinematic conflict from retention of the PCL. When the PCL is sacrificed, the conformity can be tighter.

In the lateral compartment, the design of the CR and CS inserts should be flat without a posterior rim to enable I-E rotation of the tibia on the femur like the native knee⁵ and allow unobstructed posterior roll back of the lateral femoral condyle on the tibia. An insert without a posterior rim replicates the negligible constraint provided by the lateral meniscus that rolls off the posterior tibia in deep flexion.¹⁰

The use of an anatomic baseplate that, when positioned to cover the majority of the exposed tibial resection, sets the A-P axis parallel to the flexion-extension (F-E) plane of the knee is another strategy for reducing late onset posterior wear of the insert.¹² An optimal design consists of an anatomic baseplate that covers the posterior edge of the tibial resection and a polyethylene insert that covers the posterior edge of the baseplate.⁶

A single-surgeon randomized trial compared the functional outcome of patients treated with either an MS design (SAIPH knee with resection of the PCL, www.matortho.com; $n = 53$) or a CR design (Vanguard; $n = 50$) implanted with KA principles. Those treated with the MS design had a 16-point higher self-reported Forgotten Joint Score than those treated with the CR design. The mean 80-point score of the MS design is comparable with total hip arthroplasty.¹¹ The greater anterior stability and more normal I-E rotation provided by the MS design explains the higher function when compared with the CR design, which allows anterior tibial translation very much like a partial meniscal-deficient and ACL-deficient knee.⁵ The use of the socket limits A-P oscillation in the medial compartment during activities

The movement of the normal tibio-femoral joint

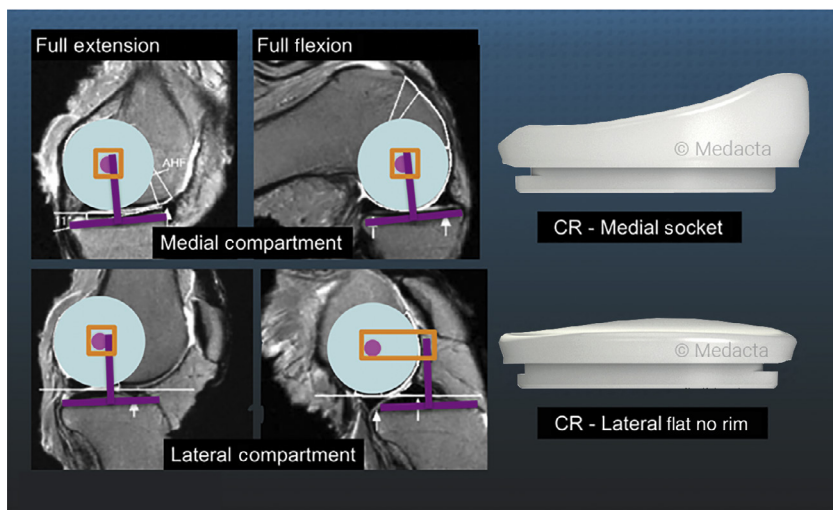


Figure 18.3 This composite shows the tibiofemoral relationship of the medial and lateral compartment of the native knee in full extension and full flexion in which the medial femoral condyle hardly moves (orange square) and the lateral femoral condyle rolls posterior in full flexion (orange rectangle). The design of the medially stabilized cruciate-retaining (CR) insert, comprised of a medial ball and socket and a lateral flat surface without a posterior rim, is a promising strategy for promoting anterior-posterior stability and reducing the risk of late tibial component failure from posterior rim wear of the insert.^{5,10} (Martelli S, Pinskerova V. The shapes of the tibial femoral articular surfaces in relation to tibiofemoral movement. *J Bone Joint Surg.* 2002;84B:607–613.) (© Medacta.)

and lowers the risk of soft tissue pain and exercise intolerance with sporting activities.

Revision of Just the Tibial Implant Often Manages the Tibial Component Failure After Kinematically Aligned Total Knee Arthroplasty

Video 18.4 shows management options and outcomes of patients treated for early and late failure of the tibial component after kinematically aligned total knee arthroplasty.

When confronted with tibial component failure, review the verification worksheet and operative note and determine whether the measurements of the thicknesses of the distal and posterior femoral resections restored the native joint lines. The use of postoperative imaging studies is inaccurate for

determining whether the femoral component was set coincident to the native femoral joint lines. When the femoral component is judged to be in KA, the surgeon only needs to revise the tibial component (Fig. 18.4).

OPTION 1

When early tibial component failure occurs after the use of a CR insert in a KA TKA, the posterior slope of the tibial component is typically greater than the native slope, and there is either posterior subsidence of the tibial baseplate or wear on the posterior rim of the insert. In such patients, the surgeon can revise the tibial baseplate, restore the native posterior slope, and leave the femoral component in situ. The use of a short cemented stem extension and, as needed, an ingrowth cone reduces the risk of impingement of the stem on the lateral tibial cortex from setting the varus-valgus (V-V) orientation of the baseplate coincident

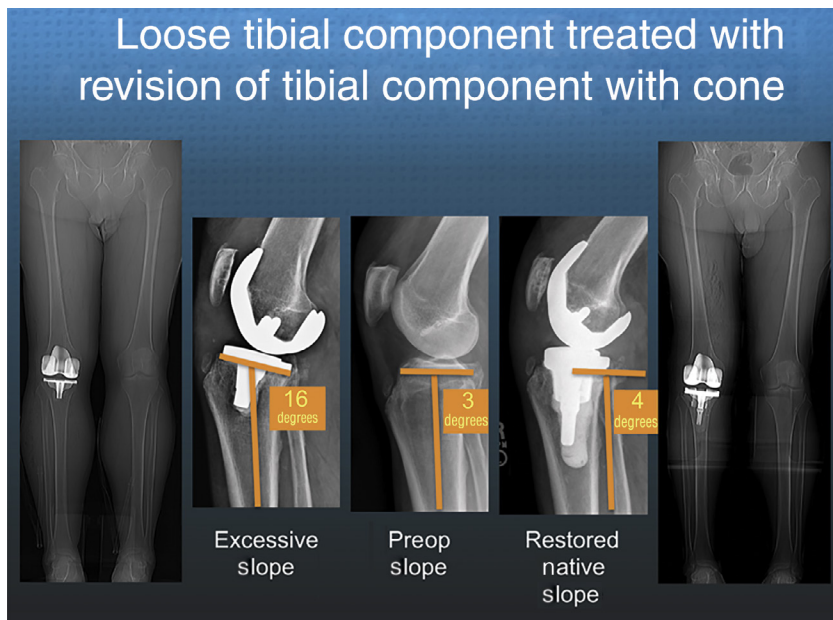


Figure 18.4 This composite shows radiographs of early tibial component failure at 2 years from posterior loosening caused by setting the tibial component in greater posterior slope (16 degrees) compared with the native preoperative slope (3 degrees). The thicknesses of the femoral bone resections verified the kinematic alignment of the femoral component, so only the tibial component was revised by restoring the preoperative slope with the use of a cone and short stem extension (4 degrees). Varus overload was not the cause of the tibial component failure, as the pre- and postrevision settings of the femoral and tibial components matched the joint lines of the contralateral native knee in the coronal plane.

to the native tibial joint line. When the stability provided by the PCL is compromised, add constraint by using either a CS insert or by revising the femoral component with an MS or PS implant design.

OPTION 2

When late tibial component failure occurs (>9 years) after treatment with a CR insert and KA of the femoral component, the posterior slope of the tibial component typically matches the native slope and there is wear on the posterior rim of the insert without posterior subsidence of the tibial baseplate. When the function of the PCL is intact, replace the worn insert with a thicker one. When the stability provided by the PCL is compromised, add constraint by using either a CS insert or by revising the femoral component with an MS or PS implant design.

Summary

The primary cause of early tibial component failure after calipered KA TKA with use of CR implant designs is not restoring the native posterior slope. Excessive slope causes posterior overload of the tibial component and either subsidence of the tibial baseplate or posterior rim wear of the insert within the first 2 to 5 years of the index surgery. The mechanism of late tibial component failure is excessive A-P translation of the tibial

component or excessive posterior roll back of the femoral component. Both abnormal motions are caused by the use of current CR implant designs, which behave like ACL- and partial meniscal-deficient knees. The excessive AP translations these designs allow enable posterior rim wear of the insert with presentation typically after 9 years. The use of the three verification checks outlined in this chapter reduces the risk of early tibial compartment failure by restoring the native posterior slope, the native laxities of the trapezoidal flexion space, and native compartment forces with a CR implant. A strategy for improving AP stability and reducing the risk of late tibial component failure from posterior rim wear of the insert is the use of an MS implant design. These tibial components have an insert comprised of a medial ball-in-socket design, a lateral flat surface without a posterior rim, and an anatomic baseplate that covers the posterior tibia. Clinical results suggest that restoring AP stability is associated with improved clinical outcomes. Early tibial component failures are frequently managed with isolated revision of the tibial baseplate. The revision tibia should use a short stem extension and possibly a cone with restoration of the native posterior slope and duplication of the native V-V alignment. To manage late failure from posterior rim wear when the function of the PCL is intact and the tibia is not loose, replace a worn insert with a thicker one and use a more medial constraint when available. Reducing the risk of tibial component failure is accomplished by restoring the native posterior slope and the use of an MS implant design.

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Reducing the Risk and Management of Patellofemoral Instability After Calipered Kinematically Aligned Total Knee Arthroplasty

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CHAPTER OUTLINE

Overview

Incidence, Time of Onset, and Causes of Patellofemoral Instability After Calipered Kinematically Aligned Total Knee Arthroplasty

Use of Femoral Components Designed for Mechanical Alignment Does Not Explain Patellofemoral Instability After Kinematic Alignment

Use of an Intraoperative Verification Check and an Anatomic Patella Component Reduces the Risk of Patellofemoral Instability

A Femoral Component Redesigned for Kinematic Alignment Should Increase the Lateral Coverage of the Anterior Femur

Options for Managing Patellofemoral Instability After Calipered Kinematically Aligned Total Knee Arthroplasty

Option 1: Observe Patients Who Choose to Cope With Patellofemoral Instability (N = 4)

Option 2: Reoperation With Arthroscopic Lateral Release (N = 2)

Option 3: Reoperation With Open Lateral Release and Medial Reefing (N = 6)

Overview

The discussion and video links in this chapter assist the surgeon in reducing the risk of patellofemoral instability and in managing it when it occurs after calipered kinematically aligned (KA) total knee arthroplasty (TKA). The first section reports the incidence, time of onset, and causes of patellofemoral instability using currently available femoral components designed for mechanical alignment (MA). The second section uses results from in vivo and in vitro kinematic studies to show that the use of femoral components designed for MA with KA is an unlikely cause of patellofemoral instability. The third describes intraoperative verification checks that minimize excessive flexion of the femoral component and the use of an anatomically designed patella component to reduce the risk of patellofemoral instability. The fourth proposes a redesign of the prosthetic trochlea to increase the lateral coverage of the anterior femur and to closely coalign the orientations of the prosthetic and native trochlear groove. The goal of these design changes is to promote

the capture and containment of the patellar implant during knee flexion. The case studies in the final section showcase options for managing patellofemoral instability, including observation, arthroscopic lateral release, and open lateral release and medial reefing. The objective is to encourage those surgeons that perform calipered KA TKA to minimize flexion of the femoral component, use an anatomic patella component, and choose a femoral component designed explicitly for KA when they become available.

Incidence, Time of Onset, and Causes of Patellofemoral Instability After Calipered Kinematically Aligned Total Knee Arthroplasty

Video 19.1 shows a patient actively demonstrating the lateral subluxation of the patella and a discussion of the incidence, time of onset, and causes of patellofemoral instability.

To determine the incidence of patellofemoral instability, a review was done of consecutive primary TKAs performed between 2006 and 2015 using KA and a femoral component designed for MA. Thirteen out of 3212 calipered KA TKAs in the cohort presented with patellofemoral instability for an incidence of 0.4% during a 2- to 9-year follow-up.¹ In 9 of the 13 patients (70%), the presentation was lateral subluxation of the patella that occurred without trauma during typical daily activities, with a mean onset of 5 months. Active quadriceps contraction caused lateral subluxation of the patella in extension during the initiation of knee flexion, and the patella spontaneously reduced into the prosthetic trochlear groove at 15–30 degrees of flexion (see Video 19.1). When an examiner passively moved the knee, the patella tracked normally.

A case-match study design identified two causes of patellofemoral instability.¹ One cause was excessive flexion of the femoral component with respect to the sagittal anatomic axis of the distal femur. The mean flexion of the femoral components in those patients with patellofemoral instability was 11 degrees, and 6 degrees in the controls (Fig. 19.1). Each 5 degrees of flexion of the femoral component moves the proximal edge of the prosthetic trochlea 5 mm distally and requires a one-size reduction in the size of the femoral component. These effects reduce the coverage and cross-sectional area of the prosthetic trochlea, compromising the capture of the patella component.^{1–3} The second cause was the use of a dome-shaped patella component, as patellofemoral instability did not occur with an anatomic-shaped patella component and an unresurfaced patella. Soft

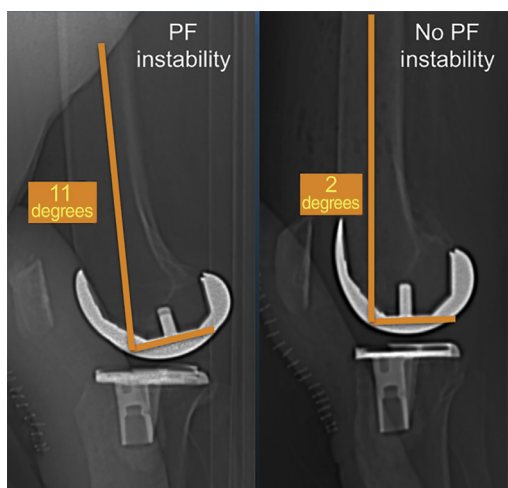


Figure 19.1 Lateral computed tomography (CT) scanograms show 11 degrees of flexion of the femoral component with respect to the sagittal anatomic axis of the distal femur in a patient with patellofemoral instability (PF), and 2 degrees of flexion in a control patient without patellofemoral (PF) instability ($P < .001$). (From 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):283–291.)

tissue overgrowth of the small dome-shaped patella component during 5 months of implantation caused a gradual loss of congruency, which explains the atraumatic and late onset of patellofemoral instability.¹

Use of Femoral Components Designed for Mechanical Alignment Does Not Explain Patellofemoral Instability After Kinematic Alignment

Video 19.2 discusses studies showing that KA of the femoral component restores patellofemoral kinematics closer to the native knee than MA.

Results from in vivo and in vitro kinematic studies indicate that the use of femoral components designed for MA with KA was an unlikely cause of patellofemoral instability.^{2,4–8} An in vivo study of patients doing a deep knee bend showed that KA with a posterior cruciate ligament retaining (CR) component placed without flexion largely restored the proximal-distal patellar contact locations of the native contralateral knee.⁷ Two cadaveric studies showed KA better restored patellar kinematics and patellofemoral contact pressure distribution closer to those of the native knee than MA TKA during flexion.^{4,5} A three-dimensional analysis of several brands of femoral components designed for MA aligned on normal femurs showed that KA more closely restored the native trochlea than MA.^{6,8} The explanation for this paradox is that KA restores the native Q-angle and patellofemoral kinematics, whereas MA increases or decreases the native Q-angle in those patients with constitutional varus or valgus limbs, respectively.⁷ Hence, the penalties for the use of MA and the consequential deviation from the prearthritic Q-angle are abnormal patellofemoral kinematics and pressures, which KA mitigates even when the femoral component and prosthetic trochlea are designed for use with MA.

Use of an Intraoperative Verification Check and an Anatomic Patella Component Reduces the Risk of Patellofemoral Instability

Video 19.3 shows the intraoperative verification check for setting the entry hole for positioning the distal femoral resection guide and use of an anatomic patella component.

In 2015, the introduction of an intraoperative verification check reduced the incidence of patellofemoral instability from 0.4% to 0.1% (2 of 2382 consecutive calipered KA TKAs) (**Fig. 19.2**). The verification check carefully controls the entry point of the starting hole for the positioning rod to minimize the flexion of the femoral component when setting the distal femoral cutting block. The entry point is started midway between the anterior and posterior cortex of the distal femur, and the verification check is a 5- to 10-mm bridge of bone between the posterior boundary of the drill hole and the anterior aspect of the notch after removal of osteophytes. This verification check limited flexion of the femoral component to 1 ± 2 degrees.³ The current clinical practice is to use an anatomic instead of a domed-shaped patella component and resurface all patella when performing calipered KA TKA. The experience of not resurfacing the patella in around 500 TKAs from November 2008 to August 2010 caused more dissatisfaction and reoperations than in those patients treated with patella resurfacing before and after this period of investigation.

A Femoral Component Redesigned for Kinematic Alignment Should Increase the Lateral Coverage of the Anterior Femur

Video 19.4 discusses the anatomic rationale for redesigning the femoral component for kinematic alignment.

Does a positioning rod or a patient-specific guide result in more natural femoral flexion in the concept of kinematically aligned total knee arthroplasty?

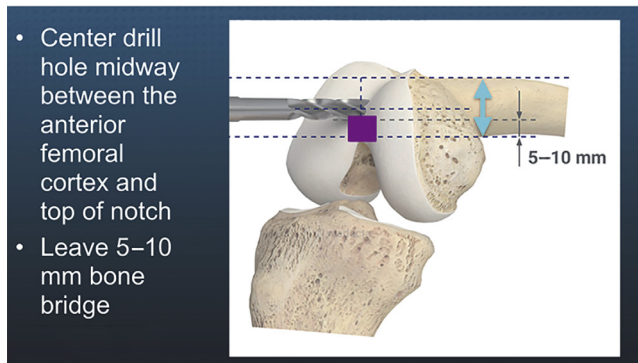


Figure 19.2 The schematic shows the method for minimizing the risk of flexing the femoral component. The verification check is a 5- to 10-mm bone bridge (magenta square) between the posterior aspect of the starting hole for the positioning rod and the anterior aspect of the intercondylar notch. (From Ettinger M, Calliess T, Howell SM. Does a positioning rod or a patient-specific guide result in more natural femoral flexion in the concept of kinematically aligned total knee arthroplasty? *Arch Orthop Trauma Surg*. 2017;137(1):105–110.)

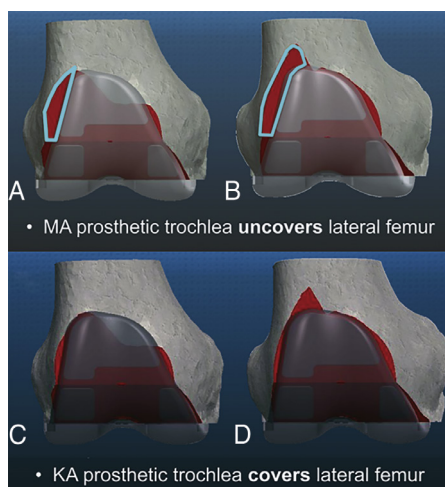


Figure 19.3 The schematics show an anterior view of a three-dimensional model of two distal femurs after kinematic alignment (KA) of the femoral component designed for use with mechanical alignment (MA) (A, B) and after KA of a femoral component redesigned explicitly for use with KA (C, D). The tracings in *light blue* show the area on the anterior lateral femur left uncovered by the prosthetic trochlea designed for MA (A, B). The femoral component designed for KA nearly covers the tracing, which promotes capture and containment of the anatomic patella in extension (C, D).

Anatomic observations provide a rationale for redesigning the prosthetic trochlea for explicit use with calipered KA. KA sets the femoral component, on average, in more valgus and internal rotation than MA, which uncovers the lateral side of the anterior femur (Fig. 19.3).^{6,9} A KA design should extend the prosthetic trochlea more lateral than MA designs, to increase the coverage of the anterior femur (Fig. 19.4). A three-dimensional analysis study of three femoral component brands showed minor changes in the medial-lateral (M-L) and radial locations of the prosthetic groove and depth of the sulcus angle are needed to more closely restore the native trochlea.⁶ These changes might promote tracking and reduce the risk of patellofemoral instability.

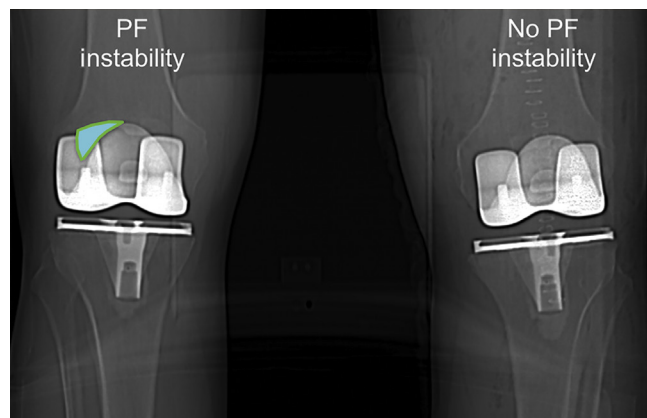


Figure 19.4 Coronal computed tomography (CT) scanogram of bilateral calipered kinematic alignment total knee arthroplasty shows a right knee with patellofemoral (PF) instability with less lateral coverage of the anterior femur by the prosthetic trochlea designed for use with mechanical alignment than the left knee. Although a prosthetic trochlea designed explicitly for kinematic alignment was not in production, its use could have provided more lateral coverage of the anterior femur (*blue shape*) and reduced the risk of PF instability.

Options for Managing Patellofemoral Instability After Calipered Kinematically Aligned Total Knee Arthroplasty

Video 19.5 shows management options and outcomes of patients treated for patellofemoral instability.

OPTION 1: OBSERVE PATIENTS WHO CHOOSE TO COPE WITH PATELLOFEMORAL INSTABILITY (N = 4)

Four of thirteen patients with patellofemoral instability presented with bothersome and not disabling lateral subluxation of the patella during flexion that they chose to cope with rather than proceed to reoperation. One confounding example is a patient treated with bilateral calipered KA TKA with identical size and brand of femoral component. Although both femoral components were flexed 10 degrees, only one TKA developed patellofemoral instability. The interaction of multiple factors, including (1) a small anterior-posterior height relative to the M-L width requiring a small femoral component that resulted in poor lateral coverage of the anterior femur, (2) additional downsizing because of setting the femoral component in 10 degrees of flexion, (3) a prearthritic valgus distal femoral joint line, and (4) the use of a prosthetic trochlea designed for MA, promoted patellofemoral instability.

OPTION 2: REOPERATION WITH ARTHROSCOPIC LATERAL RELEASE (N = 2)

Arthroscopic lateral release was successful in two patients with flexion of the femoral component less than 9 degrees. In one case example, the flexion of the femoral component was 7 degrees, and the hip-knee-ankle angle was 0 degrees without valgus limb alignment. Eight years after the lateral release, the patient reported an Oxford Knee Score of 44 (48 best) and a Forgotten Joint Score of 63 (100 best), indicating a reasonable level of satisfaction.

OPTION 3: REOPERATION WITH OPEN LATERAL RELEASE AND MEDIAL REEFING (N = 6)

Operative treatment of six patients with open lateral release and proximal medial reefing was generally unsuccessful. Four patients complained of persistent patellofemoral instability after the procedure. In the operating room, the patellofemoral instability did not occur during passive motion, so the adequacy of the proximal patella realignment could not be assessed. The median Oxford Knee score for these patients of 33 points was 11 points lower than the score of 44 points for those without instability. In hindsight, the better initial treatment might have been a revision of only the femoral component and setting the revised implant at 0 degrees of flexion.

Summary

The primary causes of patellofemoral instability after calipered KA TKA are (1) setting the femoral component in more than 6 degrees of flexion from the anatomic axis of the distal femur, and (2) the use of a dome-shaped patella component instead of

an anatomic design. The intraoperative verification of a 5- to 10-mm bone bridge between the posterior rim of the starting hole for the positioning rod and the anterior border of the intercondylar notch limited flexion of the femoral component and reduced the risk of instability to less than 0.1%. KA of a prosthetic trochlea designed for use with MA restored the native trochlea's anatomy, patellar kinematics, and patellofemoral contact pressure closer to those of the native knee than MA. The use of these femoral components with KA should pose no higher risk of patellofemoral instability than their use with MA. However, a redesign of the prosthetic trochlea to increase the lateral coverage of the anterior femur and more closely coalign the orientations of the prosthetic and native trochlear grooves are

strategies that could improve capture, containment, and tracking of the patella component. Observation can work in patients with mild symptoms of patellofemoral instability. Arthroscopic lateral release was useful in one patient without flexion of the femoral component. In those patients with flexion of the femoral component of 9 degrees or more, consider revising the femoral component and setting the revised implant at 0 degrees of flexion, as an open lateral release and medial reefing had low success. Prevention of patellofemoral instability is the best management, which is accomplished by not flexing the femoral component, using an anatomic patella component, and, when available, using a femoral component with a trochlea explicitly designed for KA.

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Retaining the Posterior Cruciate Ligament and Restoring the Prearthritic Tibial Joint Line Reduces the Risk of Early-Onset Tibiofemoral Instability After Calipered Kinematically Aligned Total Knee Arthroplasty

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CHAPTER OUTLINE

Overview

Incidence and Causes of Early-Onset Flexion and Extension Space Tibiofemoral Instability After Calipered Kinematically Aligned Total Knee Arthroplasty

Retain the Posterior Cruciate Ligament and Use Verification Checks to Reduce the Risk of Early-Onset Tibiofemoral Instability After Calipered Kinematically Aligned Total Knee Arthroplasty

Verification Checks That Restore the Native Laxity of the Flexion Space and Reduce the Risk of Tibiofemoral Instability

Verification Checks That Restore the Native Laxity of the Extension Space and Reduce the Risk of Tibiofemoral Instability

Three Intraoperative Methods That Compensate for Flexion Space Laxity When the Posterior Cruciate Ligament Is Excised or Inadvertently Injured

Options for Managing Early-Onset Flexion and Extension Space Tibiofemoral Instability After Calipered Kinematically Aligned Total Knee Arthroplasty

Option 1: Observe Patients That Cope With Mild Flexion Space Anterior-Posterior Tibiofemoral Instability

Option 2: Add Constraint and Revise the Femoral and Tibial Components in Patients With Disabling Flexion Space Anterior-Posterior Tibiofemoral Instability

Option 3: Observe Patients That Cope With Mild Extension Space Varus-Valgus Tibiofemoral Instability

Option 4: Revise the Tibial Component in Patients With Disabling Extension Space Varus-Valgus Tibiofemoral Instability

Overview

This chapter contains discussion and videos that assist the surgeon in (1) reducing the risk of early-onset tibiofemoral instability) and (2) managing the instability when it occurs after calipered kinematically aligned (KA) total knee arthroplasty (TKA). The chapter draws from the author's experience treating over 1527 primary TKAs implanted from 2017 through 2019. In each, the target for setting the components was coincident to

the patient's prearthritic joint lines regardless of knee deformity, and the restoration of native tibial compartment forces occurred without ligament release. During this time, 1200 calipered KA TKAs had retention of the posterior cruciate ligament (PCL), and 327 had an excision of the PCL. The first section reports the incidence and discusses the causes of early-onset flexion space anterior-posterior (A-P) instability (i.e., 90 degrees) and extension space varus-valgus (V-V) tibiofemoral instability. The second section recommends the retention of the PCL and the use of verification checks to reduce the risk of tibiofemoral instability. The third introduces three intraoperative methods that compensate for flexion space laxity when the PCL is excised or inadvertently injured from a transection or detachment from the tibia. The final section uses case studies to discuss options for managing symptomatic patients with early-onset flexion and extension space tibiofemoral instability. The educational objective is to encourage surgeons to retain the PCL, not release the collateral ligaments, and restore the native V-V plane and posterior slope of the proximal tibial joint, to reduce the risk of early-onset tibiofemoral instability when performing calipered KA TKA.

Incidence and Causes of Early-Onset Flexion and Extension Space Tibiofemoral Instability After Calipered Kinematically Aligned Total Knee Arthroplasty

Video 20.1 discusses the incidence and causes of early-onset flexion and extension space instability.

A search of a prospectively collected database from 2017 through 2019 identified 1527 primary TKAs, and the treatment for each was calipered kinematic alignment (KA) without ligament release. There were no exclusions because of the severity of the preoperative deformity. Intraoperatively, caliper measurements verified the femoral and tibial components restored the patient's prearthritic joint lines regardless of limb alignment. There were 1203 KA TKAs with a PCL-retaining (CR) implant design, and 327 with a cruciate-substituting design (CS) after resection of the PCL. A review of the operating room log identified three patients with early revision because of flexion space anterior-posterior (A-P) tibiofemoral instability. One patient had

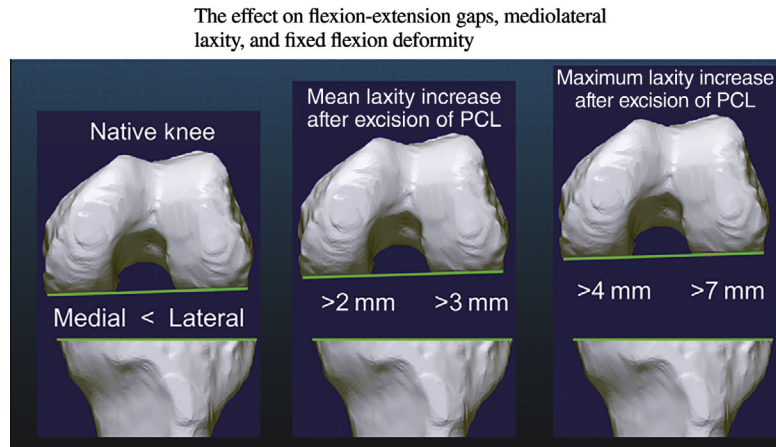


Figure 20.1 The composite shows the slack and asymmetric trapezoidal flexion space of the native knee (*left*), the mean increase in flexion space laxity after excision of the posterior cruciate ligament (PCL), and the maximum increase in flexion space laxity after removal of the PCL. The reduction of the posterior slope might compensate for smaller increases (*middle*). The use of more constrained implants might be needed to compensate for more substantial increases (*right*). The excision of the PCL creates variable, and unpredictable laxity increases in the flexion space. Retaining the PCL and restoring the pre-arthritis posterior slope reduces the risk of flexion space anterior-posterior tibiofemoral instability. (From Kayani B, Konan S, Horriat S, Ibrahim MS, Haddad FS. Posterior cruciate ligament resection in total knee arthroplasty: the effect on flexion-extension gaps, mediolateral laxity, and fixed flexion deformity. *Bone Joint J.* 2019;101-B(10):1230–1237.)

an early revision because of extension space V-V tibiofemoral instability. Therefore, the incidence of revision surgery for early-onset tibiofemoral instability was 0% in those with PCL retention (0 of 1203) and 1.2% (4 of 327) for those with PCL excision.

The cause of the revision in the three patients with early-onset flexion space A-P tibiofemoral instability was inadequate compensation for the increase in flexion space laxity caused by resection of the PCL. Studies have shown that the resection of the PCL increases the mean laxity of the medial gap by 2 ± 1.5 mm and the lateral gap by 3 to 5 mm in 90 degrees of flexion (Fig. 20.1). The standard deviation of ± 1.5 mm indicates that each gap has a different and variable increase in the laxity that ranges from around 0 to 5 mm medially and 0 to 8 mm laterally.^{1,2} The variability of the increases in the medial and lateral flexion gaps makes the intra-operative compensation for the flexion instability caused by PCL resection a challenge.

One technique for reducing flexion space A-P laxity is to set the tibial component in less posterior slope than the patient's prearthritic slope. The surgical options are to recut the tibia with less posterior slope and a build-up of the posterior third of the proximal tibia with bone graft. Another effective option is to resect more bone from the distal femur and upsize the thickness of the tibial insert to compensate for flexion space laxity. However, the limitation common to all three techniques is the changes of the prearthritic posterior slope and the elevation of the distal femoral joint line, which violates the principles of kinematic alignment.

Retain the Posterior Cruciate Ligament and Use Verification Checks to Reduce the Risk of Early-Onset Tibiofemoral Instability After Calipered Kinematically Aligned Total Knee Arthroplasty

Video 20.2 shows the importance of retaining and protecting the PCL and use of verification checks to reduce the risk of early-onset tibiofemoral instability.

VERIFICATION CHECKS THAT RESTORE THE NATIVE LAXITY OF THE FLEXION SPACE AND REDUCE THE RISK OF TIBIOFEMORAL INSTABILITY

1. Set the posterior slope and the V-V plane of the tibial resection to match the prearthritic knee when using a CR implant. Set the depth of the tibial resection to accommodate an insert 1 mm thicker than the thinnest one available. Resist making the tibial resection in excessive slope and too thick, as this increases the risk of detaching the PCL insertion on the posterior tibia.
2. Inspect the medial side of the tibial resection. Verify the resection plane is parallel to the slope of the articular surface, which restores the prearthritic posterior slope. When the slope is less than the prearthritic knee, the flexion space is too tight. Be prepared to recut the tibia and increase the posterior slope. Verify the PCL is intact by palpation and visually confirming it is not transected or detached from the tibia.
3. Place the knee in 90 degrees of flexion and insert the tightest-fitting spacer block. The surgeon should notice that rotating the handle of the block internally and externally (I-E) causes a pivot to occur about the center of the medial compartment, indicating restoration of a trapezoidal flexion space.
4. Place the knee in 90 degrees of flexion and insert trial components. Verify there is ± 15 degrees of I-E rotation, which restores the native laxity of the flexion space.^{3,4}
5. With the knee in 90 degrees of flexion, use an offset caliper and measure the distance between the anterior tibia and the distal medial femoral condyle. Compare this offset to the one taken at the time of exposure. When the offset is greater and the I-E rotation is less than ± 15 degrees, add more posterior slope. When the offset is less, add a thicker insert or set the tibial component in less posterior slope.
6. Be aware that these verification checks are ineffective when the PCL is excised, transected, or detached from the tibia.

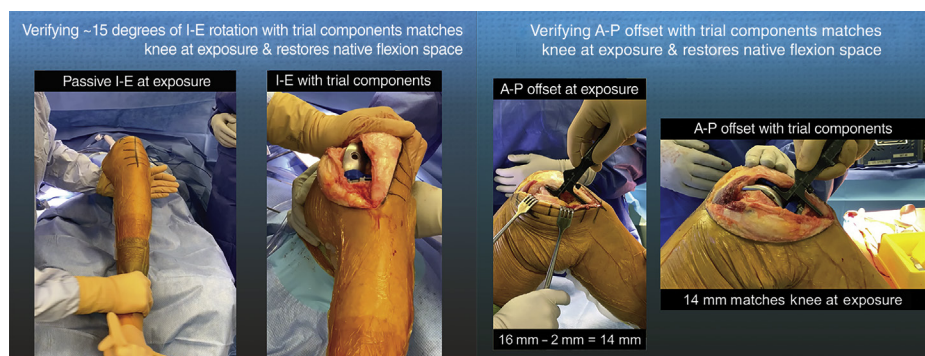


Figure 20.2 The composite shows the two verification checks performed with trial components with the knee in 90 degrees of flexion that restore the native laxity of the flexion space. Passive internal-external (I-E) rotation should approximate ± 15 degrees and match those of the knee at the time of exposure (left two images). The anterior offset of the anterior tibia from the distal medial femoral condyle should match that of the knee at the time of exposure after compensation for cartilage wear (right two images). These verification checks restore the native laxity and tibial compartment forces of the native knee. Be aware that the offset measurement becomes an ineffective verification check after the removal of the posterior cruciate ligament. A-P, Anterior-posterior.

VERIFICATION CHECKS THAT RESTORE THE NATIVE LAXITY OF THE EXTENSION SPACE AND REDUCE THE RISK OF TIBIOFEMORAL INSTABILITY

1. Insert a spacer block and place the knee in extension. The surgeon should notice negligible V-V laxity, indicating the restoration of the native tight rectangular extension space. When one compartment is tighter than the other, refer to the decision tree for balancing the KA TKA. When the lateral side opens 1 to 2 mm, perform a varus re-cut of 1 degree. When the lateral side opens 1 to 2 mm, perform a valgus recut of 1 degree.^{3,4}
2. Insert trial components and place the knee in maximum extension. Verify there is 3 to 5 degrees of hyperextension like the native knee. Adjust the thickness of the insert to set the degree of hyperextension. When the extension is limited, insert a thinner insert.
3. Apply a V-V load to the tibia and verify the V-V laxity is negligible. When one tibial compartment opens 1 to 2 mm, fine-tune the V-V plane until the V-V laxity is negligible like the native knee (Fig. 20.2).
4. Place the knee in 15 to 30 degrees of flexion and apply a V-V load to the tibia. Verify that the medial side does not open more than 1 mm, and the lateral side opens 2 to 3 mm. When the lateral side opens 4 mm or more, check the V-V plane of the tibial resection is not too valgus and that the insert is not too thin.

Three Intraoperative Methods That Compensate for Flexion Space Laxity When the Posterior Cruciate Ligament Is Excised or Inadvertently Injured

Video 20.3 shows two intraoperative strategies for tightening a lax flexion space caused by an incompetent PCL.

Surgeons should understand those factors that risk injury to the PCL. Because most surgeons use a saw blade with the same width on all patients, those patients with small femurs and narrow femoral condyles have the highest risk for an unintended transection of the PCL when performing the posterior femoral resections. Surgical errors such as a too thick tibial resection, a posterior slope greater than native, and soft bone have a high risk of detaching the tibial insertion of the PCL.

At the time of the primary TKA, one strategy for compensating for a lax flexion space from PCL insufficiency is reducing the posterior slope of the tibial component (Fig. 20.3). When a 10- to 11-mm thick insert stabilizes the knee in extension, and the TKA is lax in flexion, consider reducing the posterior slope by recutting 2 to 3 mm from the anterior tibia and using a thicker insert. When a 13- to 14-mm thick insert stabilizes the knee in extension, and the TKA is lax in flexion, consider bone grafting the posterior tibia with a 3- to 4-mm thick section of cancellous bone shaved from the cancellous surface of the tibial

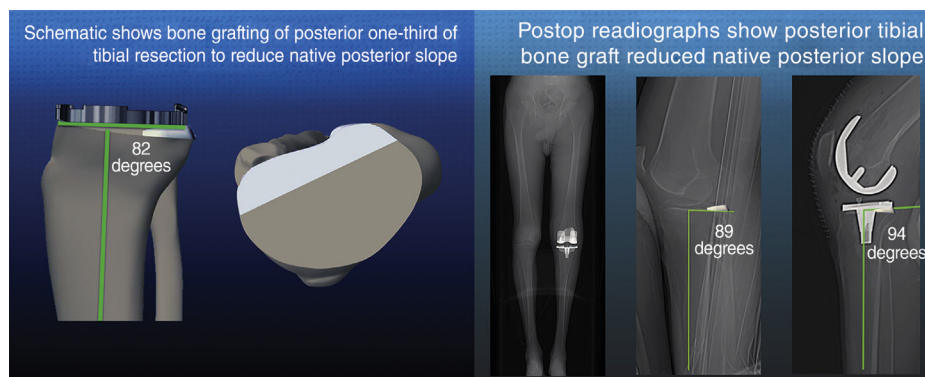


Figure 20.3 The composite shows a schematic (left) of the intraoperative method for reducing the posterior tibial slope by bone grafting the posterior one-third of the tibial resection. The radiographs (right) show a prearthritic posterior slope of 89 degrees that was reduced to 94 degrees by bone-grafting the posterior tibia, which compensates for mild increases in flexion space laxity from excision and inadvertent injury to the posterior cruciate ligament.

resection. The use of the cancellous bone graft to build up the resected surface of the posterior tibia reduces the risk of adding medial and lateral augments and a stem extension to the tibial baseplate. After placing the bone graft on the posterior one-third of the tibia, impact the trial tibial baseplate to obtain the desired reduction in the posterior slope. With trial components inserted and the knee in 90 degrees of flexion, lift the thigh until the foot is off the operating table, and apply a posterior drawer. Confirming there is no posterior subluxation of the tibial insert on the femoral component verifies the reduction in the slope compensated for the lax flexion space.

A second strategy for tightening a lax flexion space is resecting 2 mm of additional bone from the distal femur and using a 2-mm thicker insert. Preferably, the surgeon should strive to protect and retain the PCL at the outset. These “bone corrective” surgical options do not compensate for flexion space laxity from a PCL deficiency, and they violate the principles of kinematic alignment by reducing the posterior slope from the native knee and elevating the distal femoral joint line.

Options for Managing Early-Onset Flexion and Extension Space Tibiofemoral Instability After Calipered Kinetically Aligned Total Knee Arthroplasty

Video 20.4 shows management and outcomes of patients treated for flexion and extension space tibiofemoral instability.

There are several options to share with a patient with well-fixed components that present with early-onset flexion and extension space tibiofemoral instability after calipered KA TKA (Fig. 20.4). The usefulness of these options depends on

whether the verification worksheet and operative note show the measurements of the distal and posterior femoral resections restored the patient's prearthritic joint lines regardless of knee deformity without ligament release. Because calipered KA does not release ligaments, those patients with A-P flexion space instability typically lack the function of the PCL and have excessive posterior tibial slope. Those patients with extension space V-V instability have a tibial component that deviated more than 2 degrees from the prearthritic proximal tibial joint line.

OPTION 1: OBSERVE PATIENTS THAT COPE WITH MILD FLEXION SPACE ANTERIOR-POSTERIOR TIBIOFEMORAL INSTABILITY

Patients with mild symptoms of flexion space A-P instability notice excessive A-P motion of the tibia when they sit with the knee in 90 degrees of flexion, which is not disabling when walking and performing everyday activities. After counseling and weighing the consequences of revision surgery, many decide to modify or exclude the daily activities that overstress the knee and cope. A revision that replaces the insert with a 1- to 2-mm thicker one is an option; however, the patient should understand the knee may lose 2 to 4 degrees of extension, respectively.⁵

OPTION 2: ADD CONSTRAINT AND REVISE THE FEMORAL AND TIBIAL COMPONENTS IN PATIENTS WITH DISABLING FLEXION SPACE ANTERIOR-POSTERIOR TIBIOFEMORAL INSTABILITY

Those patients with loss of PCL function and excessive posterior tibial slope at the time of primary KA TKA are at high risk of revision surgery. A tempting and often temporizing “solution” is

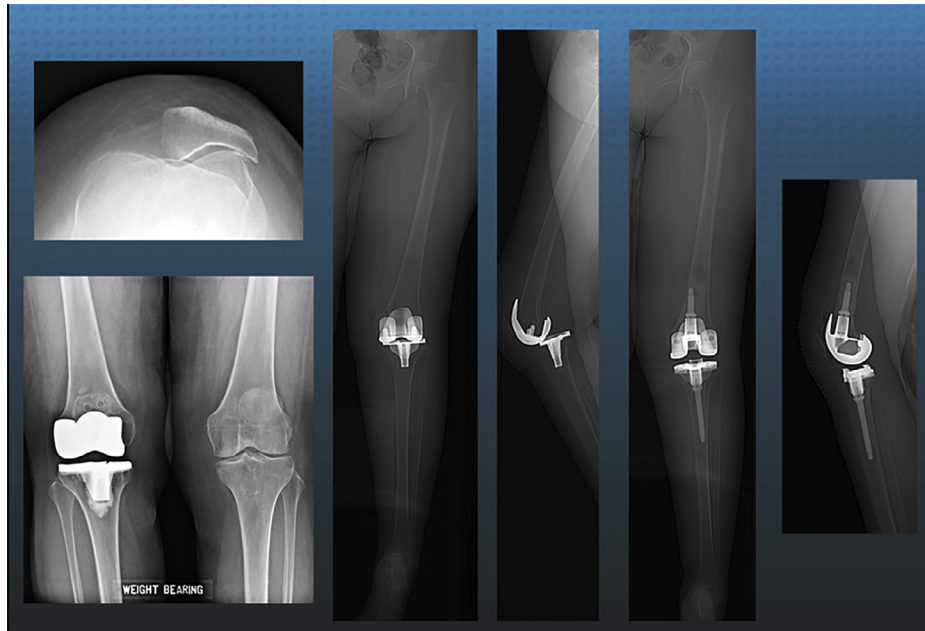


Figure 20.4 The radiographic images show the management of a patient with a well-functioning posterior cruciate-retaining right calipered kinematically aligned (KA) total knee arthroplasty (TKA), which developed, in the left knee, early-onset flexion space anterior-posterior (A-P) tibiofemoral instability because of removal of the posterior cruciate ligament (PCL). Removal of the PCL likely caused a maximum increase of 4 mm in the medial gap and 7 mm in the lateral gap at 90 degrees of flexion. A reduction in the posterior tibial slope did not compensate for this substantial increase in flexion laxity. Back-up constrained implants were not available at the time of the primary TKA. Within 2 days, the tibia dislocated posterior when the patient flexed the knee, getting out of bed. The lesson learned is to retain the PCL when performing calipered KA TKA, as this reduces the risk of early-onset flexion space A-P instability.

to revise the tibial insert with a thicker one and add constraint when the option exists. The use of this “simple solution” may afford early stability. However, there is a risk of recurrent instability that ultimately requires a revision of the femoral and tibial components with added constraint. The two lessons learned from managing several of these cases are (1) strive to retain the PCL during the primary surgery, and (2) when the PCL is transected or inadvertently injured, convert to a CS or posterior cruciate ligament substituting design and reduce the posterior tibial slope during the primary surgery.

OPTION 3: OBSERVE PATIENTS THAT COPE WITH MILD EXTENSION SPACE VARUS-VALGUS TIBIOFEMORAL INSTABILITY

Patients with mild symptoms of extension space V-V instability notice a change in the alignment of the limb when they stand and shift weight from the medial to the lateral tibial compartment. They may not complain of symptoms when walking and performing everyday activities. After counseling and weighing the consequences of revision surgery, most decide to cope. Revision with a thicker tibial insert is not a practical option. This strategy does not correct the underlying cause, which is that the V-V setting of the tibial baseplate did not restore the native proximal tibial joint line.

OPTION 4: REVISE THE TIBIAL COMPONENT IN PATIENTS WITH DISABLING EXTENSION SPACE VARUS-VALGUS TIBIOFEMORAL INSTABILITY

Those patients with disabling symptoms of extension space V-V instability and limb malalignment require revision of the tibial component. The V-V correction for the revised tibial component is the angular difference between the tibial component and the prearthritic or contralateral proximal tibial joint line. The

addition of a short-stem cemented extension, and a bone in-growth cone lowers the risk of impingement of the tip of the stem on the lateral tibial cortex when compared with a long stem extension. One lesson learned from several of these cases is to verify in full extension that the V-V laxity is negligible with the spacer block and with trial components.^{3,4} Another lesson is to test V-V stability with the knee in 15 to 30 degrees of flexion and verify that the opening of the gap is not more than 1 mm medial and 3 mm lateral. These two verifications are especially important with a medial ball-in-socket design because the implant has inherent sagittal stability in extension.

Summary

The educational objective of this chapter is to encourage surgeons that perform calipered KA TKA to retain the PCL, not release collateral ligaments, and restore the native V-V plane and posterior slope of the proximal tibial joint line. The incidence of revision surgery for early-onset flexion space A-P instability was 0% when the PCL was retained (0 of 1203) and 1.2% (4 of 327) when the PCL was excised. When an intentional resection or inadvertent injury occurs to the PCL, add more constraint with a CS or PS component design, and reduce the posterior tibial slope by either recutting the tibia or by bone grafting the posterior one-third of the tibial resection. To reduce the risk of extension space V-V instability, visually inspect the extension space with a spacer block followed by trial components and verify there is negligible V-V laxity, like the native knee. When flexion space A-P instability occurs, consider revising the tibial and femoral components using more constraint, and reducing the posterior slope. When extension space V-V instability occurs, consider changing the tibial component and restoring the prearthritic V-V plane of the proximal tibial joint line, which restores the prearthritic alignment of the limb.

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Revision Total Knee Arthroplasty Using Kinematic Alignment Principles

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CHAPTER OUTLINE

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Cementing Components

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Last Thoughts

Overview

This is the last chapter in a book conceived of as a resource for surgeons interested in rethinking alignment in total knee arthroplasty (TKA). The aim is to improve the function of TKAs above and beyond the currently accepted standard. The idea that an individualized approach to TKA alignment focusing on the restoration of the patient's native joint line and axis of rotation as the foundational element by which to restore normal knee kinematics has been discussed in prior chapters. In the following pages, a few thoughts will be offered to propose a rationale for revising symptomatic, mechanically aligned (MA) TKAs back into native alignment (kinematic alignment [KA]) as a means to addressing the patient's symptoms (Fig. 21.1). These are knees that are not necessarily loose or infected, but which are painful, unstable, or have symptoms consistent with instability. Based on MA standards, these knees "look great" but are painful.

We will review the rationale for this indication for revision TKA and the surgical technique will be presented in detail. We will report the early retrospective results from a single surgeon series at the end of the chapter.

How We Got Here: The Rationale for Mechanical Alignment and Its Implications for Revision Total Knee Arthroplasty

It is important to acknowledge that the "rules" for knee alignment were developed as solutions to problems surgeons encountered 30 years ago. These pioneers were working with first- and

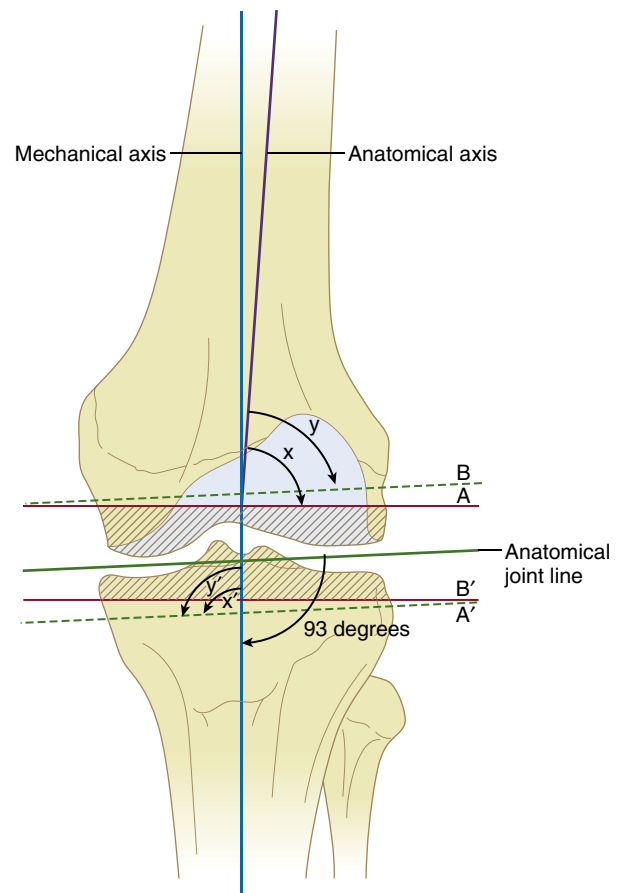


Figure 21.1 Illustration of existing bone cuts following a mechanically aligned total knee arthroplasty and the desired bone cuts if one wishes to restore or approximate kinematic alignment in the context of a revision. For the purpose of illustration, the knee's natural tibial joint line angle (TJLA) is in 3 degrees of varus and the femoral joint line angle (FJLA) angle is 9 degrees of valgus. The native femoral anatomy shows the asymmetric bone resections performed, leading to the existing femoral and tibial bone cuts (A and A') subtending a 6-degree FJLA (x) and a 0-degree TJLA (x'). The desired plane of the bone cuts required to position the revision components in kinematic alignment (B and B') subtending a 9 FJLA (y) and a 3-degree TJLA (y') are also shown. The femoral cut is based on the medial condyle's most lateral edge, as that is the last remaining available natural anatomy for reference.

second-generation devices with varied and flawed designs,^{1,2} manufactured with imperfect techniques,³ and implanted with limited instrumentation⁴ using experimental cement formulations.^{5,6} Early poor and unreliable results led to restrictive patient selection criteria and conservative age limits.

In an effort to improve clinical results, surgical techniques were standardized around several principles, the most foundational of which was the theory of MA.⁷ To optimize loading across joints in implants that were highly susceptible to asymmetric forces, it was deemed optimal that the femoral head, knee, and ankle should be aligned along a linear loading axis and that the joint line should be parallel to the floor. However, frequently achieving MA required a “correction” of the patient’s native bony anatomy with trapezoidal and often asymmetric bone cuts. As a result, the joint would become unbalanced. A complex set of soft tissue releases was therefore devised to “balance” the knee in two positions: full extension and 90 degrees of flexion.^{8,9,10}

Several considerations need to be addressed that impact the question of revision surgery. The first is that the implants and instrumentation available to us today have little relationship to the devices for which MA principles were developed. These devices involved flat-on-flat designs, shallow trochlear grooves, and sterilization in air long gone. Today’s instruments are far more accurate and can take advantage of computer navigation and robotics. Further, the ideas that the hip, knee, and ankle need to axially aligned, that the tibial tray need be aligned perpendicularly to the anatomic axis of the tibia, and that the femur be externally rotated to match the transepicondylar axis have all been questioned.^{11,12} The problem is that these tenets essentially act as limits or boundaries to what can be done with respect to knee alignment and are based on the fear that if they are not followed, the implants will fail because of eccentric loading or instability.¹³

However, this mindset also limits our ability to innovate. It is similar to imagining that the speed limits on our freeways had remained at 55 miles per hour (mph) despite the advances made in the automotive industry. In the 1960s, most cars could not handle taking corners at high speeds, their brakes were poor, and mortality from accidents was high. In that context, the 55-mph speed limit made sense. However, in the days of airbags, antilock braking system (ABS) brakes, crumple zones, and cars that can take a 75-mph curve without human intervention, a 55-mph speed limit makes little sense. The same is true of today’s TKA implants; the bearing surfaces can handle higher loads,⁹ the components have congruent bearing surfaces that are more stable,¹⁴ implants are anchored to bone using more durable techniques such as biologic fixation and improved cementation techniques,¹⁵ wear is no longer prevalent as a cause of failure,¹⁶ and the improved designs of inserts provide more physiologic motion than ever before.¹⁷ The proof that these devices are more durable than prior generations is represented in the survivorship data of many national registries. Because the target of MA has not changed, and variation between intended and actual alignment continued unabated, the ability to achieve north of 90% survivorship at 15 or more years in increasingly younger patients can be ascribed in large part to the devices themselves.^{18,19} And yet, we are holding these devices slave to rules and ideas developed to solve problems that were solved long ago.

MA principles are even more codified in the revision knee arthroplasty world than they are in the primary knee world. In

revision surgery, the design of the implants essentially forces the surgeon into an MA philosophy, thanks to the orthogonal design of the tibial stems relative to the base plate and the 5- to 7-degree fixed angulation of the femoral stem relative to the joint line of the femoral component. Further, revision devices for the most part reflect dated implant design features that are restrictive rather than permissive in their engineering.

It is therefore not surprising that revision implants as a rule do not improve range of motion in patients undergoing revision TKA for pain and stiffness. If the optimal alignment for a knee reflects a person’s individual anatomy and not an artificially orthogonal alignment, it follows that limits in kinematic function following revision TKA may be preordained by a revision implant designed to essentially replicate the position of an existing, and poorly functioning, knee replacement.

The following technique for revising a failed MA TKA into KA describes the use of existing devices to achieve an outcome they were designed to avoid. The instrumentation will hinder success, not enable it, and several tricks (and more than a little trial and error) are required to achieve the restoration of the prearthritic axis of rotation and joint line of the native knee.

Candidates for Kinematically Aligned Revision

Not all TKAs performed in MA complain of pain or instability. Some 80% or so do reasonably well. From this data it can be concluded that patients on the whole have a significant tolerance to alterations of their knee’s native axis. This tolerance is probably within a 2- to 3-degree range because this spread encompasses approximately 80% of patients’ native variation from neutral alignment. Thus the best candidates for revision of an MA knee to a KA knee are those whose standing anatomy was altered by 3 or more degrees in any plane, as they are the most likely to benefit from restoration of their normal alignment.

Furthermore, the clinical symptoms that the patient complains of should be those that are associated with malalignment, namely: (1) stiffness and/or (2) midflexion instability. Often these symptoms are accompanied by swelling, nonfocal pain, and a history that the knee never felt “quite right,” and that their surgeon told them that the X-ray images “look great.” Many patients are prescribed physical therapy and antiinflammatories and, when these do not work, a manipulation under anesthesia for stiffness and a brace for instability. The latter seldom achieves the desired improvement, and the knee remains basically at its baseline.

Stiffness in MA knees is often caused by the fact that balanced gap techniques externally rotate the femoral component relative to the posterior condylar axis, to close down the lateral gap at 90 degrees of flexion, thus creating posterior-lateral conflict between the femur and the tibia in a space that, in the natural knee, has 2 to 4 mm of laxity. By closing the lateral flexion gap required for roll back, medial pivot and flexion, the knee inevitably loses flexion.

Midflexion instability is caused by the fact that the components are not aligned with the anatomic axis of rotation of the knee. A useful visual image is to consider a wheel whose axle was simply translated backwards by one inch but at exactly the same height. The wheel, when static, would stay in the exact

same position (i.e., balanced in full extension). However, once the wheel rotates, it will start to be very unstable until it returns to the exact same position. In an MA knee, the components are positioned off-axis, like the wheel whose axle has been moved. In extension, where the knee is balanced because the true and false axes are coplanar, the implant is stable. It is only when the knee is bending and the rotational axes are no longer coplanar that midflexion instability arises and the knee becomes unstable. The most common symptoms of midflexion instability are knee swelling with activity, and pain with walking hills, descending stairs, and arising after prolonged sitting. Many midflexion instability patients also complain of “global knee pain” with extended activity but may not identify any one specific activity as the root cause. They often will run their hands all over their knee when asked to point to the area of pain. This pain is caused by a global tendonitis of the knee caused by constant off-axis rotation of the components that places the ligaments of the knee under abnormal stress throughout the gait cycle.

Indeed, on physical exam, the knee may or may not be red or swollen. However, palpation of the ligaments and tendons around the knee may arouse pain at the patellar tendon, collaterals, the iliotibial band, and the popliteus. Further, there may be flexion instability at 90 degrees and patellar maltracking in midflexion, and in all cases the knee will open up several degrees when stressed in either varus or valgus between 20 and 40 degrees of flexion, something the native knee does not do.

Imaging generally shows a “well-aligned and well-positioned implant,” often with a tilted patella, but no evidence of aseptic loosening or infection. Comparison with standing preoperative hip to ankle images when available (or contralateral images when not) suggests that the joint line was corrected by more than 3 degrees to achieve MA; frequently, the joint line is in valgus relative to the floor and the femoral and tibial anatomic axis are nearly colinear.

In summary, the best candidate for revision of a TKA from MA to KA are those whose alignment was changed from their prearthritic anatomy by over 3 degrees, whose symptoms suggest a chronic tendinitis, and whose physical examination suggests midflexion instability or a posterolateral conflict.

Contraindications to Kinematically Aligned Revision

It follows from the earlier description that patients whose native alignment was within a couple of degrees in all planes of their postoperative anatomy, who have no midflexion instability, and whose symptoms and imaging do not suggest rotational or angular malalignment greater than 3 degrees as referenced from preoperative native knee imaging are contraindicated for a KA revision and may benefit instead from another procedure such as a liner exchange, an increase in constraint, or a ligament-substituting procedure.

In patients in whom no clear identifiable cause of pain is isolated, consideration of sources of referred pain, chronic pain syndromes, and secondary gain should be entertained while an infection work up is performed. Thus, knees with symmetric laxity in flexion or extension or recurvatum caused by an excessive femoral resection, and those with ligament insufficiency, may be addressed using traditional revision techniques, particularly if their native alignment was close to the TKA alignment.

Absence of collateral ligaments or severe bone loss on either side of the joint that compromises the integrity of the collateral ligaments or their origins is also a contraindication, as KA relies on these structures being intact.

Challenges to Kinematically Aligned Revision/Implant Selection

One of the key challenges to effectively achieving KA alignment in the revision setting is the fact that all revision systems have stems that arise from the components at a fixed angle. The geometry of such devices thus dictates MA. Further, surgeons rely on stems for implant fixation following resection of existing implants. Fortunately, recent literature has shown that short, cemented stems can be as effective as diaphyseal-engaging press-fit devices for achieving durable implant fixation in revision knee surgery. Because these shorter and narrower stems need not engage the diaphysis, they can be aligned with a certain degree of freedom both in the tibia and the femur. Short, cemented stems thus enable implantation fixation in a more anatomic position than diaphyseal-engaging uncemented stems.

On the tibial side, in patients with compromised bone, the use of metaphyseal cone reconstruction coupled to cemented stems offers greater freedom of alignment than traditional constructs. As the cones themselves are agnostic to overall alignment and require only axial stability associated with maximization of bone contact to work, they can be an excellent complement to short, cemented stems where the residual cancellous bone following resection is not deemed adequate for isolated cement fixation. Indeed, some surgeons are foregoing stems altogether in the context of cone-based reconstructions with adequate bone stock and cemented tibial trays.

On the femoral side, rotational alignment of the femoral component can be easily restored with standard augments and, as with the tibia, cones can be coupled to cemented stems to achieve excellent stability and freedom of alignment.

What is presented below is a technique to make KA revision relatively simple using standard manual instruments. Doubtless, many refinements will be forthcoming, and the advent of robotic revision surgery and digital planning tools will simplify matters greatly.

Reverse Engineering Total Knee Arthroplasty Alignment: The Theory

SURGICAL PLANNING

Two reference points are generally needed to reverse-engineer the patient's native anatomy with revision TKA devices, the native tibial joint line angle (TJLA) and the femoral joint line angle (FJLA). These values need to be measured on both preoperative X-rays that show the patient's normal anatomy and images of the patient's existing knee replacement. Both images need to be taken from true anteroposterior (AP) views without rotation. In the absence of a preoperative image for measurement, the patient's contralateral knee can often provide an adequate set of surrogate measurements or a less arthritic version of the knee in question. The goal is to determine what the patient's normal coronal anatomy was before surgery (Fig. 21.2).

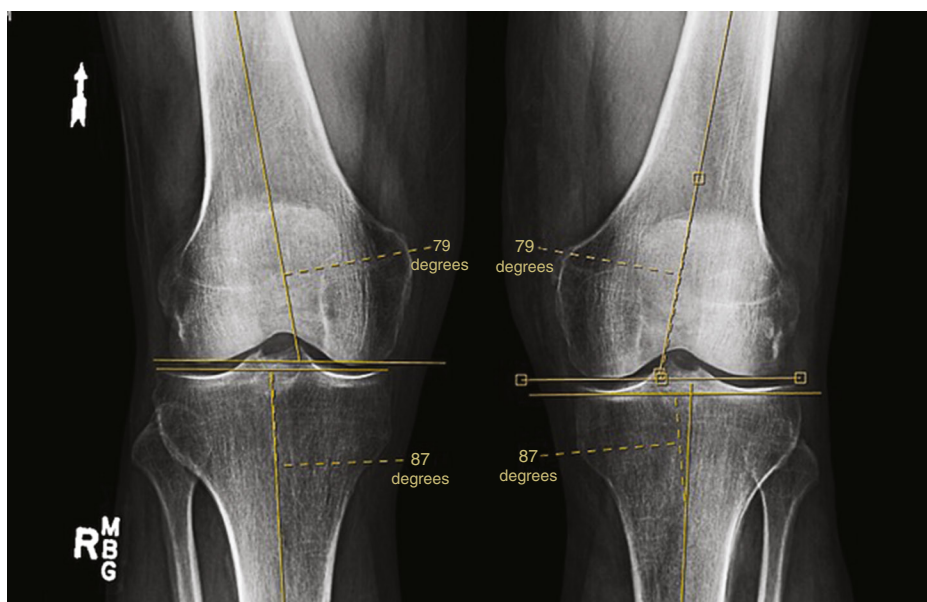


Figure 21.2 The tibial joint line angle of the native knee is measured as the angle subtended by a line drawn on a preoperative image along either 1) a line drawn between the most lateral margins of the tibial plateau (*right knee*), or 2) a line drawn between the inferior most margin of the subchondral plates on both tibial plateaus (*left knee*), and the tibial anatomic axis (centered on the talus and extending proximally to the center of the tibial spine if a long leg view is available). Conversely, the femoral joint line angle is defined as the angle subtended by a line drawn between the distal most points of the medial and lateral femoral condyles and a line drawn along the anatomic axis of the femur. Generally, the left and right knee angles are symmetric before the onset of arthritis and contralateral, less diseased knees can be used to check the overall accuracy of the measurement and desired final alignment. As noted elsewhere, these measurements are susceptible to interobserver variability and consistency in measurement technique between pre- and postoperative X-rays is paramount if one is to draw any valid conclusions.

First and foremost is the TJLA. Ideally, a true, standing AP image of the tibia from knee to ankle is needed to define the relationship between the patient's native tibial joint line and their tibial anatomic axis. For the native reference points, the angle can be identified from a number of sources such as preoperative radiographs, images of the contralateral knee if it has not been operated, computed tomography (CT) scans and scout views, or any X-ray of the proximal tibia obtained at any time in the patient's adult life. In the absence of full-length views, short cassette standing views can be used with some caution. To measure the alignment of the TKA that is to be revised, similar views need to be taken and angles measured.

The TJLA of the native knee is measured as the angle subtended by a line drawn on a preoperative image along either (1) the inferior-most margin of the subchondral plates on either tibial plateaus or (2) a line drawn between the most-lateral margins of the tibial plateau and a line that follows the tibial anatomic axis (centered on the talus and extending proximally to the center of the tibial spine). For the postoperative X-rays, the TJLA is subtended by a line that connects matching points on the medial and lateral aspects of the tibial tray and the anatomic tibial axis. It is recommended that standing X-rays be used if short films are used. Should there have been wear and bone loss from the preoperative tibia and an absent contralateral or historical image before bone loss, an older image or the contralateral knee is a good substitute. Usually, however, some aspect of the original tibial anatomy is available from which to judge an appropriate approximation of the joint line.

As noted earlier, the native TJLA should be more than 2 degrees in variance from the existing implant's anatomy to justify revision. This will be true in the majority of cases where the patient's anatomy was changed to neutral from an original varus alignment, as it has been documented that the average angle in such patients is 4.5 degrees.^{11,20}

The extent of a patient's native tibial slope is of interest, but as nearly all revision implants use a posterior cruciate-sacrificing design, it is likely that the tibial slope will need to be placed in neutral regardless, to avoid flexion instability.

The femoral reference points need to be evaluated on the preoperative images next. The patient's native FJLA is the angle subtended by a line drawn across the distal-most aspects of the medial and lateral femoral condyles and the anatomic axis of the femur (a line drawn from the piriformis fossa to the center of the femoral condyles; [Fig. 21.1](#)). The same lines and angles need to be drawn and obtained from the postoperative images and any variance noted. In this example, the surgeon successfully restored the patient's native FJLA, but the TJLA went from 2 degrees of varus to 4 degrees of valgus, a 6-degree shift. Interestingly, the surgeon chose to use a semiconstrained insert at the index operation, suggesting ligamentous instability ([Fig. 21.3](#)).

Armed with this data and the variance in the angles thus measured, the surgeon must decide how much correction is desired to restore the implants into native alignment. The angles of the tibial joint line relative to the tibial anatomic axis in the pre- and postoperative X-rays are compared. From here the variance in tibial component alignment is calculated. It could be argued that the distal femoral cut should be addressed first, and that it should be used to define the tibial cut. Logically, this makes sense. However, practically, intramedullary femoral cutting guides are inaccurate, and the residual bone stock in the femur is often not sufficient to stabilize the femoral cutting blocks. Thus, the tibia is simply an easier and more reliable starting point than the femur for the purpose of reverse-engineering the original joint line.

REVISION IMPLANT SELECTION

Implant selection for the revision is important. Revision components suitable for KA alignment must accept a short, cemented stem that will allow placement of the implants at the desired angle both in the femur and the tibia without abutting the cortex. Stems longer than 50 mm frequently limit the amount of varus that can be placed on the tibia and/or valgus on the femur and should be avoided. The implant system should also have a native matching tibial cone or be able to accept a cone from another company, as frequently the metaphyseal bone is too compromised for an isolated short, cemented stem revision.

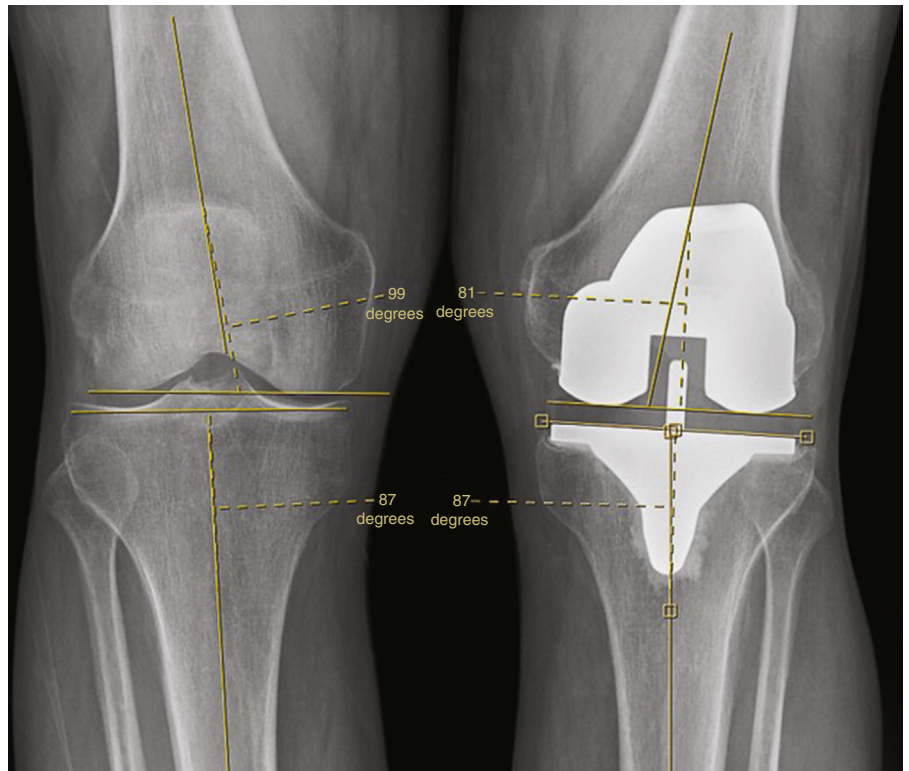


Figure 21.3 The tibial joint line angle (TJLA) and the femoral joint line angle (FJLA) of the native knee was shown in Fig. 21.2, whereas the contralateral knee's TJLA and FJLA can be used as surrogates. In this example of a left total knee replacement, the surgeon successfully restored the patient's native FJLA, but the TJLA went from 2 degrees of varus to 4 degrees of valgus, a 6-degree shift. Tellingly, the surgeon chose to use a semiconstrained insert at the index operation, suggesting ligamentous instability.

Sleeves that are fixed to press fit stems may not be as flexible in their positioning and should be used with caution.

The surgeon should avoid using cemented stem designs that create a challenge for removal. Offset stems or stems larger than 9 to 10 mm do not confer additional stability to the construct and should be avoided. The longest stems that are needed are approximately 50 mm in length, with shorter stems working very well in most cases. Not using stems at all in the context of a well-fitted uncemented cone with a cemented tibial tray has also been described, but the author has no personal experience with this technique.²¹ The author prefers to use antibiotic-loaded cement in all revision cases.

Constraints have not been linked to a higher degree of failure in most studies,^{22,23} and a well-balanced KA revision knee should be very stable without needing to increase the level of constraint. However, in case of future challenges because of instability, using a femoral component that can accept a semi-constrained insert, whether or not one is used, is considered good practice. Lastly, it is advisable to have the primary femoral and tibial knee-cutting instruments available to help with the proximal tibial and distal femoral recuts.

EXISTING IMPLANT REMOVAL: CONSIDERATIONS

Before removing the implants, the surgeon should take note of several landmarks and attributes of the existing TKA. The knee's range of motion under anesthesia should be noted, a mark should be made with the saw in the anterior femoral cortex just above the center of the trochlea to mark femoral component rotation, the distance of the distal medial femoral condyle to the joint line should be measured with a flexible ruler, and patellar tracking should be checked for tilting. On the tibial side,

the tibial component's rotation should be marked on the tibia with electrocautery and, as per routine, the implants should be checked for any evidence of implant loosening. If possible, working at the metal/cement interface with a saw or osteotome (rather than the cement-bone interface) will allow the surgeon to minimize bone loss. The author prefers using short, thin power saws coupled with osteotomes to separate the implant from the cement mantle. Unless indicated by wear, delamination, asymmetric cuts or incorrect height, a well-fixed patella button, if present, can be retained.

Surgical Technique

PATELLA FIRST

If the patella is to be revised, it is best that it be done carefully, with an eye toward creating a patella of normal height relative to the contralateral knee and not leading to a thin, avascular patella prone to fracture. Our goal is a residual patellar thickness greater than 10 mm.

TIBIA SECOND

Correcting the tibial cut back to natural alignment is the first priority for the surgeon once all the components have been removed and bleeding controlled. Most commonly, the available tibial cutting guide is an extramedullary guide that allows the surgeon to adjust the cutting block by as many as 6 degrees of varus or valgus from the midline. Further, the jig usually allows the changing of the posterior tibial slope to a neutral cut if the original cut was in an anatomic slope. To achieve the desired level of correction in the coronal plane, the cutting block is positioned so that there is no bone cut at the lateral most tibial margin of the tibia and that as much bone as necessary on the medial side is

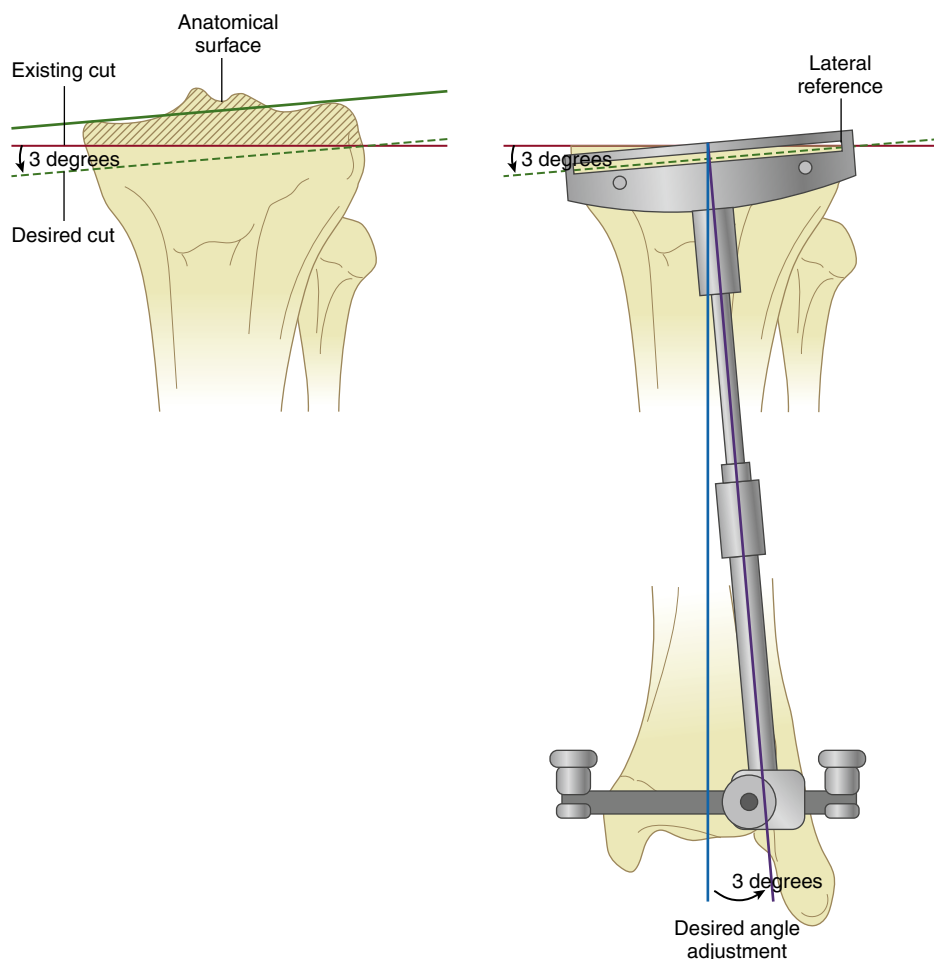


Figure 21.4 Illustration of orientation of desired and existing planes of the coronal tibial cut. The desired cut will be parallel to the native joint line, which subtended a 3-degree varus angle. Using the superior-lateral margin of the existing tibial cut as referent, the extramedullary alignment jig is positioned to enable a 3-degree varus cut by swinging the base of the alignment guide into the desired angle.

resected to achieve the desired new TJLA (Fig. 21.4). The “angel wing” or even a saw blade can be placed in the cutting block and rested on the lateral bone margin to be protected. It will act as the fulcrum around which the cutting block is rotated using the jig until the desired angle is achieved. The block can then be pinned in place. Assuming little or no bone loss, the millimeters of bone resected at the medial joint line should be approximately equal to the number of degrees being corrected. Thus, for a desired 3-degree correction, after aligning the extramedullary guide with the anterior tibia and shifting the base of the main stem of the guide (generally this sits over the ankle) laterally, the cutting guide should be positioned so that a saw blade should skim the surface of the lateral side of the tibia and remove approximately 2 to 3 mm of bone medially, with some compensation for any bone lost during implant resection. In the eventuality of significant bone loss, the extramedullary (EM) guide will provide a reasonable estimate of the angle of the cut based on the guides available at the level of the ankle. When in doubt, an intraoperative tibial X-ray will provide excellent guidance, although the surgeon needs to take parallax into consideration.

FEMUR THIRD

Once the tibial cut has been made, it will serve to inform the appropriate angle of the femoral cuts. With the knee in full extension and all osteophytes removed, laminar spreaders can be placed on both the medial and lateral side, to place the collateral ligaments in approximately equal tension. If a tibial trial can be

seated and is stable, it helps to seat one in the tibia for the next steps. Because the goal is now to create a perfectly rectangular extension gap, the surgeon has to decide how much bone needs to be resected to create a distal femoral cut that is parallel to the new tibia cut and if the joint line has been raised enough to justify the use of augments. The preoperative measurements taken of the native knee can be used by the surgeon to calculate and judge the subsequent bone resections, such that the femoral component, with or without augments, is restored to the native position.

If the space created by the laminar spreaders is rectangular, there is no need to recut the distal femur unless the surgeon wishes to cement the device into better bone. If the gap is trapezoidal, however, bone needs to be cut from the distal femur, usually on the lateral side, to create a balanced, rectangular extension gap (Fig. 21.5). This can be easily done using the standard (not revision) intramedullary (IM) instruments and adding 1 degree of valgus to the distal femoral cutting block for every millimeter of bone that needs to be resected from the lateral side. Thus, if it was determined that an extra 3 mm of bone should be resected from the lateral femoral condyle, and that the femoral component had been seated in the standard 6 degrees of valgus, the IM guide should be set to 9 degree of valgus to resect 3 mm of bone from the lateral side and none from the medial side. A saw or angel wing can be used to ensure that the saw blade does not resect any bone on the reference side and resects approximately 3 mm on the opposite side. The cutting block is then pinned, and the cut performed. Following the cut, the gap can be checked for symmetry with a spacer block, taking care to not damage the bone surfaces.

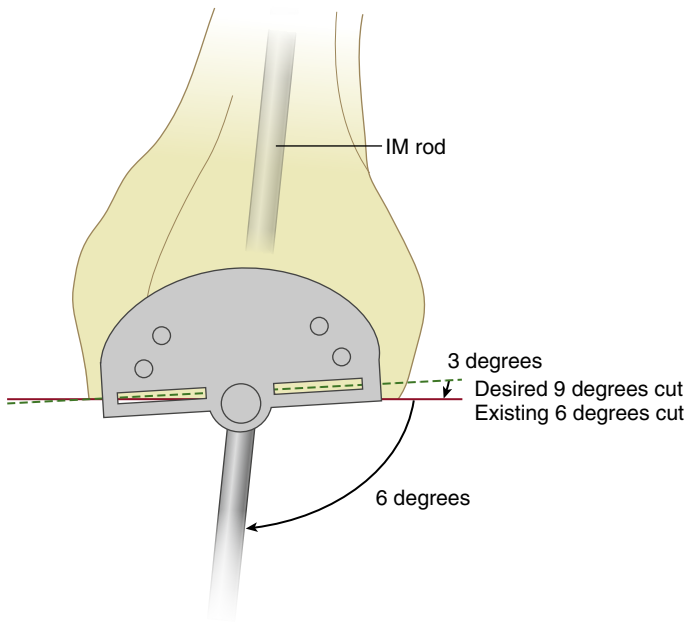


Figure 21.5 Illustration showing the use of the intramedullary alignment guide from the primary total knee instrument set to recut the distal femur into the desired valgus alignment. Note that the residual medial femoral condyle is used as a reference to position the cutting block and that the bone resection is mostly from the lateral condyle. IM, Intramedullary.

At this point, the joint line has also been raised a few millimeters above its original position. Normally in KA techniques, this is not advised. However, as all revision implants are posterior stabilized and the posterior cruciate ligament (PCL) is sacrificed, raising the joint line is often a necessary means by which to balance the flexion gap. If there was bone lost during implant resection, the surgeon may choose to take as much bone as is necessary to make space for the augments to restore the joint line.

Having set the distal femoral cut in sufficient valgus to match the new tibial varus and create a balanced extension gap, the knee is flexed to set the appropriate femoral rotation. Generally, we can use the IM rod from the surgical instrument tray as a guide for the “4-in-1” cutting block. The rod helps keep the cutting block in position. Any necessary distal augments are applied based on perceived bone loss that occurred during revision. The appropriate-size cutting block for the appropriate femoral component must be selected, with the goal of being flush with the anterior cortex of the femur and restoring the patient’s preoperative posterior offset. Assuming that the existing component was not judged to be over, or undersized on X-rays, a component from the revision system matching in size the implant that was removed should be selected. Not restoring the offset will lead to flexion instability.

Because most MA surgeons set the femoral component in 3 degrees of external rotation from the posterior condylar axis, and the posterior condylar axis is the rotation we are trying to replicate, the femoral cutting block needs to be internally rotated at least 3 degrees from where the components were previously seated (Fig. 21.6). Unlike in extension, where we hope to achieve “balanced gaps,” in flexion we would like to see 1 to 2 mm of lateral opening at 90 degrees of flexion while maintaining a snug medial compartment. To achieve this, the 4-in-1 block is seated against the distal femoral cut with any necessary distal augments applied as mentioned previously. Using the IM rod

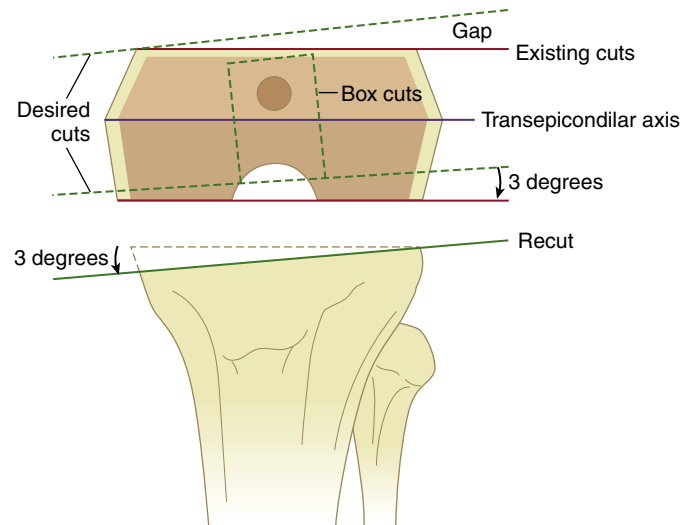


Figure 21.6 Illustration showing the existing and desired planes for the posterior condylar cuts of the femur and their relationship to the recut proximal tibia. The transepicondylar axis is shown, as it can be used to judge external rotation of the “4-in-1” femoral cutting block. Note that the plane of the posterior condylar cut and the proximal tibia should ideally not be parallel but rather divergent, subtending approximately 2 degrees one from the other to restore the normal trapezoidal flexion gap.

to assist with AP stability, an angel wing is passed through the anterior chamfer slot to match the anterior (dorsal) cortex of the distal femur. With an assistant distracting the flexion space manually or by using laminar spreaders, the 4-in-1 block is now rotated internally 3 degrees from the prior component orientation (Fig. 21.7). There is no easy way to do this using most systems, but the outcome should normally lead to 2–3 mm of bone resection laterally and no or very little bone medially, when using the “0-mm” posterior chamfer slot. If needed to stabilize rotation in the context of absent bone on the medial side,

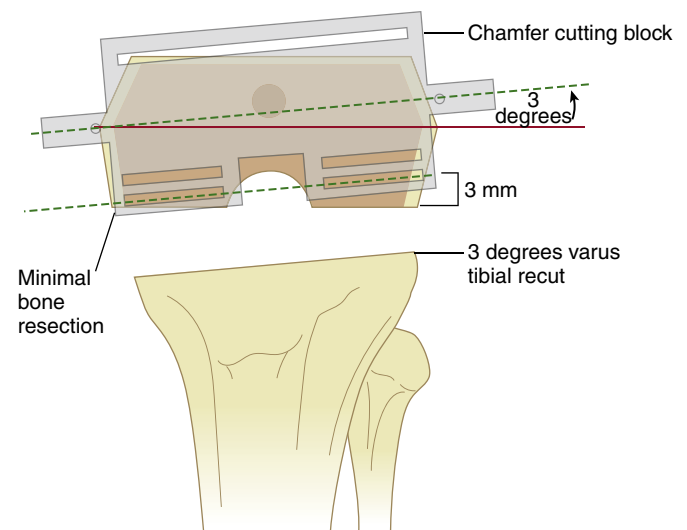


Figure 21.7 Illustration of the rotational placement of the 4-in-1 femoral cutting block relative to the proximal tibial cut, which was already placed in the appropriate amount of varus in a prior step. Note again that a trapezoidal flexion gap is desirable, and that the spacer block is tight medially but allows for a little play laterally, usually 1 to 2 mm. If the popliteus tendon has been inadvertently cut, the flexion gap can be more symmetric.

the saw can be passed through the +5-mm slot, leading to the resection of additional bone. Adding a 5-mm posterior medial augment will then stabilize the component in the required rotation and flexion gap. The femoral cuts are now completed, to accept the basic femoral trial implant without stems. It is not recommended to prepare the components any further until the final adjustments are made.

ASSESSING STABILITY AND MAKING ADJUSTMENTS

At this point we have achieved provisional bone cuts based on our best efforts at reverse-engineering the patient's native anatomy. Once again, it is worth noting that soft tissue damage such as the absence of the PCL, potential deficiencies in the collateral ligaments, and the occasional absence of the important popliteus tendon may alter the kinematics of the knee. For this reason, the next step is to insert the femoral and trial components without the stems, take stock of the situation, and adjust the provisional cuts accordingly. Balancing the knee, in revision as in primary KA, is performed by adjusting the bone cuts, not releasing ligaments.

Once the trial implants are in place with the appropriate augments, the knee is taken into full extension and the overall limb alignment checked. This is an important step, as it may impact how the surgeon approaches any further bone cuts. At this point, reviewing preoperative full-length alignment X-rays of both limbs and comparing them to visual alignment on the operating table will help provide a reference point for the surgeon. Having the contralateral leg prepped into the field for comparison can also be useful.

Our stability goal for the knee as it is ranged from extension to flexion using standard (not stabilized) trial components is for there to be less than 5 degrees of hyperextension, no (zero) gaping medially or laterally in full extension, no midflexion instability (10- to 50-degree arc) beyond a degree or so of opening laterally, and an asymmetric 90-degree flexion gap. In this latter position, a force applied lateral to medial (varus thrust) with the knee at 90 degrees should lead to a lateral opening of about 1 to 2 mm, and a medial to lateral force (valgus thrust) applied at 90 degrees should not lead to any opening at the medial joint line. The patella should track centrally throughout the arc of motion unless the surgical exposure required a long arthrotomy of the quadriceps tendon and/or a quad snip, in which case the surgeon will need to apply clamps or temporary sutures to the arthrotomy, to judge patellar tracking.

Hyperextension is generally caused by an alteration in the height of the joint line and should be addressed with distal augments on the femoral side. Symmetric instability in flexion can be addressed with a larger femoral component, bringing the femur more posterior with a symmetric increase in posterior augments both medially and laterally, using a thicker tibial insert (assuming it does not compromise extension), and ensuring that there is no posterior slope on the tibial cut.

Asymmetric instability in extension can be addressed by resecting more bone medially or laterally from the tibia in 1-to 2-mm increments until the gaps are symmetric. Distal femoral cut revision is more complex but needs to be judged as an alternative option for balancing a knee that is unstable in extension where the tibial cut is thought to be correct.

Performing adjustments to tibial and femoral provisional cuts can be challenging and requires the surgeon to either

freehand the cuts if the adjustments are minor or modify the instrumentation to enable the desired cuts. By not inserting the intramedullary guides fully the surgeon can adjust the angle of the cutting block relative to the current cuts by the desired amount and either pin or manually stabilize the cutting jig while performing the necessary adjustments. Extramedullary guides on the tibia can be adjusted with more ease.

When adjusting varus or valgus alignment, the surgeon should reference the apex of the provisional cut; the lateral or medial border of the bone, not the center of the prior cut. If custom or proprietary "recutting" blocks are not available, this cut can be done by placing a saw blade or an angel wing through the slot in the cutting block so that it rests on the most lateral or medial edge of that side of the tibia or femur that is not to be cut (usually, this is the wider side of the asymmetric gap). This point will serve as the fulcrum for moving the cutting block, or as reference point for the cut. The alignment guide and cutting block are then rotated around this point, to resect 1 or 2 mm of bone on the opposite side. Resecting more than this amount of bone is not recommended at any one time. The block is then pinned or otherwise stabilized, and the cut performed with the appropriate saw blade. Balance is then rechecked, generally with a thicker tibial insert.

Once the surgeon is pleased with the overall stability of the components, the preparation for the stems needs to be completed and the appropriate stem selected. As there is no biomechanical benefit to using a larger-diameter stem in cemented fixation, the smallest stem is generally recommended, usually a 9- or 10-mm stem, to allow the most flexibility in component positioning relative to the femoral canal. Similarly, the length of the stem should not prevent the tibial tray from seating in the corrected amount of "varus" and the femoral component in "valgus."

Once preparation is completed, the trial components should be inserted and again tested for stability, range of motion, offset, and patellar tracking.

MANAGING SCARRING AND CONTRACTURES

If the components are correctly aligned, there should be no kinematic conflict to motion. Thus, over time, as scar tissue and inflammation subside, the soft tissue envelope around the knee, particularly the posterior capsule, will soften and relax. In an active patient that is "using" their knee, revision knees tend to loosen up and gain motion in both flexion and extension over time. This process can take several years to play out, not the conventionally accepted 12 months, and can decrease TKA stability over time if the surgeon does not foresee and allow for this process at the time of surgery. A knee that was perfectly stable at 12 months following revision surgery can present at 3 to 4 years follow-up with swelling, pain, and instability, usually in flexion. For this reason, it is not recommended that the surgeon try to establish full extension (if this requires raising the joint line) or accept any instability in flexion at the time of revision surgery. This is particularly true if the patient presented with significant contractures and scarring before surgery. The surgeon should instead consider accepting a few degrees of flexion contracture (up to 5 degrees) and no more than 2 to 3 mm of anterior/posterior drawer in flexion before closing if, in their judgment, such limitations are largely attributed to contractures of the hamstrings, or capsule or extensor mechanism, rather than mechanical conflict between components.

Experienced arthroplasty surgeons also consider and adjust for the impact of contralateral contractures of the knee and hips

and spine deformity when setting patient expectations for the expected eventual motion of the operative knee. These latter topics are beyond the scope of this particular chapter, but it is important to recognize that the art of revision knee surgery is in part related to understanding and adjusting for the complex interplay between the abnormal bone anatomy and the scarred and irritated soft tissue envelope that surrounds it, as well as the impact of joints above and below the knee being operated. A long-term view of clinical outcomes is required for midterm success.

CEMENTING COMPONENTS

There are a few considerations relative to cement technique that are not specific to KA revision but are worth mentioning. Ensuring excellent fixation of each component is paramount, and cementing in two stages with the use of irrigation, cement restrictors, and pressurization is recommended. Further, cementing in two stages, one for the tibia and one for the femur/patella, is generally considered good practice, to ensure that all components seat exactly where they were intended to seat. Again, it is noted that the stems may very well not follow the anatomic axis of the long bones at all and should be selected to be short enough and small enough to enable component implantation at the desired angles (Fig. 21.7). Using antibiotics in revision surgery is also generally considered reasonable, although the data on their efficacy at preventing infection has been debated. Control of bleeding at cementation is also indicated to ensure good penetration of the cancellous bone by the cement.

Closure is performed as per usual, with attention paid to imbrication and possible reinforcement of the medial arthrotomy repair if there is tension on the closure. A drain can be used and is often indicated for the first 24 hours in revision surgery.

POSTOPERATIVE CARE

The peri- and postoperative care for KA revision TKA is no different than for MA revisions. The use of tranexamic acid, peri-articular injection cocktails, perioperative low-dose steroids, cryocuffs, sequential compression stockings, chemical anticoagulation, and multimodal pain management are important adjuncts. The current length of stay for revision TKA in our institution is approximately 2 days. As with primary knee recovery pathways, there has been a tendency to allow the knee to heal with gentle range-of-motion exercises and normal ambulation for the first 4 weeks following surgery, with more aggressive physical therapy taking place once basic healing has taken place. Weight bearing is “as tolerated” immediately and no bracing is required.

Case Study

CD is a 55-year-old attorney and former hockey player who presents 1 year following an MA total knee replacement performed elsewhere. His chief complaint is pain and a sensation of instability. After walking he can barely move his knee. The patient felt the surgery never went well despite doing physical therapy and using a continuous passive motion (CPM) machine. He states that his swelling never improved and that his surgeon felt that the knee was “loose.” The patient takes occasional ibuprofen and tries to walk 20 minutes a day but is unable to do more than six blocks. He is not using a cane or other assistive device but requires one hand support to climb stairs.

BOX 21.1 CANDIDATES FOR REVISION INTO KINEMATIC ALIGNMENT

1. Three degrees or more variance from prearthritic anatomy
2. Midflexion instability
3. Loss of flexion
4. Pain and/or swelling with activity
5. No other obvious reason for pain (aseptic loosening, infection, referred pain, etc.)

BOX 21.2 TOOLS OF THE TRADE

1. Primary instrumentation
2. Cementation equipment (brush, restrictor, pressurization gun)
3. Porous ingrowth sleeves available
4. Short, narrow-diameter cemented stems
5. Laminar spreaders or other distraction instruments

On physical examination he is 5'11" and 220 lbs (BMI: 30.1). His examination is remarkable for range of movement 10 to 105 degrees, midflexion instability of 2 to 3 mm at 30 degrees of flexion with a solid endpoint, and a moderate effusion. The knee was found to translate anteriorly 5 mm in 90 degrees of flexion. Hip and back examination is normal. A work-up for infection, including laboratory work and aspiration were normal.

Imaging: Preoperative imaging of the native knee demonstrated a TJLA of 5 degrees of varus and a FJLA of 7 to 8 degrees of valgus (Fig. 21.8).

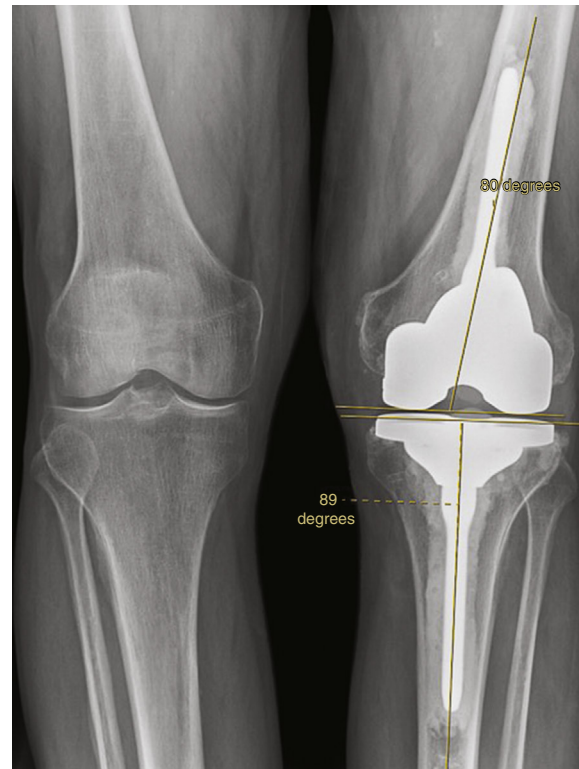


Figure 21.8 In this example, the femoral joint line angle required the femoral stem to be in a different alignment from the anatomic axis of the femur; this illustrates the need for short, narrow stems that allow asymmetric positioning of the implant in the canal. Note that the revised kinematically aligned total knee arthroplasty was stable without the use of a semiconstrained liner.

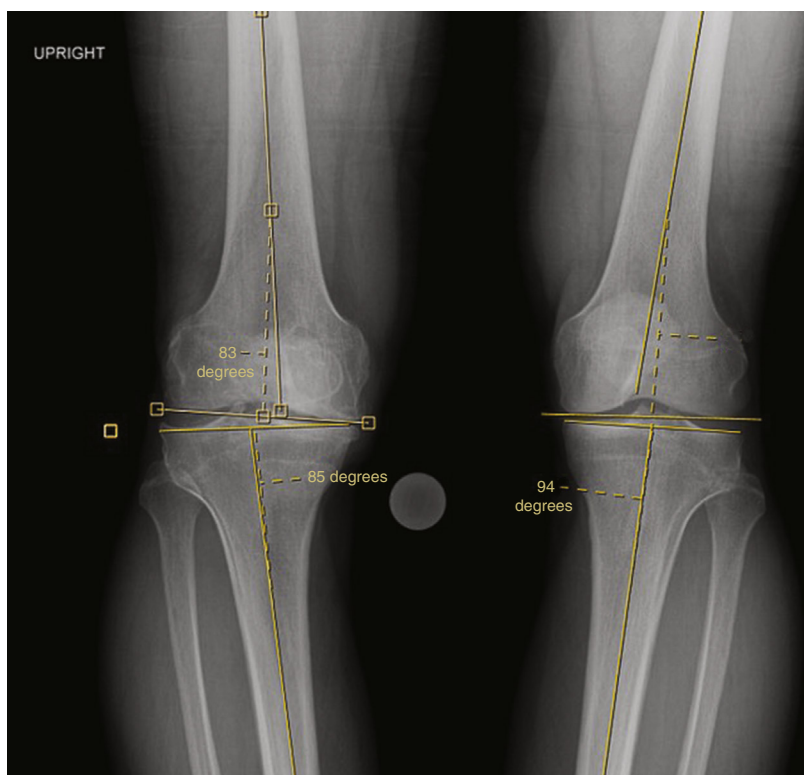


Figure 21.9 Case study: Preoperative imaging of the native knee demonstrates a tibial joint line orientation angle of 5 degrees on the right and 6 degrees on the left knee, and a femoral joint line orientation angle of 7 degrees on the right and 8 degrees on the left. Variations in measurements can be 1 or 2 degrees, so it is important to ensure that the same technique is used when comparing images for variance in these anatomical angles.

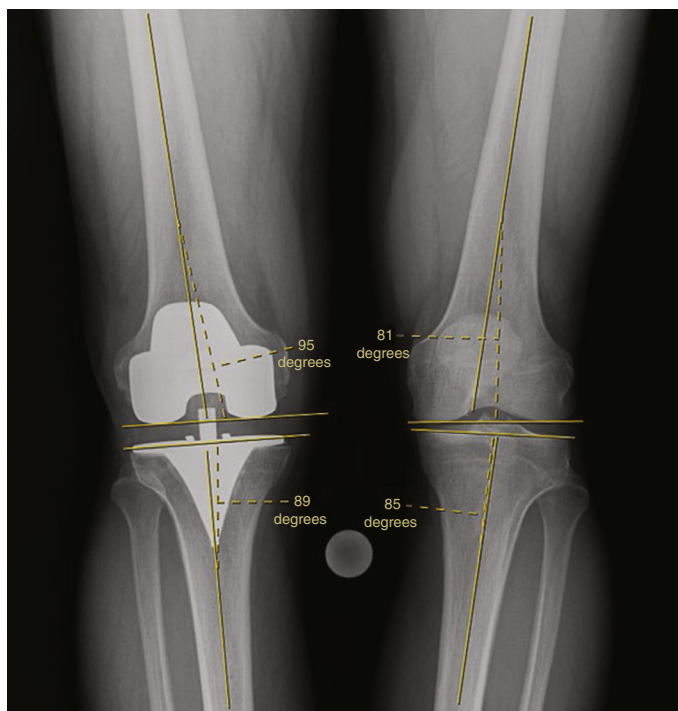


Figure 21.10 Following primary total knee arthroplasty, the tibial joint line orientation angle was 1 degree of valgus (a 6-degree variance from preoperatively) and the femoral joint line orientation angle was 5 degrees of valgus, a 2-degree variance from preoperatively. Note also that the contralateral knee's measurements have changed from Fig. 22.8. This lack of accuracy in measurement can be disconcerting unless one realizes that these measurements are directional in nature and intended to identify major changes to a patient's native kinematic axes that could explain a patient's symptoms.

Following his primary TKA, the TJLA was 1 degree of valgus, and the FJLA was 5 degrees of valgus (Fig. 21.9). There was no loosening.

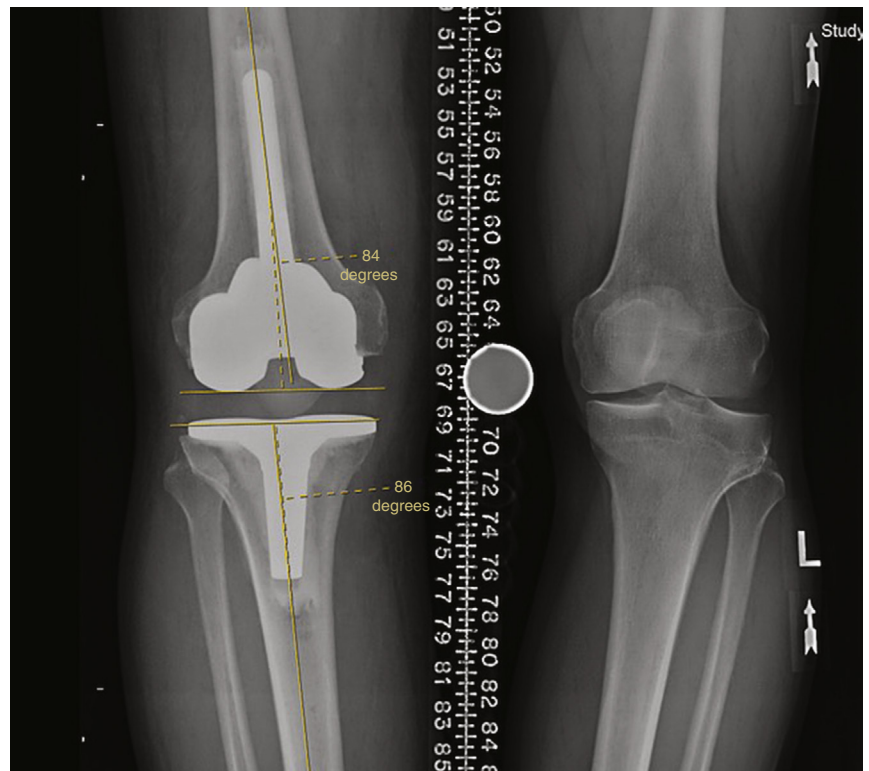
The patient was taken to surgery to revise the TKA into more KA. Intraoperatively, all components were well fixed, cultures were negative for infection, and the components were removed with relative ease with the expected amount of bone loss. The bone surfaces were recut to reproduce physiologic angles, and short, cemented stems were used to stabilize the femur and tibia revision system. Images taken after surgery show that the knee was returned to a more physiologic alignment (the TJLA is 4 degrees and the FJLA is 6 degrees, within measurement error of the preoperative images; Fig. 21.10).

On follow-up at 1 year, the patient was very pleased with his result. He had returned to normal activity with no limits, did not require any assistive devices, reported no pain, and was not taking ibuprofen for his knee (Fig. 21.11). On exam, he was found to have a painless 0- to 125-degree range of motion and no midflexion instability. His knee continued to swell occasionally with extended activity.

Last Thoughts

The procedure outlined earlier was devised to achieve an outcome that current instrumentation is designed to avoid. This makes it challenging to perform, particularly the step where femoral component rotation is set. Easy in theory, hard in practice. However, the outcomes to date have been gratifying. Range of motion has been improved, pain has decreased, and midflexion instability resolved without the use of constrained or semi-constrained devices. What cannot be proven from the existing

Figure 21.11 Following revision, the patient's native tibial joint line orientation angle is largely restored to 5 degrees of varus and the femoral joint line orientation angle to approximately 5 degrees of valgus. Note again the position of the tibial stem, which does not follow the anatomic axis of the tibia. As all current tibial components are designed with stems that are orthogonal to the tibial base plate in the coronal plane and the normal human tibial joint line is, on average, in 3 degrees of varus relative to the anatomic axis, revising total knee replacements into kinematic alignment will frequently lead to the placement of the stem at an angle that is not colinear with the anatomic axis of the femur or tibia.



data is that a routine revision would not have been equally satisfactory. However, there is one truism in arthroplasty surgery that supports the idea that KA in revision surgery might be a useful answer: “don’t operate if there is nothing wrong.”

Wrong in this context is relative to MA. Do not operate, experienced MA surgeons will tell you, on painful knees with perfect radiographic alignment. They will not get better. This may be because the revision aims to restore the same exact alignment. There is therefore no reason to expect that the result should be any different.

In this chapter, the concept has been put forth that in these painful knees, the “perfect” radiographic alignment is, in fact,

the problem. Further, our limited experience suggests that the solution works best in the patient whose anatomic alignment was “corrected” into a nonphysiologic MA from its native constitutional varus.

Further work needs to be done to prove this concept and better instrumentation needs to be developed to simplify the procedure.

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