# Haptic Robotics Enable a Systems Approach to Design of a Minimally Invasive Modular Knee Arthroplasty

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## Abstract

**Novel arthroplasty tools present opportunities for exploring new implant designs, and such is the case for surgeon-guided or haptic robotic technology. These systems allow surgeons to sculpt bone precisely with or without direct visualization of the surgical site.**

**It is in this context that we explored a novel system of implant components for modular knee arthroplasty intended to maximize the benefits of the robotic tools.**

**In this article, we present the constraints, data, and decisions made to produce a version of a system of implant components for robot-assisted modular knee arthroplasty of the cruciate-intact knee.**

Current robotic systems for surgery can be classified as autonomous (eg, RoboDoc[1] [RoboDoc, Sacramento, CA]), teleoperated (eg, da Vinci Surgical System[2] [Intuitive Surgical, Inc., Sunnyvale, CA]), or haptic or surgeon-guided (eg, Acrobot Sculptor [Acrobot Company, Ltd., London, United Kingdom], MAKO TGS System [MAKO Surgical Corp., Fort Lauderdale, FL]).

In surgeon-guided systems, the surgeon provides power for instrument motion while the robot constrains instrument position and/or orientation within some anatomically registered volume.[3] In the case of knee arthroplasty, a surgeon-guided robotic system provides virtual cutting guides for bone removal with either saw or burr. This capability provides the potential for accurately sculpted, patient-specific, free-form bone resection in which less bone is removed than in traditional piecewise resections with a saw and cutting jigs. In addition, a surgeon-guided system with dynamic bone position tracking allows the possibility of keyhole surgery, in which a patient-specific graphics display provides the surgeon a heads-up virtual visualization of bone removal.

The ability to perform accurate, minimal-exposure bone resection leads naturally to consideration of alternatives to monoblock total knee arthroplasty components and potentially to a staged, tissue-conserving treatment paradigm for knee osteoarthritis. All else being equal, there might be functional benefit to replacing only damaged compartments (and retaining the normal ligamentous structures) if one can address progression of disease in other compartments without revision of components already in place.

There is a long history of performing multicompartment arthroplasty with discrete components. Laskin[4] reported in 1976 that good pain relief and acceptable clinical results were achieved at 2 years in patients with biunicondylar knee replacement, and other authors have reported on biunicompartmental knee arthroplasty producing successful clinical outcomes.[5,6] Banks and colleagues[7] reported that the kinematics of biunicompartmental arthroplasties during gait demonstrated some of the basic features of normal knee kinematics. Argenson and colleagues[8] reported in 1995 on a series of patellofemoral replacement patients, 104 of whom also received simultaneous medial unicompartmental arthroplasty, performed between 1972 and 1990, but the clinical results of the bicompartmental patients were not separated from the overall series. Another series of patellofemoral replacement patients also included 2 bicompartmental patients.[9] These reports suggest that a modular approach to resurfacing the knee can be successful and produce satisfactory clinical and functional results. Furthermore, it is reasonable to assume that a system of arthroplasty components specifically designed for modular resurfacing and robot-guided surgical placement should perform at least as well as those previously implanted with free-hand or crudely instrumented techniques.

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> **“Surgeon-guided robotic capabilities present a unique opportunity to rethink knee arthroplasty design from a fresh perspective.”**

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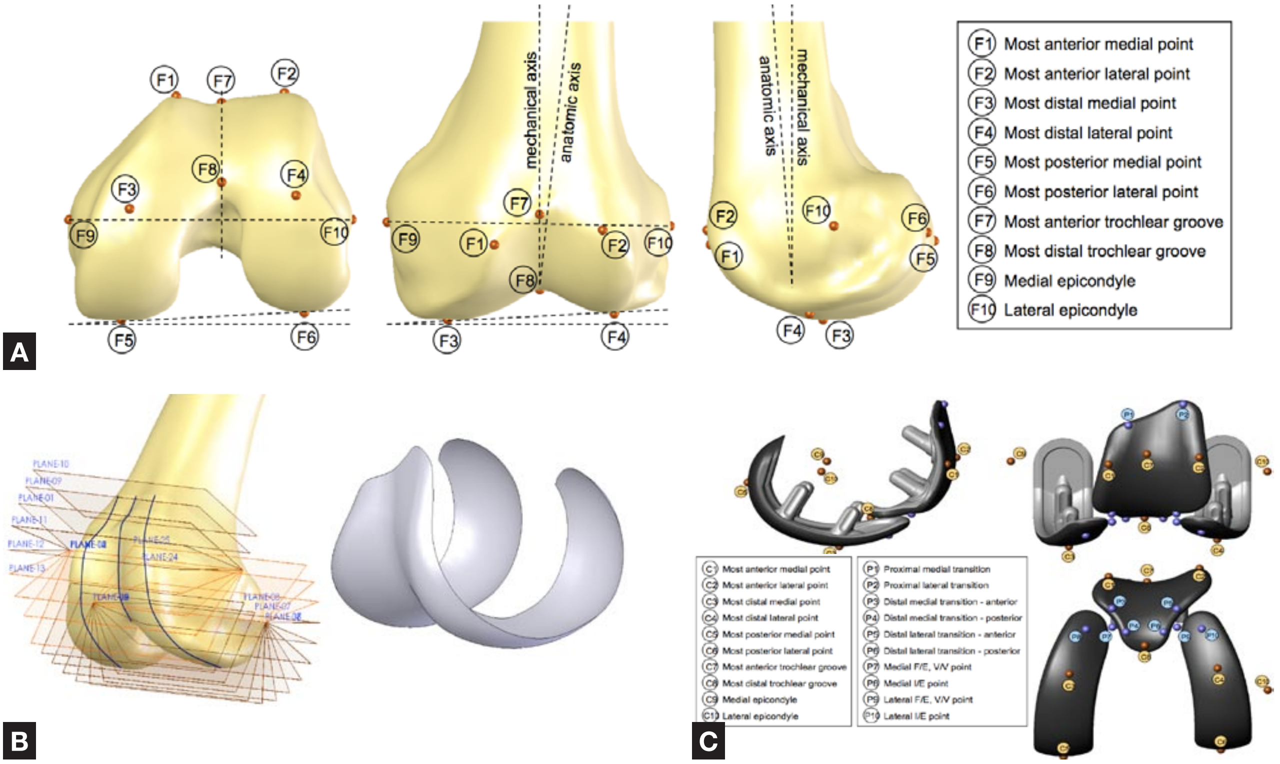

**Figure 1. (A) Ten fiducial anatomical landmarks and associated reference axes were identified and used to permit repeatable alignment of the femoral anatomy such that the articular surface geometry could be consistently characterized. (B) Data from 121 femur computed tomography (CT) scans were sectioned by 25 planes to identify local maxima/minima and to map articular surface pathways. These data were grouped into 8 sizes, and mean articular surface geometries were developed for each size. (C) Ten component fiducial points corresponding to the same femur fiducial points and 10 planning fiducial points (patella transition and intercomponent) were identified from the mean surfaces to provide rough and final alignment of the components with respect to each other and with respect to the bone and cartilage during implant planning.**

perspective. The essential question is, "With these capabilities, how might we design a system of arthroplasty components to address a specific spectrum of disease in a way that maximizes the benefits of the robotic-surgery approach to the patient and the surgeon?" The remainder of this article provides an example of the considerations and design decisions that can be made in answering this question.

## ARTHROPLASTY REQUIREMENTS

The first step of any design exercise is to specifically determine the use and performance requirements for the system or device. These requirements provide both a means to make objective decisions in the design process and the benchmarks for determining if the design meets the project goals. In considering a robot-enabled approach to knee arthroplasty, we developed 8 general requirements for the system and its constituent components:

1. Anatomically shaped to minimize bone resection.
2. Implant sizes should fit patients worldwide.
3. Bicruciate retaining.
4. Fixed bearing.
5. Discrete, unlinked compartmental components for 1-, 2-, and 3-compartment disease.
6. Discrete, unlinked compartmental components for size interchangeability.
7. Minimal incision.
8. Bone preparation using surgeon-guided robotic system.

In terms of implant design, the major requirements can be grouped to address 3 specific aspects of a novel system: articular surface design, bicompartmental and tricompartmental modularity, and fixation surfaces.

### Articular Surface Design

The requirements for minimal bone resection, bicruciate retention, and the ability to fit knees across the size, gender, and cultural spectrum demand a careful study of knee anatomy. For the femur, 121 computed tomography (CT) scans from 55 healthy knees, 50 knees with medial osteoarthritis, and 16 cadaver knees were collected with appropriate consent and approvals. The CT images were segmented (Mimics, Materialise NV, Leuven, Belgium), and bone surface models were created using custom programs written in Matlab (The MathWorks, Inc., Natick, MA). A semiautomated procedure was performed to align the femoral anatomy in a standard reference pose based on the mechanical, anteroposterior, and posterior condylar and transepicondylar axes, and 10 fiducial points were identified (F1–F10; Figure 1A). These data were collected in 8 distinct size ranges, and mean fiducial locations and articular profiles were used to generate representa-

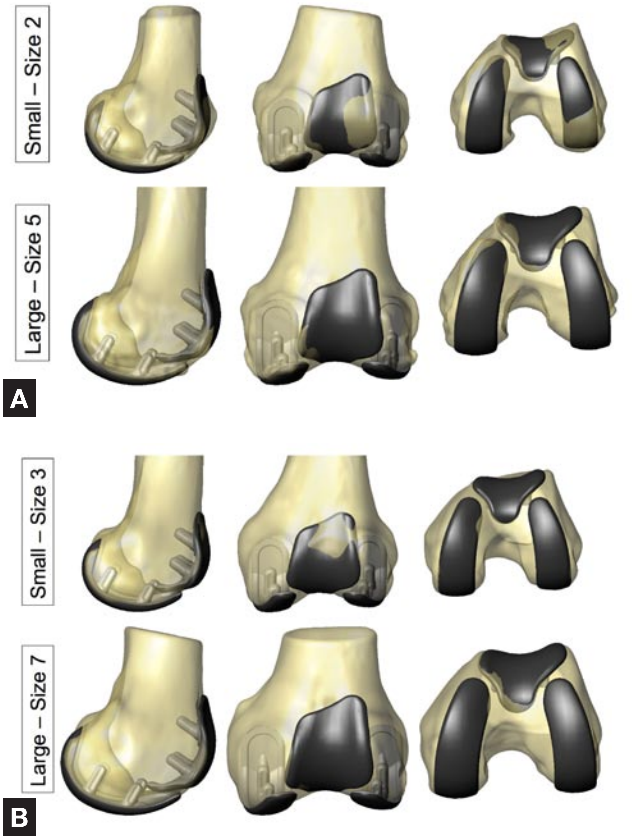

**Figure 2.** The femoral components were virtually implanted in their nominal intercomponent position onto female **(A)** and male **(B)** bones from the computed tomography database to assess fit, alignment, and the required bone resection volume. Individual sizing and positioning of each component could further improve fit.

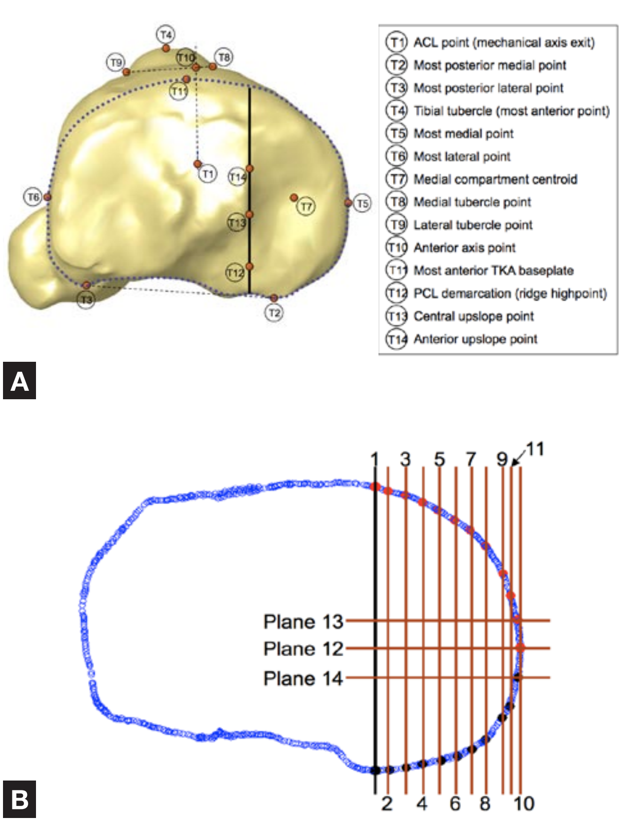

**Figure 3.** **(A)** Fourteen fiducial anatomical landmarks and associated reference axes were identified and used to permit repeatable alignment of the tibial anatomy such that the baseplate footprint geometry could be consistently characterized. **(B)** The tibial perimeter 6 mm below the medial condyle was mapped and divided into 11 anteroposterior sections and 3 mediolateral sections from which size-specific footprints for inlay components and onlay tibial baseplates could be generated.

tive surfaces for each size (Figure 1B). A set of component fiducial points was then defined to describe the articular surfaces and the key geometric locations between the discrete tricompartmental components (C1–C10 and P1–P10; Figure 1C). Placement of these components on a range of male and female femurs from the CT database showed excellent duplication of the articular profiles with little discrepancy between the implant articular surfaces and the preresection anatomical surfaces (Figures 2A, 2B).

Tibial plateau shape also was carefully studied using a set of 115 CT scans for 55 healthy knees, 50 knees with medial osteoarthritis, and 10 cadaver knees. The images were segmented and bone models created using the same methods as for femurs. A custom program (Matlab) was created to identify a set of 14 fiducial points on the proximal tibia (Figure 3A). The tibial bone model was then aligned according to axes determined from the fiducials. The tibial eminence was mapped to establish the central margins of tibial components, and the tibial perimeter shape 6 mm below the medial articular bone surface was determined (Figure 3B). These parameters were determined for all bone models, sorted according to size, and representative tibial component footprints were developed for both onlay and inlay tibial components in 8 sizes. The aspect ratio for the best-fit tibial peripheral contours was found to be lower than that of many contemporary unicondylar tibial baseplates; the mediolateral width is as much as 3 mm narrower in the largest sizes (Figure 4). Finally, nominal components were fit to a series of bone models to assess the fit of the tibial component footprint (Figure 5).

## Bicompartmental and Tricompartmental Modularity

The transition interval between the femoral condylar component(s) and the femoral trochlear component presents a critical implant design element, as surgical treatment can involve 1, 2, or 3 compartments operated on in simultaneous or staged fashion. The native or prosthetically replaced patella must track smoothly across this region to maximize patient function and implant longevity. This requirement constrains the relative placement of the trochlear and condylar components and dictates that their surfaces must provide a continuous support surface for the smoothest possible patellar tracking.

This aspect of the design was studied and refined using both computational and physical modeling. A multibody

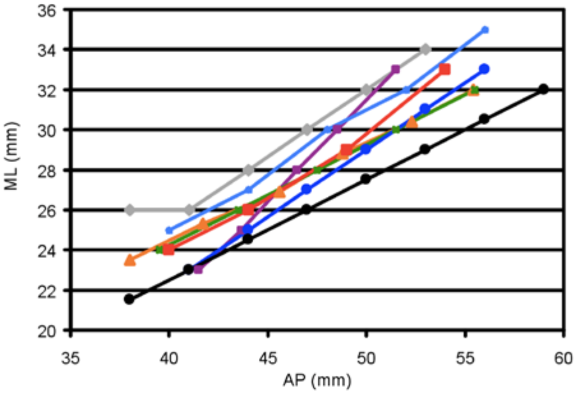

**Figure 4.** The tibial anatomical study revealed a smaller ratio of mediolateral (ML) to anteroposterior (AP) dimensions in the best-fit tibial baseplate footprint (black line) than is found in many commercial unicondylar arthroplasty systems (colored lines). This discrepancy results in up to 3-mm differences in mediolateral width in the largest components.

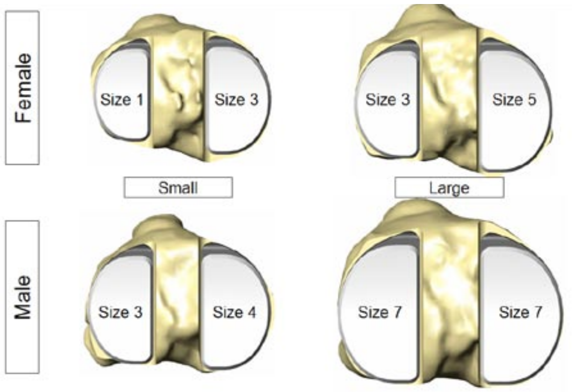

**Figure 5.** Nominal onlay tibial components were placed onto tibias across the size range in female (top row) and male (bottom row) knees to assess shape compatibility and the need to intermix sizes in a biunicondylar application.

dynamics knee simulation was performed (KneeSIM; LifeModeler, Inc., San Clemente, CA) to evaluate varying configurations of femoral and patellar components and to assess bounds for acceptable implant placements (Figure 6). In the case of a replaced patella, these simulations clearly showed that a dome-shaped patellar component provided a smoother and more consistently smooth track along the femur during flexion than did a sombrero-shaped patellar component (Figure 7).

The bicompartmental and tricompartmental implant components can be designed for optimal function, but this is achieved only when the implants are surgically placed with accurate relative positions. Critical component fiducial points (Figure 1C) and geometric relations for each implant component are defined to maintain alignment appropriate for smooth patellar tracking across the discrete components. These relations are an integral part of the surgical planning and robotic bone preparation steps required to realize appropriate implant function customized to each patient's anatomy.

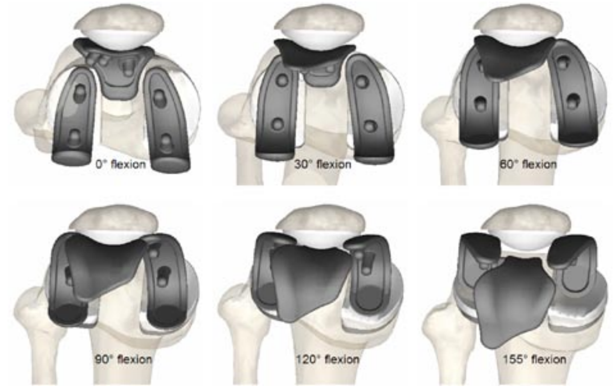

**Figure 6.** A dynamic computer model was constructed for a tricompartmental resurfacing arthroplasty and used iteratively to assess patellar tracking from 0° to 155° flexion.

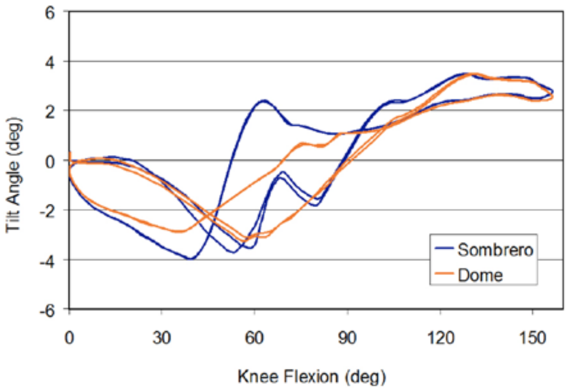

**Figure 7.** Dynamic computer modeling was used to assess patellar tracking for a variety of patellar shapes in a tricompartmental knee resurfacing arthroplasty. The orange line shows a dome-shaped patellar component following a smooth path of patellar tilt angles across the range of flexion, and the blue line shows a sombrero-shaped component exhibiting larger deviations in the transition region from the trochlear component to the femoral condyles.

## Fixation Surfaces

Traditional bone cuts are made with saws (for larger resections) and drills, burrs, reamers, and osteotomes (for detailed surface features). In similar fashion, haptic robots can provide attachment for a range of cutting tools, but at the expense of more time and surgical complexity. The advantage of the robotic tool is increased when the implants are designed to work harmoniously and efficiently with that tool. For the modular knee system, it was decided that all bone surface features should be realized with a single cutting burr so that instrument changes would not be required during the procedure. Thus, all pegs and cement pockets have been shaped to share a common radial dimension with the cutting tool (Figure 8). This aspect of the implant design will dramatically reduce the number of cutting tools and guides normally required for bone preparation. Completed and ongoing mechanical testing and finite element analyses suggest these bone fixation surfaces will provide comparable implant/bone mechanical support and fatigue characteristics to contemporary unicondylar and patellofemoral implants.

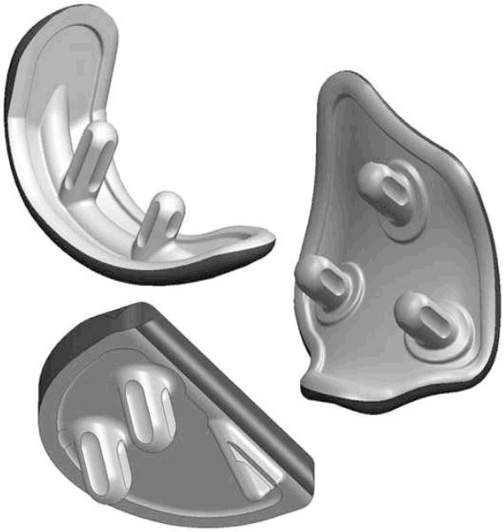

**Figure 8.** The fixation features of the modular knee system were adapted for fixation to bone surfaces prepared with a single ball-shaped burr. These surfaces provide typical features in terms of pegs, keels, and cement pockets, but the dimensions have been optimized for bone preparation with a single robot-guided instrument.

## CONCLUSIONS

Just as cellular phone technology has enabled new modes and practices of communication, surgeon-guided haptic robotic technology might similarly affect the procedures, practices, and design of knee arthroplasty. Current handheld phones are remarkably different from the desktop devices they have supplanted, and a similar evolution in knee arthroplasty components can be envisioned.

This article presents only a few of the constraints, considerations, and decisions that have been made in pursuit of a system of implant components for knee arthroplasty with a surgeon-guided robotic device. We used the latest data resources and computational and experimental tools to draft these designs. Historical precedent and rigorous design evaluation suggest that the proposed designs will provide clinical performance equivalent or superior to that of previous modular knee systems. Only clinical experience with comprehensive and critical follow-up monitoring will prove if this design concept provides a reliable treatment option for the treatment of osteoarthritic degeneration in the cruciate-intact knee.

## AUTHOR'S DISCLOSURE STATEMENT AND ACKNOWLEDGMENTS

Dr. Banks wishes to note that he is a named inventor on one or more patents issued to MAKO Surgical Corp. and licensed by the University of Florida. He also wishes to note that his laboratory at the University of Florida receives research support from MAKO Surgical Corp.

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