ORIGINAL ARTICLE

Praxiteles: a miniature bone-mounted robot for minimal access total knee arthroplasty

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Abstract

We have been working to develop a compact, accurate, safe, and easy-to-use surgical robot for minimally invasive total knee arthroplasty (TKA). The goal of our bone-mounted robot, named Praxiteles, is to precisely position a surgical bone-cutting guide in the appropriate planes surrounding the knee, so that the surgeon can perform the planar cuts manually using the guide. The robot architecture is comprised of 2 motorized degrees of freedom (DoF) whose axes of rotation are arranged in parallel, and are precisely aligned to the implant cutting planes with a 2 DoF adjustment mechanism. Two prototypes have been developed and tested on saw bones and cadavers – an initial one for open TKA surgery and a new version for MIS TKA, which mounts on the side of the knee. A novel bone-milling technique is also presented that uses passive guide and a side milling tool.

Keywords: Computer-assisted orthopaedic surgery, robot-aided surgery, medical robotics, minimally invasive total knee arthroplasty, bone milling

Paper accepted: October 2005
Published online in Wiley InterScience (www.bjs.co.uk). **DOI:** 10.1002/rcs.59

INTRODUCTION

Miniature robotized surgical instrumentation can potentially increase the precision and capabilities of the surgeon, improve outcomes and recovery times for the patient, and reduce the large number of mechanical instruments required in the operating room, without imposing impractical variations from the conventional surgical technique. Even though conventional total knee arthroplasty (TKA) is in general a very successful operation, TKA is an attractive application for robotic assistance for a number of reasons. Firstly, knee mal-alignments of as little as 3° in the frontal plane (Figure 1) have been correlated to early failures, so a high degree of implant placement accuracy is key for good clinical results [1]. Secondly, conventional TKA instrumentation systems that rely on mechanical jigs to aid bone resurfacing have been known to produce variable and suboptimal results with respect to implant alignment and fit of the femoral component [2]. Saw-guides, for example, that reference the anterior, posterior, and chamfer cuts from the distal cut may produce an outer femoral surface which is incongruent with the inner surface of the implant [2–4]. Furthermore, manual instrumentation systems usually require that a number of guides be available in the operating room to cover the entire range of implant sizes (typically one template for each of the five to eight sizes), which can take up valuable space around the operating table and increase sterilization costs.

In conventional TKA, the surgeon strives to achieve accurate alignment by adequately exposing the knee joint, properly orienting cutting guide blocks across the exposed aspects of the bones from the anterior side of the knee, and sawing off the

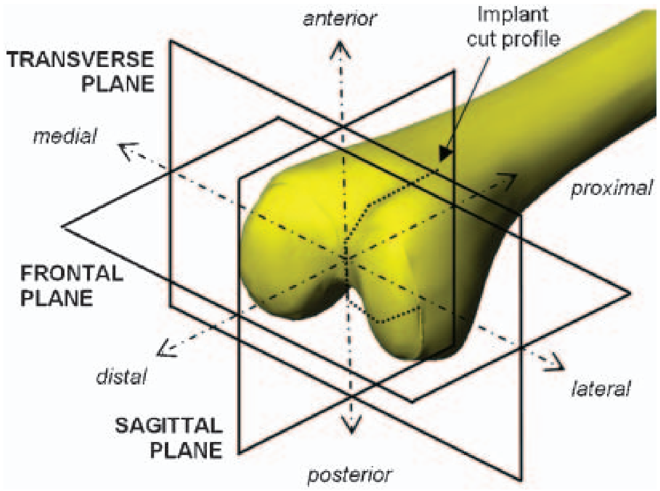


Figure 1 Anatomical co-ordinate system of the femur. The implant cut profile (...) is projected onto the sagittal plane, illustrating the five planar cuts of a typical TKA femoral implant.

worn joint surface by using the block surface or slot to guide the oscillating saw-blade. The standard approach uses a 25–30 cm anteromedial skin incision extending proximally from just distal to the level of the tibial tubercle, followed by a medial 20–30 cm parapatellar arthrotomy which extends superiorly through the quadriceps tendon [5]. Although the extent of the incision allows for lateral eversion and dislocation of the patella, thus exposing most of the structures in the knee joint, dividing the distal third of the quadriceps muscle in this manner can have several repercussions for the patient. These include increased pain, blood loss, and time to ambulation, prolonged post-operative hospital stay and rehabilitation, and decreased range of motion and knee strength [6].

Surgeons are beginning to use "minimal access" or "minimally invasive" surgical (MIS) techniques for TKA. Some techniques preserve the quadriceps mechanism entirely, while others use a ~2 cm vastus medialis snip to facilitate patellar subluxation [6–8]. Femoral cuts are made from the anterior or medial side through a 6–14 cm "mobile" incision that is moved to expose different aspects of the joint by flexing and rotating the knee. Approaching the bone cuts obliquely or medially circumvents the need to evert the patella, thus reducing morbidity and trauma to the extensor mechanism, and improving post-operative knee function, recovery rate and pain.

The primary surgical challenge in minimal access TKA is attaining precise implant cuts and alignment with the reduced bone exposure. Currently, the bone cuts are carried out by pinning a downsized cutting-block onto the side of the knee. Because sawing accuracy diminishes quickly with extension of the sawblade beyond the cutting-block, however, achieving accurate and reproducible cuts is very challenging [4].

Our goal is to develop a miniature robotic bone-milling and sawing guide that increases cutting precision in minimal access TKA. Following a brief review of robotic TKA systems, we describe the bone-mounted robot prototype that we initially developed for conventional TKA. We then report on the modifications that we made to this initial design to make the robot appropriate for use in minimal access TKA. Finally, we describe our proposed surgical technique and our first experiences using the device on saw-bones and cadavers.

BRIEF REVIEW OF ROBOT-AIDED KNEE ARTHOPLASTY

Robotic TKA systems have been mainly categorized by two factors: size and function. Over the past decade, several groups have proposed relatively large floor or table mounted robotic systems [9–16]. Recently, more and more development has been aimed at smaller, bone-mounted robots [17–19]. Both types of systems can either position cutting-guides for the surgeon, or they can carry out bone-milling autonomously. They have been classified as being either semi-active or active, respectively [11, 19]. Most large research systems use industrial type robotic arms that have been modified for use in surgery, by for example, incorporating a force sensor in the end-effector and redundant encoders in the joints.

The ACROBOT system (The Acrobot Company Ltd, UK, www.acrobot.co.uk) was one of the first specially built large robots for TKA that uses a 'hands-on' approach where the surgeon controls the position of the milling tool using a handle instrumented with a force sensor [11]. The robot architecture is comprised of a unique backdrivable roll-pitch-yaw mechanism mounted on a gross positioning arm which brings the ACROBOT head into the vicinity of the knee [13]. This active constraint control scheme allows the surgeon to move the milling tool under servoassistance within preprogrammed regions as determined from pre-operative CT scan reconstructions, providing enhanced control during the milling process while preventing the milling tool from entering forbidden regions of the patient.

Miniature robotic guide positioning devices have more recently become available for TKA [16, 17]. The PI-Galileo Positioning Device (PLUS Orthopedics AG, Switzerland, www.plusorthopedics.com) system uses a hybrid navigated-robotic device which clamps onto the mediolateral aspects of the distal femoral shaft [16]. Two linear motorized axes slide a '4-in-1' saw-guide in the proximal-distal and anterior-posterior directions so that one cutting block can be positioned for the entire size range of one specific implant geometry. Another commercially available system (Medacta, Switzerland, www.medacta.ch) uses a 5 DoF motorized architecture which automates positioning of each cutting plane in all DoF. The robot mounts on the medial, lateral, and anterior portions of the exposed femur and occupies a cubic volume of $\sim$20 cm^3 around the knee [17].

Similar to the MARS [19] miniature orthopaedic robot (Mazor Surgical Technologies, Israel, www.mazorst.com), the MBARS [18] robot employs a parallel platform architecture. This active bone-mounted system has been demonstrated for patello-femoral joint arthroplasty, where a small pocket surface is machined in the trochlear groove area of the femur. The parallel 6 DoF architecture allows for automated "CNC" machining of complex implant bed surfaces within a relatively small workspace. Rigid fixation of the miniature platform is achieved with three pins in the medial, lateral, and anterior femoral regions.

A primary difference between floor/table mounted robots and bone mounted systems is that in the former, the bones have to be immobilized as rigidly as possible, typically by clamping them to the operating table. Kienzle and colleagues describe a 6 DoF fixturing arm equipped with heavy duty locking joints [8]. The fully active 'ROBODOC' milling system (Integrated Surgical Systems, Davis, California, www.robodoc.com) has a mechanical sensor in addition to the bone clamp to monitor and to stop cutting if any bone motion has occurred with respect to the robot base [15]. More technically complex alternatives involve tracking and compensating for small bone motions during cutting. A key advantage of bone mounted robots is that there is no need to immobilize the limb or compensate for motion, and hence they impose a less dramatic departure from the conventional surgical technique [19]. A current drawback to most bone-mounted robotic TKA systems, however, is that they require substantial incision of the quadriceps muscle and reflection of the patella in order to rigidly fix the robot to the three sides (medial, lateral, anterior) adjacent to the bone cutting area.

3 PRAXITELES - INITIAL CONCEPT AND PROTOTYPE DEVELOPMENT FOR CONVENTIONAL TKA

We first developed an initial bone-mounted prototype of a 'universal' mini-robotic guide positioner for bone sawing and milling in conventional TKA [20]. The device is universal in the sense that it can be used to position a single saw or mill guide at any cutting plane orientation and depth in the sagittal plane so that the distal femoral bone surface can be prepared for any implant geometry that is comprised of planar cuts see Figure 2.

A. Description of robot architecture and components

The modular device consists of three primary components:

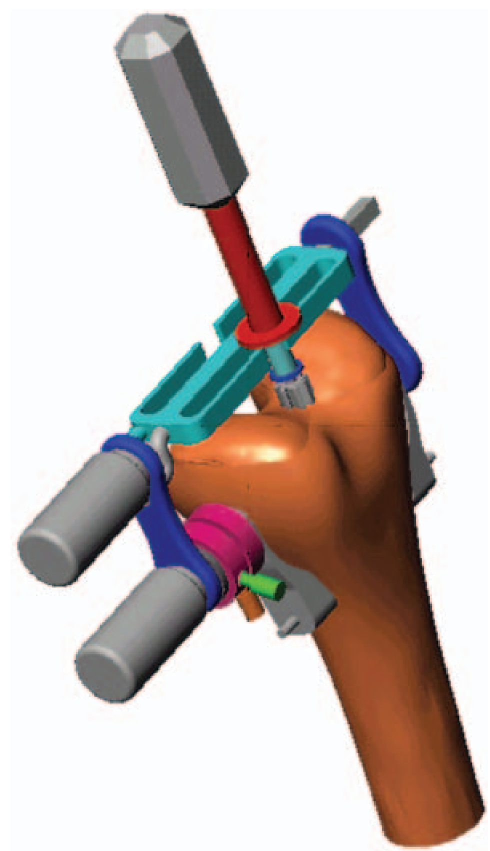


Figure 2 Initial concept for the Praxiteles surgical robot for conventional TKA.

1) a fixation and adjustment system that secures the robot to the bone and incorporates a 2 DoF adjustment mechanism which permits the surgeon to manually align the robot motor axis to the implant profile in the frontal and transverse (or axial) planes;
2) a cutting tool interface that guides a saw-blade or milling tool;
3) a 2 DoF actuation unit which has two motorised rotational axes arranged in parallel and moves the cutting guide interface relative to the bone fixation/adjustment system.

The modular design permits attachment of the guide interfaces for the various supported cutting techniques. We chose a robot architecture that has two motorised rotational DoF that can be aligned perpendicularly to the profile of the implant cuts (i.e. in line with all 5 cutting planes, figure 1) so that we could precisely control the following variables:

1) global implant alignment in the sagittal plane,
2) global antereoposterior (AP) implant positioning,
3) global proximal-distal (PD) implant positioning,
4) implant geometry (shape), and
5) implant scaling (size)

This leaves the surgeon with two variables to adjust manually during surgery: 1) global frontal plane and 2) global transverse plane implant alignment, both of which are controlled using the 2 DoF manual adjustment mechanism under computer navigation.

B. Initial prototype construction

Before conducting any rigorous workspace or kinematic analysis, we manufactured an initial prototype of nominal dimensions to investigate the general feasibility of using this architecture in conventional TKA see Figure 3. In this initial system we rigidly connected the medial and lateral fixation bases with an arch shaped frame that traverses the anterior aspect of the femur. This helped to better distribute the loads on either side of the bone and keep the axis straight. We incorporated the orthogonal adjustment mechanism on the inner side of the frame in-between one of the fixation bases and the arch. On the opposite side, we put a clamping mechanism that advanced the opposing fixation base into the bone so that we could clamp the frame onto different size femurs. Screw holes were added on either side of the frame so that the arch could be rigidly fixed after initial clamping adjustment of the axis. Once the arch is fixed, the 2 DoF motor unit and saw-guide is attached and the angular position of each motor axis is calibrated with respect to the bone in a single step using an optical marker (rigid body) placed in the cutting-guide slot.

ROBOT REDESIGN FOR MINIMAL ACCESS TKA

From our preliminary feasibility experiments on cadavers with our first prototype, we found that the usability, visibility and stability of the guide during cutting were in general very satisfactory. However, it was evident that a number of modifications had to be made to use the devise in minimally invasive TKA. These included:

A. redesigning the fixation and mechanical adjustment systems such that the robot could be mounted only on one side of the bone, completely within the MIS incision with minimal disruption of the surrounding soft tissues
B. redesigning the passive milling tool guide to improve the ergonomics and kinematics
C. improving safety during positioning of the motorized guide and reducing its overall size and weight
D. optimize the guide positioning and workspace such that
   a. the leading edge of the saw-guide is positioned as close as possible to the start of the cut, and
   b. the robot can be made as compact as possible while still being able to reach all of the cuts for any TKA implant size or shape

A. Redesigning the fixation and mechanical adjustment systems

To make our prototype system compatible with the constraints of MIS TKA, we reduced the size of the 2 DoF manual adjustment and fixation system so that we could attach it only to the medial side of the bone using two pins (percutaneous fixation on the opposite side could cause vascular issues or nerve

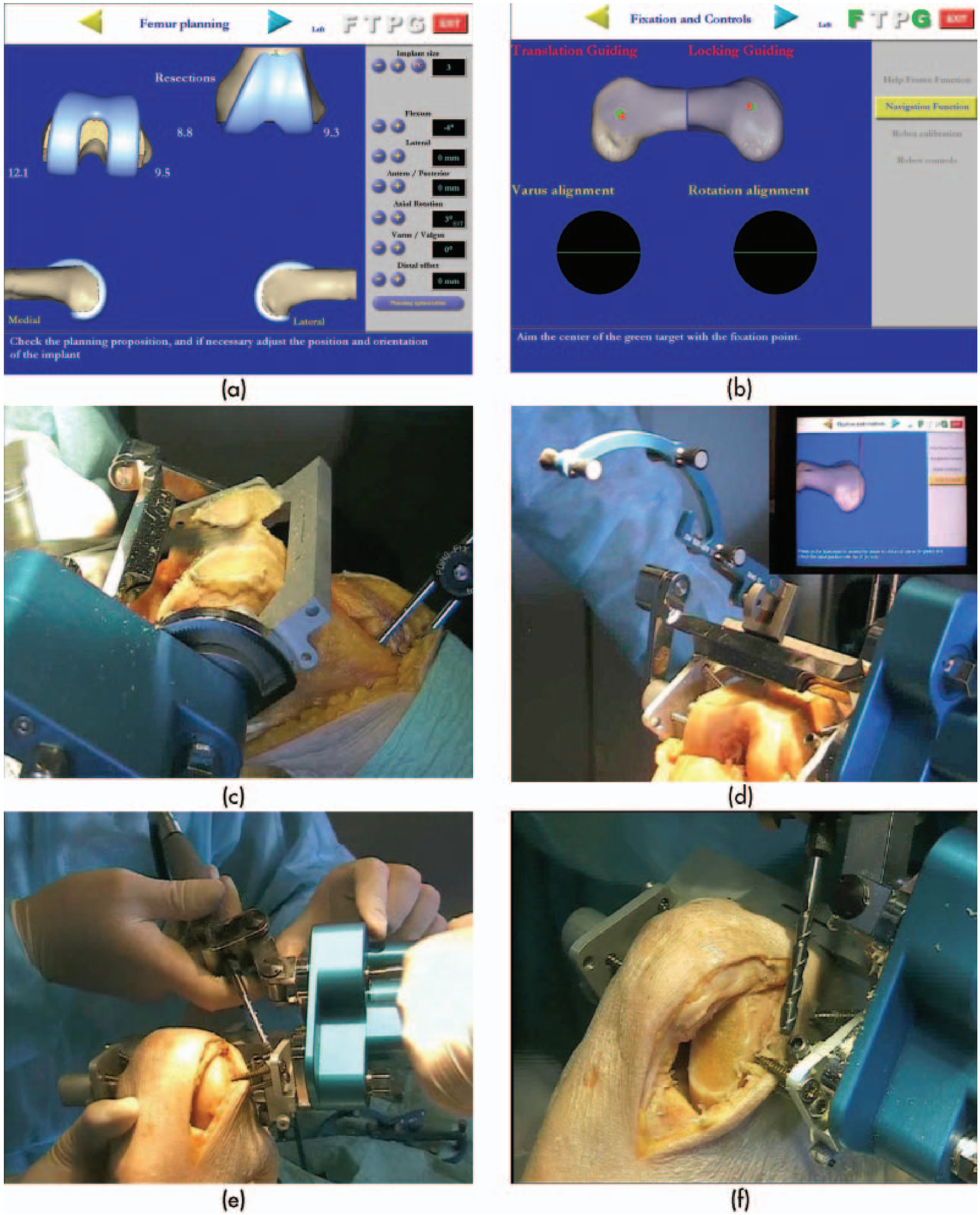


Figure 3 Cadaver experiments with our first prototype robot: a) Intra-operative planning of the femoral component position and size; b) Navigation of the fixation arch on the bone; c) making the anterior chamfer cut with the saw-guide in position; d) verifying guide position before making the distal cut; d) percutaneous fixation of the arch and attachment of the milling guide; e) milling the distal cutting plane in uni-compartmental knee arthroplasy (UKA).

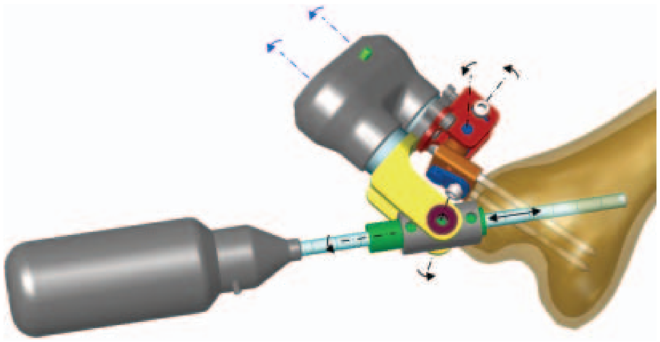


Figure 4 CAD model illustrating the various manual (-.-.-) and motorized (-.-.-) DoF of the Praxiteles minimal access TKA robot.

injury). The adjustment system is similar to a universal joint, with two rotational axes arranged perpendicularly to each other see Figure 4. The two pins can be inserted bicortically in patients with severe osteoporoses where the bone quality is very soft and weak.

B. Redesigning the passive milling tool guide to improve ergonomics and kinematics

We decided to implement a fully passive cutting system in which the surgeon is in full control of the cutting process, as in manual surgery, as these types of systems seem to be more easily accepted by clinicians than automated cutting systems in which the robot is in control of the cutting path. Risk of injuring soft tissues can be minimized by using a soft tissue guard at the tip of the milling tool.

Bone-cutting is performed with an anteromedial approach using either a sawing technique or a side-milling technique and a novel method of tool guidance. We designed a passive 2 DoF milling guide which allows the tool to both rotate and slide in the cutting plane while having a fixed entry point into the cut. The milling tool guide is positioned for each of the five femoral cuts such that the entry is always through the minimal incision window. An indexing system permits discrete advancement of the milling tool into the cut after making each cutting swing. This decoupling of freedom facilitates efficient and rapid cutting and makes milling easy to control as each DoF can be independently controlled.

C. Assuring safety during guide positioning and reducing the overall size and weight of the dual motor unit

We considered several possible scenarios in which the robot could potentially cause harm to the patient or surgeon, including power/motor failure, control malfunctions, etc. For each of the potentially hazardous scenarios, we specify a corresponding preferred result see Table 1.

We incorporated a manual ‘‘safety’’ button that the surgeon must hold down in order to allow motion of both actuators see Figure 5a. This ensures that (1) the cutting guide maintains its position during cutting regardless of the state of the actuators, and (2) the motors cannot move the guide unexpectedly at any time if the button is not pressed down.

Since the brake mechanism bares the loads applied to the guide during the cutting phase, the motors need only provide enough power to position the cutting guide. We use small low-torque motors that provide sufficient power to lift the cutting guide, but not enough force to pose any significant threat. Moreover, the surgeon can over-power the motors and backdrive the system.

For the case of an actuator or cable failure in surgery, we designed a modular system in which both actuators are encapsulated in a separate housing so that they could be easily detached from the gear unit and replaced. As the chemical sterilization protocol (washing in a toxic bath of diluted glutaraldehyde solution) and autoclave (temperature 135 °C, water vapour pressure 2.1 bar, relative humidity 100%, duration of cycle >20 minutes) inflicts harsh conditions on the actuators, electrical cable, and connections, we assumed that after a high number of sterilization cycles the actuation unit with integrated electronic positioning sensors may need to be replaced. The configuration allows the hospital to use the actuators until the end of their lifespan, and then to dispose of and replace them in surgery without having to dismount the robot. Additionally, the motor unit and power cable do not need to be connected to the robot during the cutting or milling phases (when the surgeon is

Table 1 Risk table of guide positioning

Potential Problem	Desired Result
disruption of the robot power supply during cutting	the guide should maintain its current position
irreversible actuator failure during surgery	actuators should be easily replaceable at any stage of the procedure
controller malfunctions	actuators should be physically incapable of moving the guide, unless authorised by surgeon
	the system should be back-drivable to allow manual positioning to safe zones

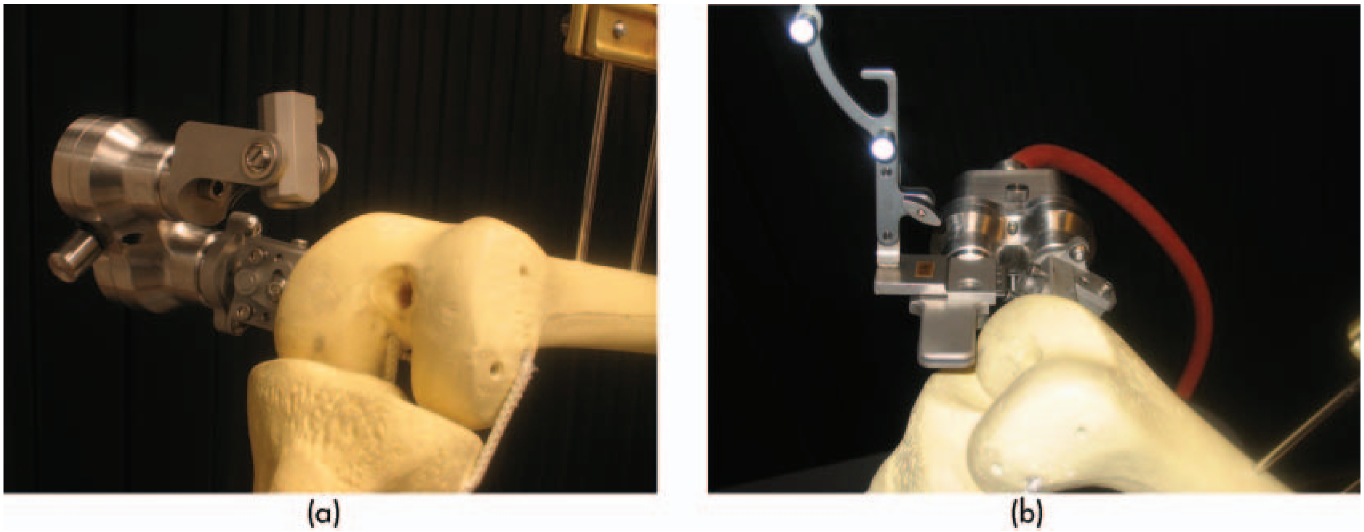


Figure 5 *Praxiteles* second prototype for milling and sawing in MIS TKA. (a) The 2 DoF milling tool guide allows rotation and translation of the milling tool within the cutting plane. A single brake release button frees both axes of rotation when pressed. (b) A sliding joint in the plane of the saw-guide allows the guide tip to be abutted directly against the bone surface before making each cut. Robot shown with detachable motor.

typically standing directly beside the knee) making the guide very compact and lightweight. This option becomes more important in patients having very poor quality bone, where the fixation rigidity could be compromised.

D. Optimizing the robot positioning, size, and workspace

To optimize the guide positioning and workspace such that the leading edge of the saw-guide is positioned as close as possible to the start of each cut, we conducted a study to investigate how the guide positioning varied as a function of all the input variables [21]. We considered the inner geometry of 63 femoral implants in total (10 implants each having a range of 5–7 sizes). We used a non-linear constraint optimization to determine the optimal placement of the robot on the bone such that the bone-guide gap distance was minimized (the constraint was that the guide could not collide with the bone). We then analysed the how this optimized gap distance changed as a function of the robot geometry (i.e. the length of each link L_1, and L_2).

In general, we found that by optimally positioning the robot on the bone in relation to the five cutting planes, we could reduce the maximum gap distance for all five cuts to ∼5 mm for over 90% of the implants tested. However, the robot geometry which resulted in the best positioning did not correspond to the most compact design (figure 6) [21]. In addition, we thought that having to fix the robot on the bone in a very precise location could result in a more cumbersome and time consuming surgical procedure. We therefore decided to incorporate a sliding joint in the saw-guide plane so that the surgeon could abut the guide manually against the bone surface for all cuts, providing greater flexibility in robot placement and eliminating the cutting gap entirely for all cuts (figure 5b). This also allowed us to reduce the size of the robot such that the

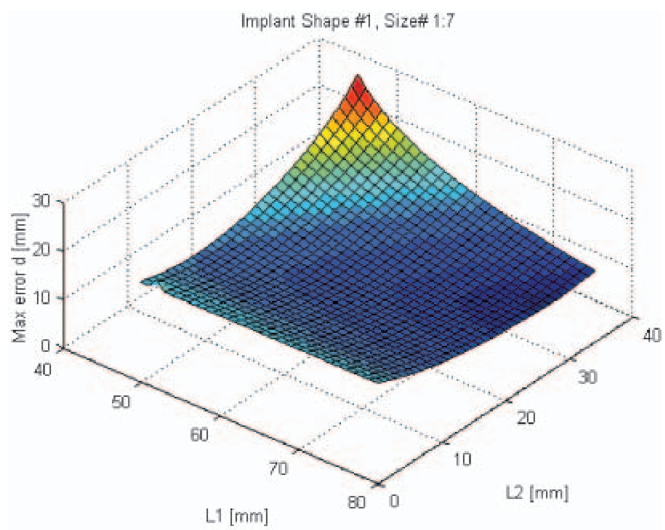


Figure 6 Cost function illustrating how the distance between the saw-guide tip and the start of the cut varies with the robot geometry. L_1, is the distance between the two robot axes, L_2 is the distance from the second robot axis to the guide tip. Max error d the maximum gap distance for all implant sizes of one geometry.

workspace is just large enough to reach all the cuts of the largest size implants.

INITIAL RESULTS ON ROBOT POSITIONING AND MILLING ACCURACY, REPEATABILITY, AND STIFFNESS

There are several factors which influence the positioning repeatability of the robotic cutting guide, including the accuracy and precision of the mechanical adjustment mechanisms, the mechanical drive systems, the actuation sensors, and the optical camera. To evaluate a user's ability to orient and lock the mechanical adjustment mechanism relative to a planned implant position, we had two untrained users adjust and lock the guide on a synthetic 'sawbone'. Adjustment precision measured with the "G" rigid body was found to be $<0.3^{\circ}$ standard deviation (SD, $n = 5$ trials each) in both DoF for both users (an averaging filter was used to reduce the camera measurement noise and to stabilize the readings). We quantified the positioning reproducibility, stiffness, and backlash of the robot by rigidly clamping a 0.01 mm resolution dial-gauge to the fixation base and measuring the deflection at the cutting-guide plane. The motor and gear positioning repeatability was determined by commanding both motors to rotate by a random value, returning them to their initial positions, and then noting the dial-gauge value. The variability in positioning was <0.01 mm SD, with a maximum error range of 0.04 mm ($n = 13$). The stiffness of the mechanical system (adjustment mechanism, gears, brake, and cutting guide) was measured by hanging a weight on the cutting guide with the brake engaged, and measuring the deflection at the point of the applied load. Masses of 540 and 1080 grams suspended from the milling guide support resulted in deflections of 0.04 and 0.09 mm, respectively. No measurable backlash was recorded on the dial gauge for either axis.

Initial milling experiments were also conducted on a sawbone to gauge the accuracy and repeatability of the milling system. Milling was carried using a custom built electronic milling motor operating at 15000 RPM, and equipped with a standard medical side-cutting burr (Figure 7). The final bone-cut surface was measured on each medial and lateral condyle, and across both condyles using a flat plate and the planar probe. Cut surface repeatability was found to be $1.0 \pm 0.5^{\circ}$ (absolute mean error $\pm$ SD) with a range of 0–2° for all measurements. The largest errors were on the lateral posterior condyle, where the extended milling tool length was the greatest, indicating that a stiffer milling tool attachment piece may be required.

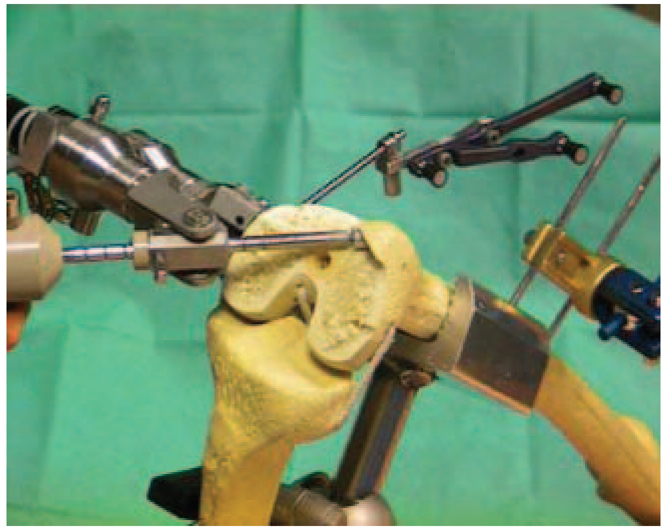


Figure 7 Preliminary cutting experiments using a custom built milling tool on synthetic bones.

PROPOSED SURGICAL TECHNIQUE WITH NEW PROTOTYPE ROBOT

We are currently integrating the robotic cutting guide into the *Surgetics Station*® (Praxim medivision, www.surgetics.com), an open platform surgical navigation system that uses image-free BoneMorphing® (deformable statistical) models to reconstruct the three-dimensional shape of the femoral and tibial surface intra-operatively [22].

The surgical workflow is presented in Figure 8. First the "T" and "F" shaped rigid bodies are fixed to the tibia and femur, respectively, and the point probe "P" and planar guide probe "G" are calibrated. These rigid bodies and probes each have at least three passive retro-reflective markers that are localized in three-dimensional space by an optical infrared camera.

A. Preliminary cadaver test

We conducted a preliminary cadaver experiment to test the feasibility of the proposed surgical technique with the constraints of minimal access TKA. To access the knee joint, we used a medial parapatellar approach with a skin 9.5 cm incision, (about two times the length of the patella). The incision was continued down through the anterior joint capsule and patellofemoral ligament. A 2 cm incision in the vastus medialis made in the direction of the fibres

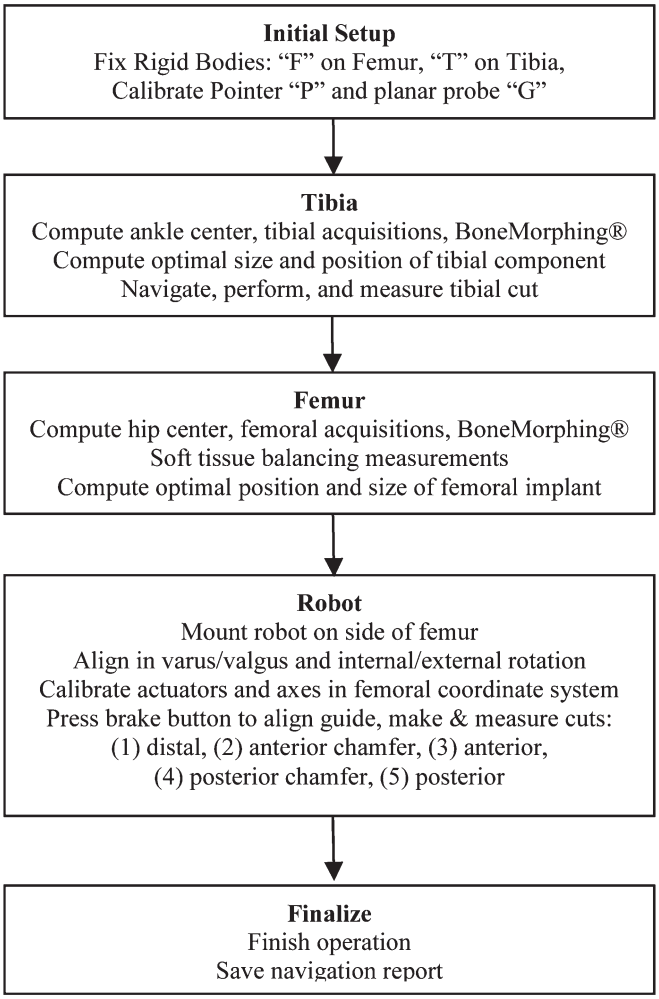


Figure 8 Surgical workflow of the robotic TKA technique.

facilitated the exposure, along with resection of the tibial meniscus and cruciate ligaments.

The tibial malleoli are first digitized to compute the ankle centre, followed by the tibial plateaus. These data determine the initial attitude of the BoneMorphing® model. The tibial surface acquisitions are then made by manipulating the tibia with respect to the femur in flexion, extension and rotation, to help bring the various bone areas into the incision (Figure 9a). The patella was not reflected but retracted or subluxed laterally. The tibial cut was then navigated and made using a saw-guide.

The femoral acquisition begins with kinematic identification of the hip centre without any rigid bodies in the pelvis. The posterior condyles and Whiteside’s line are then digitized, followed by the femoral BoneMorphing® surface acquisition. Again, the tibia is flexed, extended, and rotated relative to the femur to expose the different femoral surface areas. There is now more space in the knee as the tibial plateau has already been removed; the tibia can be compressed against the femur and the patella can be retracted laterally. A curved probe facilitates acquisition of the posterior femoral areas with the knee in flexion, and the lateral areas with the knee in extension see Figure 9b. Once the surface acquisition is complete, ligament gap measurements between the uncut femoral condyles and the tibial cut surface can be performed at various flexion angles to optimize femoral component positioning and sizing [19]. The system then automatically suggests the optimal position and size of the femoral implant based on the mechanical axis, the bony landmark features extracted from the BoneMorphing model, and the ligament balancing acquisitions. This proposed position can then be checked and modified using the tactile screen. Once the femoral implant size and position has been validated, the locations of the five cutting planes are stored in the femoral coordinate system.

Two pins are then fixed in the medial femoral condyle. To ensure that the pins do not intersect any of the five cutting planes, each cutting plane location, along with the position and orientation of the system probes are displayed in real time on 3D models (Figure 10a). The insertion site of the medial collateral ligament along with the planned insertion points of the two fixation pins can be marked on the bone surface to facilitate the insertion. The pin insertion area on the medial femoral side is bounded by the following structures: posteriorly – by the anterior border of the medial collateral ligament when the knee is in full extension; anterosuperiorly – by the posteroinferior border of the vastus medialis muscle when the knee is in flexion; anterodistally – by the anterior, anterior chamfer and distal cutting planes see Figure 10b. Fixing the robot in this area permitted uninhibited flexion and extension of the knee, and access to all five cuts through the mobile incision.

The pre-assembled robot is then mounted onto the fixation pins see Figure 11a. With the calibrated planar probe inserted in the slot of the guide, robot axis is aligned in varus/valgus and internal/external rotation using the navigation display. Each DoF can be navigated and locked separately for ease-of-use.

Once the adjustments are aligned relative to the planned implant profile, the motor unit is attached and the two kinematic axes and motor angles of the robot are calibrated. This is accomplished by

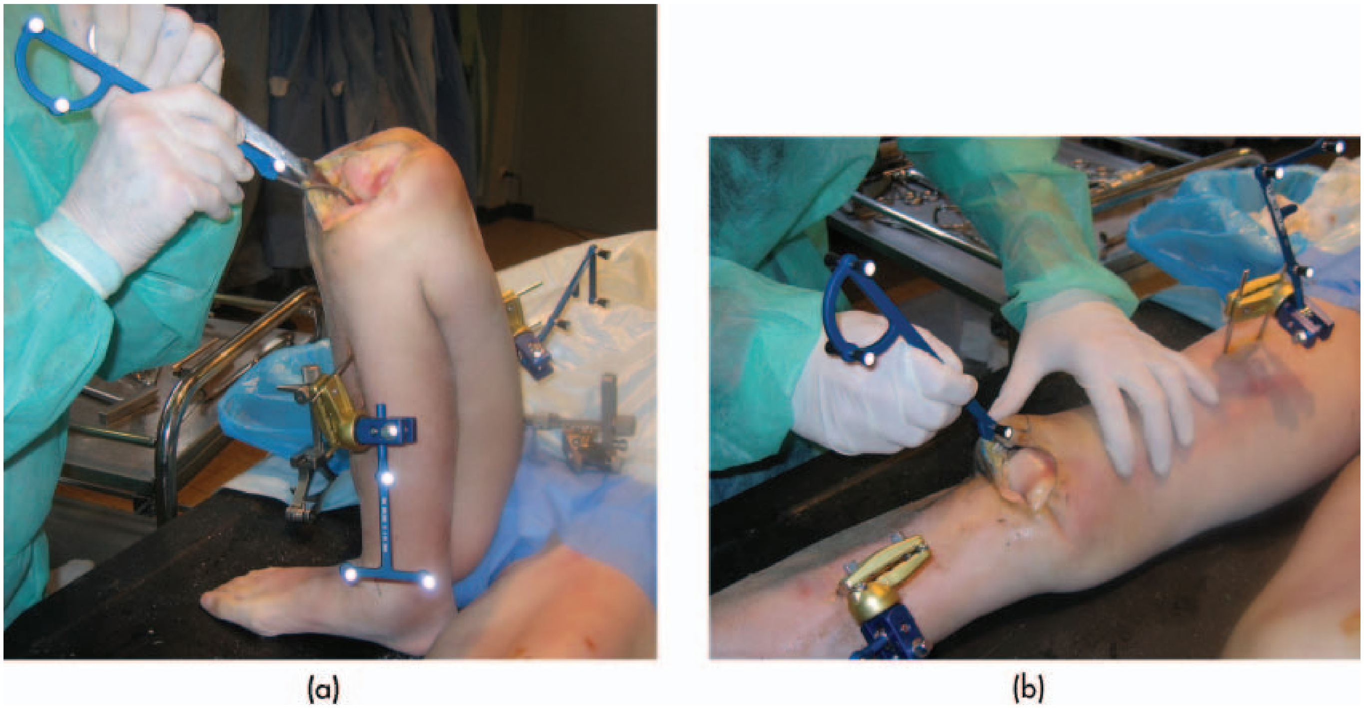
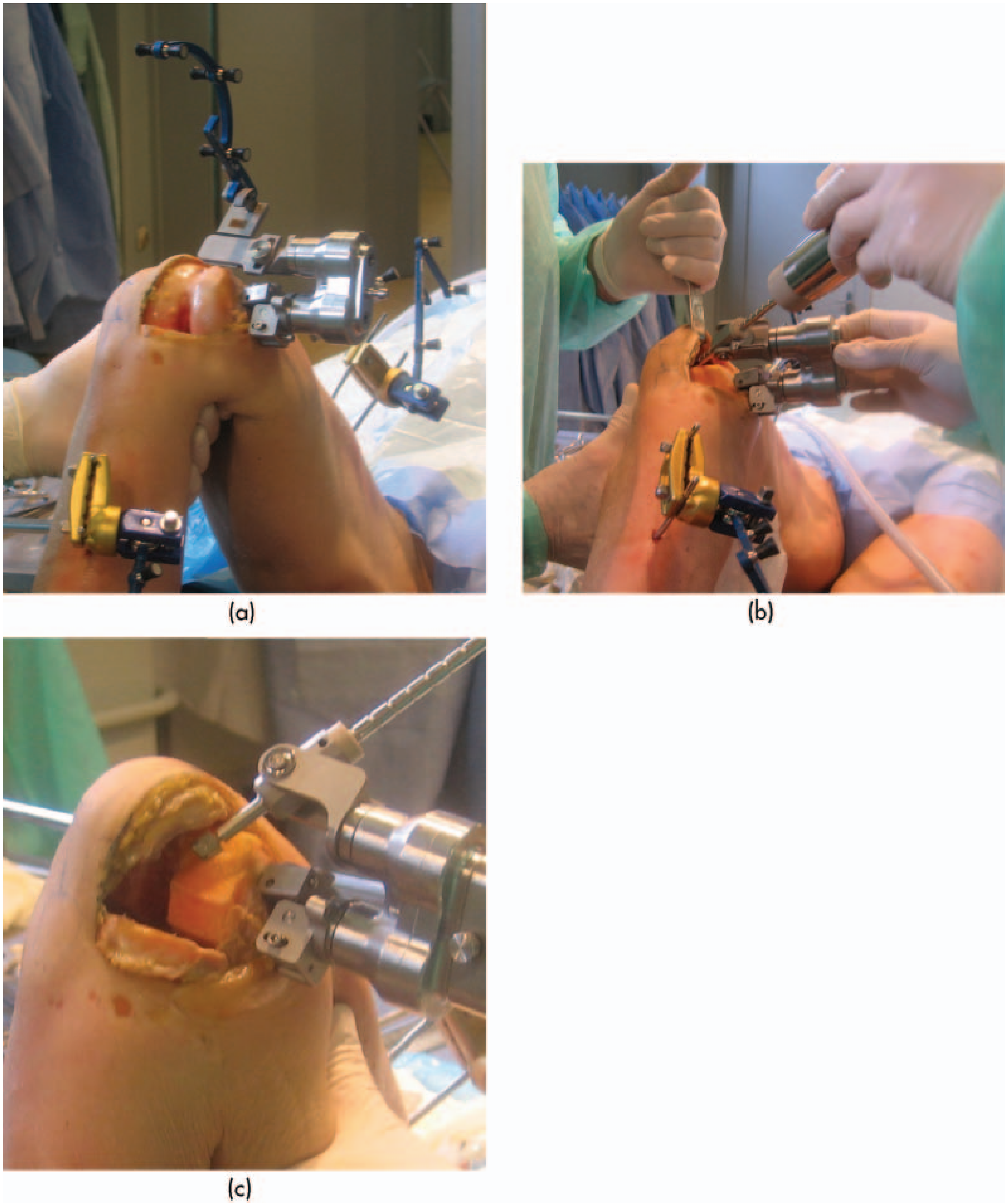


Figure 9 Tibial (a) and femoral (b) surface acquisitions. (a) The tibia is flexed, extended and rotated relative to the femur to aid exposure of the anterior, medial and lateral sides of the joint. (b) There is more room in the joint to digitize the femur once the tibia cut is made. With the knee in extension and the tibia compressed against the femur, the patella is subluxed and the lateral aspects of the femur can be accessed.

Figure 10 Insertion of the robot fixation pins. (a) the point probe can be used to guide and check pin insertion to avoid interference with the femoral cutting planes; (b) the pin insertion area on the medial femoral side is bounded by the following structures: *posteriorly* – by the anterior border of the medial collateral ligament when the knee is in extension, *anterosuperiorly* – by the posteroinferior border of the vastus medialis muscle when the knee is in flexion, *anterodistally* – by the anterior, anterior chamfer, and distal cutting planes.

pressing the brake release button on the 2 DoF gear unit, and manually rotating the first robot axis through a range of motion of $\sim 90^{\circ}$. Simultaneous measurement of the actuator positions and of the "G" rigid body location with respect to the "F" femoral reference frame are made using the motion controller and the optical camera, respectively. Using an inverse kinematic model that considers the robot geometry and the position of each cutting plane relative to the robot kinematic axes, the



(a) (b) (c)

Figure 11 (a) The robot position is calibrated by inserting the planar probe into the slot. (b) The leg is positioned in various degrees of flexion depending on the cut to make room during milling. (c) All five cuts are accessed through the 'mobile window' with the *Praxiteles* milling guide.

system calculates which motor command values correspond to each of the five cutting planes.

At this point the robot motors are enabled and the guide can be advanced to the first cut by pressing the system foot pedal and the robot brake release button. The controller monitors the sensor values, notifying the surgeon to engage the brake once the guide is in position. In addition, the planar guide probe can be inserted in the mill or saw-guide slot to verify the guide position before making a cut. To facilitate milling of the five femoral cutting planes, the leg is placed in various degrees of flexion to make more room in the joint see Figure 11b. The planar cuts are made with 'sweeping' motions of the milling tool, using retractors to distract the surrounding soft tissues. All five cutting planes are accessed through the mini-incision with the milling tool guide see Figure 11c.

The sawing order we prefer is (1) distal, (2) anterior chamfer, (3) anterior, (4) posterior chamfer, and (5) posterior cut. The distal cut typically is made first because it allows the surgeon to visually gauge overall varus/valgus and internal/external rotational alignment, as well as distal cutting depth, before making any of the femoral bone cuts. We make the anterior chamfer cut next followed by the anterior cut so that the cutting guide can be positioned directly against the start of the cut for both cuts, which is an improvement over most conventional 4-in-1 and 5-in-1 types of cutting guides [4]. This can be important when using an oscillating saw, as cutting accuracy is known to diminish with extension of the saw-blade beyond the cutting guide. Moreover, making the anterior cuts before the posterior ones frees more space in the joint for making the posterior cut, which is more difficult due to the position of the tibia and the delicate soft tissues behind the knee. Although we prefer this sequence, the cutting order is not rigid and can be easily reprogrammed by using the forward or back switches on the system foot pedal to cycle through the cutting sequence.

We are currently undergoing a complete evaluation on a number of cadaver specimens to assess the overall system accuracy and repeatability in positioning and cutting with the sawing and milling configurations. In addition, we will be conducting a study to evaluate the rigidity of our fixation technique in fresh cadaver bones of varying density and strength before commencing a series of clinical trials on patients.

CONCLUSIONS

As surgical robots become smaller and more dedicated, their architecture can be optimised to suite the application, so as to minimise the disturbance on surgical workflow and operating time. We present a new miniature robot for positioning sawing and milling-tool guides in minimal access TKA. Initial results on sawbones and cadavers with the device are very promising, and we hope to start a series of clinical trials with the coming months.

ACKNOWLEDGEMENTS

We thank Drs. Bertrand Faguer and Antoine Leroy, and Mr. Bruno Thibaut of the Grenoble University Hospital for there assistance with the cadaver trails. This work was supported in part by the ANRT France (CIFRE Convention), and NSERC Canada.

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