Robotic Assistance in Orthopaedic Surgery
A Proof of Principle Using Distal Femoral Arthroplasty

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The term "robot" refers to a precision mechanical device that is accurately controlled by a computer using intelligent software. The term "robotic assistance" refers to the use of such a device to aid a surgeon in the optimal conduct of a procedure, particularly one requiring specified geometrical relationships. The authors have been exploring the application of robotic assistance in situations in which accuracy and precision are required in orthopaedic surgery. The initial application concerned the planning, positioning, and orientation cuts and holes of the bone required for the femoral component of a total knee arthroplasty. A three-dimensional digitizing template allowed the surgeon to specify the desired position and orientation of the component's articular surfaces in relation to the distal femur. The robotic system used this spatial relationship, along with its knowledge of the geometry of the component selected by the surgeon, to plan the precise location of the required bone cuts and holes. Finally, the robotic assistant sequentially positioned saw and drill guides with respect to the distal femur so that the surgeon made these cuts and holes in the locations necessary for optimal component fit, position, and orientation. The robotic assistant functioned easily in the operating room environment; increased the accuracy; and decreased the time, equipment, and personnel required for the conduct of the geometrical part of this surgical procedure.

The clinical outcome of total knee arthroplasty (TKA) depends on many factors, such as patient selection, prosthesis design, soft tissue balancing, and postoperative care. The prostheses are manufactured so that the geometry of their joint surfaces meet very high tolerance standards. Yet the precision and accuracy of the surgical technique by which a surgeon implants these components is much less rigorous. Two aspects of the surgical procedure involve precise geometrical relationships. The first is the positioning of the prosthetic joint surfaces so that optimal kinematics can be achieved. The second is the location and orientation of the bone cuts and holes to fit the back of the component exactly, providing a durable bone–prosthesis interface. The optimal execution of such a geometrical procedure is nontrivial: the relationship of each component to the bone has six degrees of freedom. These include three directions of translation (proximal–distal, medial–lateral, and anterior–posterior) and three directions of rotation (flexion–extension, internal–external rotation, and varus–valgus). Furthermore, the implantation of each component requires several bone cuts and holes. Each cut plane has one translational and three rotational degrees of freedom. Each hole has two rotational and two translational degrees of freedom. Each of these degrees of freedom represents a possible surgical error that can compromise the kinematics of the joint or the durability of component fixation.
Conventionally, procedures such as TKA are planned using two-dimensional templates superimposed on two-dimensional radiographs. Two-dimensional planning cannot specify all of the necessary variables for a three-dimensional arthroplasty. Even if a three-dimensional plan were established, for example, using computed tomograms or scaled physical models, there is no way for the surgeon to assure that the planned relationships would be achieved at surgery.

Cutting and drilling guides are in common use in TKA. These guides have some definite disadvantages, however. Different guides are required for each size, side, and design of prosthetic components. The surgeon must go through a learning curve with each new guide system. The preoperative plan is not linked rigorously to the positioning of these guides at surgery. Cutting guides do not allow the surgeon to preview where the prosthetic joint surfaces will be located at the conclusion of the procedure.

Robotic assistance offers the surgeon a unique opportunity to establish a complete three-dimensional geometrical plan and then to execute that plan at surgery with precision, accuracy, and efficiency. The robot can only be an assistant, however. A robot cannot attain the ability of an orthopaedic surgeon to make the surgical approach to the knee, to carry out the appropriate soft tissue releases, or to judge the depth of a bone cut so that it does not injure the popliteal neurovascular structures.

The results from the application of a robotic assistant to the geometrical challenge of a distal femoral arthroplasty are included. The distal femoral arthroplasty was selected for this initial investigation because of the complexities imposed by its multiple cut planes and drill holes. Also included is a demonstration in the operating room, using the knee of a cadaver. In this demonstration, a high priority has been placed on safety, so that the risk to the patient from robotic malfunction was minimized.

The authors are unaware of previous attempts to apply robotics to the geometrical problems of TKA. Although this investigation is confined to the distal femoral arthroplasty, analogous potential applications exist for the proximal tibial arthroplasty, other joint arthroplasties, and osteotomies.

MATERIALS AND METHODS

THE ROBOT

A six-axis, commercially available robot was selected for this investigation (Puma 260 Unimation Inc., Pittsburgh, Pennsylvania) (Fig. 1). The small size of this robot (16 kg) fit well in the confines of the operating room environment and did not dominate the environment. Only low payloads were
required because the robot was unpowered during the planning phase and immobile while the surgeon carried out the cutting and drilling. At no point during the procedure was the robot required to support a load greater than 1 kg. This low payload maximized safety in the event of a controlling malfunction.

**Surgical Tools**

Few instruments were necessary for the geometric bone part of this procedure. These included: (1) an immobilization jig to fix the femur rigidly to the operating table (Fig. 2), (2) three-dimensional distal femoral arthroplasty templates (Fig. 3), (3) a saw guide (Fig. 4), (4) a drill guide, (5) a standard sagittal saw, and (6) a standard power drill.

Along with the robot, computer, and software, this small ensemble of instruments provided all the tools necessary for the planning and the execution of the femoral cuts and drill holes for the placement of the femoral component. The only increment in equipment necessary to accommodate different sizes, sides, and designs of components would be additional three-dimensional templates. Inventories of specialized guides, cutting blocks, and alignment tools would not be necessary to implant different component designs.

**Tool Recognition**

The system employed a single robotic arm to assist the surgeon in all of the planning, cutting, and drilling steps. Because each of these steps required different tools, the robot was equipped with an automatic tool identification system so that the controlling system was always cognizant of which tool the robot was holding.

**Fig. 2.** The distal femoral immobilization halo fixes the femur rigidly to the operating table in a convenient operating position. Sharp points and chocks gain purchase on the aspect of the distal femur usually exposed in TKA. The upper half of the ring opens for ease of mounting the femur. The other end of the femur is fixed by the weight of the patient’s pelvis.

**Fig. 3.** The surgeon indicates the desired position of the prosthetic joint surface using a transparent three-dimensional template attached to the robot.
FIG. 4. The saw guide is positioned by the robot so that it establishes the correct planes of the bone cuts required by the specific component. The anterior and distal cuts have been made and the posterior cuts are being completed. The power saw is held by the surgeon while the robot assistant determines the plane of the cut. The curved shape of the saw guide enables the surgeon to approach the femur through a wide variety of paths, all of which lie in the specified plane. The same guide is positioned by the robot for each of the different cuts required by the prosthesis.

TEMPLATE

Three-dimensional distal femoral templates (Fig. 3) allowed the surgeon to select the optimal position of the articular surface of the component with respect to the distal femur. The tool recognition feature informed the system of the design, size, and side of the component. The system held in storage all of the relevant geometrical information concerning each component in the surgeon’s armamentarium. The attachment of a specific template to the robot arm caused the system to recall the geometry of the component represented by the template, including the relationship of the cut planes and holes to the articular surface.

THE SUPERVISORY SYSTEM

The robot was directed by a microcomputer. A custom computer language was designed for the description and direction of a wide variety of robot-assisted surgical procedures. This language was constructed in a generic, modular manner so that the basic procedures, such as Remember Position or Position Saw Guide, could be readily adapted to different surgical procedures. Supervisory interface software was written for checking errors of the serial communication between the microcomputer and the robot. A touch-sensitive computer screen was used as the interface with the operating team (Fig. 1). For use in the operating environment, the screen could be covered by a sterile transparent drape. The screen presented the meaningful and safe menu of procedural options to the surgeon. Each step involving movement of the robot required an initial and then a confirming command to assure that the surgeon had an opportunity to reconsider each step.

As an additional safety measure, the software set up an imaginary safe sphere around the knee. The robot would not penetrate the radius of this sphere except along explicitly commanded straight line motions in the plane of various cuts, or along the axis of the various holes. The surgeon moved the tool by small sequential steps along these planes and axes by using the command Move Closer on the touch screen. When moving from one cut or hole to the next, the tool always exited the safe sphere along the same path it entered and then moved along the boundary of the safe sphere to the next position. This feature eliminated the possibility that the robot would contact the knee while actively moving.

PROCEDURE

The surgeon selected the template for the prosthesis that in his or her judgment provided the optimal replacement for the distal femoral articular surface. The template was mounted on the robot, so that the tool recognition feature informed the control system of the design, size, and side of the selected component. The robot was switched to the passive mode in which the robot served as a three-dimensional digitizer. The surgeon then positioned the template so that the articular surface was in the desired position with respect to the femur. When the surgeon touched Remember Position on the touch screen menu, the system recorded the position and orientation of the component with respect to the femur in terms of the complete set of six positional variables. Knowing which component had been selected, its geometry, and its desired position and orientation in relation to the femur, the robot system calculated the exact positions and orientations of the bone cuts and
holes for positioning the articular surfaces of the selected component in the desired location. These calculations were made without any surgeon participation.

THE CUTTING AND DRILLING GUIDES

The saw guide was constructed in a curved configuration so that it could be applied closely to the femur. This curvature also allowed the surgeon to make a cut in the correct plane from any of several different approaches (e.g., anterior-medial, straight anterior, or anterior-lateral). The drill guide was a hardened steel cylinder that determined the path of the drill in making holes for the pegs of the component. The tool recognition feature assured that the system knew which instrument was being held by the robot; therefore, the robot would not position the drill guide for a cut or the cutting guide for a hole.

The software allowed the surgeon to select the order of the steps in bone preparation. By selecting Anterior Cut, Posterior Cut, or Distal Cut from the touch screen menu, the surgeon told the robot to position the cutting guide in the plane to make the selected cut. The surgeon then inserted the saw blade through the guide and made the cut with the usual surgical precautions, to avoid injury to neighboring soft tissues.

The surgeon used the touch screen menu to sequence through the procedure. When all cuts and drill holes were made, the surgeon placed the component securely against the prepared bone surface (Fig. 5).

EXPERIMENTAL PROCEDURES

Tests were carried out to determine the stiffness of the robot arm and the reproducibility of robot positioning. Next, five surgeons performed arthroplasties on plastic femora using both conventional and the robotic-assisted technique. The ease of learning, as well as the accuracy and efficiency of the two methods, were compared. Finally, a demonstration of the technique was performed on a full cadaver in the operating room under surgical conditions including standard draping.

RESULTS

STIFFNESS

The small, low-load robot arm used in this demonstration had a relatively long lever arm with substantial flexibility. A force of 18 N produced 2.5-mm displacement. When a stiffening link was added, the displacement with the 18-N force was reduced to less than 0.1 mm.

REPRODUCIBILITY

A highly accurate dial gauge was placed in the robotic workspace angled 30° above horizontal, along the same axis normally occupied by the femur at surgery. The saw guide was brought into contact at its midpoint with the tip of the dial gauge. The gauge was set at zero. The robot then was moved back and forth 20 times between this zero position and a second position 10 mm away along the axis of the gauge. In every trial, the zero position was within ±0.025 mm of the target. This ex-
experiment was repeated using the template in place of the saw guide with identical results, demonstrating that the high degree of reproducibility was independent of tool choice.

A similar method was used to determine if the robot arm shifted position when the robot was switched from the passive mode, actuators off, to the active mode, actuators on. The dial gauge target was set up along the femoral axis and the template attached to the robot. The robot was placed in its passive mode and the tool was brought by the surgeon to the target position. The robot then was placed in its active mode and the template was released by the surgeon, whereupon gravity took up any slack in the joints. For 52 trials total, the mean displacement from the intended position was less than a millimeter.

**ROBOT VERSUS CONVENTIONAL SYSTEM**

A series of trial procedures was performed by a group of five practicing orthopaedic surgeons. Each surgeon performed femoral component arthroplasties on four plastic femurs: two with a commercially available guide system and two with the robotic assistant. The surgeons had little or no familiarity with either system, although all were experienced in TKA. In the opinion of the five surgeons, the difficulty of learning the robotic procedure was no greater than the conventional guide system.

**TIME OF PROCEDURE**

The total average time for performing a conventional distal femoral preparation and the robot-assisted preparation were virtually identical, 22.6 ± 5.3 minutes and 21.1 ± 1.8 minutes, respectively. The robot times included an average of 4.2 minutes applying and removing the stiffening link. Thus, if a stiffer robot had been used, the time for the robot system would have been reduced to 16.8 minutes. Further time could have been

![RMS ERROR FOR 3 CUT ANGLES](chart.png)

_Fig. 6._ Comparison between the conventional and robotic-assisted distal femoral preparation. RMS error for five surgeons each doing two arthroplasties using the conventional system (black columns) and two using the robotic-assisted system (line).
saved by using faster robot speeds and by eliminating the time-consuming repeated verification of the surgeon's commands to the robot.

**Accuracy of Results**

The fit of the component was determined by the relationship of the three major cuts: anterior, distal, and posterior. The posterior cut can be thought of as two cuts, one per condyle. Three data sets were recorded to provide a measure of relative accuracy: (1) the angle between the anterior and distal cut; (2) the angle between the posterior lateral cut and the distal cut; and (3) the angle between the posterior medial and distal cut. Group analyses of all three sets of data yielded a two-degree root-mean-square error for the robot and five-degree root-mean-square error for the conventional system (Fig. 6). The distribution of these errors was such that for the conventional system, 16 of 30 were within two degrees of the intended angle. For the robotics system, 24 of 30 angles were within two degrees of the desired value. The extreme errors allowed by the conventional system were not allowed by the robotic system.

**Operating Room Demonstration**

To examine the function of the robot in the operating room environment, a demonstration of femoral component arthroplasty was performed on a cadaver in the operating room. Although no attempt was made to perform this demonstration under sterile conditions, sterility could be achieved through a combination of tool sterilization and draping. The knee was draped as a standard TKA. The distal femoral replacement was performed with the knee exposed through the standard paramedian incision, without alteration of the menisci or tibia, and without sacrifice of the anterior or posterior cruciate ligaments. No additional dissection was required beyond that normally used for TKA. After the patella had been reflected laterally, the distal femur was mounted in the immobilization jig. The jig provided excellent fixation of the bone in a position where the femoral condyles and proximal tibia were well exposed.

The surgeon selected the template that best matched the articular surface geometry of the distal femur and attached it to the robot. At this moment, the tool recognition system informed the controlling software of the component selected. The surgeon then placed the template so that its articular surfaces were oriented optimally with respect to the distal femur. This position then was recorded by touching the Remember Position command on the screen. At this moment, the system software determined all the cut planes and drill holes for the arthroplasty.

The template then was exchanged for the saw guide. The surgeon used the touch screen to select which cut was to be performed. The robot oriented the saw guide for the selected cut and allowed the surgeon to approximate the guide to the bone in the selected plane using the Move Closer command. The accuracy of the cut was maximized by approximating the saw guide to the femur and by using the stiffening link. The surgeon used a standard sagittal saw to make the cut, taking precautions to avoid soft tissue injury. Subsequent cuts, and the two drill holes required by the component, were made in a similar manner. After the bone preparation, the robot was dismissed and the distal femoral component was driven into position by the surgeon. An excellent press fit was attained, with the prosthesis in excellent alignment. After the prosthesis was inserted, the knee was removed from the halo and found to be capable of a range of motion from 0° to 135° and to have excellent stability in the anterior–posterior and varus–valgus directions.

Except during the initial surgical exposure of the knee, the surgeon needed neither the assistance of a surgical assistant nor a scrub nurse to carry out the procedure. This was because the only instruments required were the template, the saw guide, the drill guide, a standard surgical saw, and a standard surgical drill. The position of the femur was main-
tained by the immobilization jig. The surgeon proceeded from one step to another, interacting with the robotic assistant using the touch sense screen.

**DISCUSSION**

The peer-reviewed literature on surgical robotics is sparse. Some articles refer to "robot arms" or "iron interns" that are only fixed, self-retaining retractors, rather than true precision motion control devices. A robotic scanning laser hand piece has been used in the treatment of cutaneous vascular disorders. A laboratory evaluation of "surgeon robot prostatectomy" also has been reported. In neurologic surgery, a robot-assisted system has been used in the excision of thalamic astrocytomas. In that procedure, a surgical retractor is held and manipulated using a small robot. It also included some three-dimensional presurgical planning. Other neurosurgeons have used robotics in stereotactic surgery. Those investigators stress the importance of the linkage between the three-dimensional plan and the execution of the procedure.

An article reviewing 80 references on computer applications in orthopaedics describes preoperative planning and surgical rehearsals using three-dimensional computer displays, but does not suggest a method by which these plans can be linked rigorously to the patient in the operating room. In this review article, robotics are mentioned only as aids to the physically disabled patient.

Recently a number of reports described the use of a robot to prepare the proximal femur to receive a proximal femoral implant. That procedure involved a preliminary surgery in which three reference pins had to be placed in the femur. It then required the patient to have a computed tomographic scan from which the procedure was planned. At the definitive joint replacement surgery, the robot referenced the three points in the preparation of the bone. The robot, not the surgeon, assumed the responsibility of moving the power tool during the bone preparation. In laboratory tests, the dimensions cut by the robot surgeon were reported to be "ten to forty times better than with hand-held tools." The report mentions that the robotic procedure had been tried in dog hip arthroplasties.

Much of orthopaedic surgery depends on the surgeon's judgment, experience, and knowledge of safe surgical technique. Elements such as the feel of having cut all the way through a bone and recognition of the proximity of the popliteal artery are difficult to teach a robotic surgeon. Orthopaedics also provides substantial geometrical challenges, however, such as making and executing a plan requiring the exact location of cuts and holes. In industry, accuracy and precision in this type of activity are the province of robotics. In spite of the widely recognized need for geometrical accuracy and precision in orthopaedics, there has been minimal exploration of the possible role of robots. The authors believe that a partnership could be established between a surgeon and a robotic assistant that would maximize their respective skills.

In the investigation reported here, robotic assistance successfully addressed the need for accurate planning and execution of the preparation of the femur for TKA. It is important to note that the robot assisted but did not carry out any of the invasive steps: the authority and responsibility of the surgeon were always preserved.

The authors wish to demonstrate that the concept of robotic assistance can be applied in an orthopaedic operating room, not to advocate the use of robots in orthopaedic surgery. A detailed discussion of the practicality or cost-benefit ratio of such a robotic system is beyond the scope of this initial exploration. It appears, however, that a robotic system, such as that described here, would have a cost and size of the same magnitude as the high-quality portable x-ray units used commonly in operating rooms.

A robotic assistant has the potential benefit to the surgeon and patient of assuring that the preoperative plan is formulated and executed.
with accuracy and precision. The effect of these improvements on the functional outcome and durability of TKA and other orthopaedic procedures must be determined by future investigation.

REFERENCES


