Computer-assisted orthopaedic surgery is defined as the use of computers and robotic technology to assist the orthopaedist in providing musculoskeletal care. In the operating room, this technology includes: pre-operative planners, intra-operative navigation equipment, smart tools, and remote surgery technologies. Computers augment orthopaedic surgery by taking advantage of five fundamental characteristics; geometric precision, reproducibility, perfect “memory,” lack of fatigue, and insensitivity to radiation. The synergy of these characteristics combined with an orthopaedic surgeon’s inherent judgment, experience, adaptability, and knowledge is crucial to the success of computer-assisted orthopaedics.

Definitions

**Computer-assisted orthopaedic surgery (CAOS)** or **image guided orthopaedic surgery (IGOS)** is an area in which machine capability is coupled with human judgment and skills to perform a task better than either could do alone.¹,²

**Robotic surgery** is a semi-autonomous procedure performed by a robotic arm under direct or indirect physician control.³ The first human robotic surgery was performed in 1992 in California using the ROBODOC® system (Integrated Surgical Systems, Sacramento, CA).

**Registration** matches the virtual world of images to the real world of the patient and operating room environment.⁴ Registration refers to the correlation between CT or fluoroscopic images and a fixed point on the patient’s anatomy. It relies on the relatively rigid characteristics of bone to allow tracking of one segment in relation to another. This permits a sensor outside the direct operative field to correlate with the bone segments of interest. This, however, becomes a limitation when the segments are not rigidly fixed such as between vertebral levels in the spine, free fragments following an osteotomy, or in the setting of an unreduced fracture.

**Connection** is the actual or virtual link between the patient and the CAOS system. The most common type of connection is via light emitting diode (LED) arrays (Flash-Point™ System: Image Guided Technologies, Boulder, CO) placed on the instruments, which provide better than 0.3 mm accuracy. Used with 2 or more optical sensors in the OR (Optotrak, Northern Digital Imaging, Waterloo, Ontario, Canada), this allows adequate triangulation to calculate a threedimensional (3D) localization. Combined with the data from the registration, these connections allow real time tracking of instrumentation with the patient’s anatomy. Accuracy ranges from 0.1 mm to 3.0 mm, depending upon specific technology used.⁵,⁶ A direct connection is also used with robotic arms to compensate instantly for relative motion between the bone and robotic arm, stopping the system if movement greater than 2 mm is detected.⁷

**Surgical navigation** is the intra-operative display of the operative field with the location of a probe or instrument overlaid onto any image such as fluoroscopic data, an MRI, or CAT scan.⁸

**Smart tools** are standard or customized orthopaedic instruments whose 3D characteristics have been taught.

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to the CAOS system to allow their display on a navigation system. This involves attaching a tracking array to the handle of an instrument to form a connection between the handle and the system. The working end of the instrument is then placed onto a known location, and a registration between the handle and working tip of the instrument is made, including the offset and orientation of the device. Additionally, the “direction” of an instrument such as a drill or osteotome can be input and displayed on screen.

Applications

Total Hip Replacement

CAOS and related systems are used for two main problems in the area of total hip arthroplasty. The first is the reduction of dislocation rates by modeling acetabular component orientation and then recreating a maximum primary arc of impingement-free motion. The second is the improvement of bone ingrowth of cementless femoral stems by accurately modeling femoral canal size and using a robotic arm to precisely machine the medullary cavity to the stem dimensions, thereby maximizing initial stability and contact area.

Impingement can cause acute hip dislocations, painful subluxations, and increased polyethylene wear. With early ceramic liner designs, impingement led to catastrophic failure. By altering the variables of neck offset, head neck ratio, and most importantly the anteversion and inclination of the cup, the surgeon can decrease primary impingement. He can also increase the primary arc of motion, as well as re-direct this primary arc to maximize the functional arc.

Using data from a fine cut CT scan of the patient’s pelvis and proximal femur, HipNav® (Center for Medical Robotics and Computer-Assisted Surgery at The Robotics Institute, Pittsburgh, PA, http://www.mrcas.ri.cmu.edu/projects/hipnav.html) creates a 3D model of the hip articulation. The surgeon then overlays a template of a chosen acetabular cup, stem and head/neck combination onto this model. A range of motion simulation is performed to determine the location and degrees of articulation prior to impingement between the neck, cup, trochanter, osteophytes or ileum. This information can be displayed as a table of numbers, a graph, or via a graphical simulation sequence.

Once in the operating room, the surgeon makes a standard approach to the hip, removes the femoral head and then performs a registration between the pre-operative CT scan, pre-operative plan and the current position of the acetabulum. Because the acetabular location is tracked by an LED array rigidly fixed to the ilium, any malpositioning due to patient size or movement of the pelvis within the lateral patient positioner will not affect the system’s accuracy. By attaching an LED array to the acetabular reamer, the surgeon creates a smart tool. He can then display in real-time the position and angulation of the cup relative to the pre-operative plan. This position can be displayed as a line drawing of the acetabulum with indicator marks to “steer” the surgeon to the planned position, much like an instrument approach in an airplane. The surgeon maintains control of the reamer at all times, and can alter the plan if bone quality is not as expected or for any other reason.

An LED array is then attached to the acetabular inserter, and again the position of the shell relative to the pelvis and the planned position are displayed. By moving his hand, the surgeon can view a simulation of the resulting primary arc of motion. After securely press-fitting the component, screws can be used if desired. The position can then be re-acquired to assess any motion during the screw insertion. The system can also be adapted to cemented cup orientation such as in a revision setting. The final position is recorded for later comparison to a clinical outcome research database. This allows recording of the component position far more accurately than “standardized” office radiographs.

To maximize bone ingrowth in a cementless femoral component requires good initial stability, with micromotion less than 150 µm, and a gap distance of less than 100 µm. Standard broaching can leave gaps of 1 to 3.5 mm between bone and implant, with only 21% of the prosthesis in initial direct contact. Using a 5-axis robotic manipulator arm, with a MIDAS REX (Dallas, TX) pneumatic high-speed burr to machine the femoral cavity, can improve the accuracy of this preparation. The ROBODOC® prepared cavity has a 40 to 50 micron cavity dimensional accuracy, with up to 96% contact, promoting initial stability as well as enhancing the potential for bone ingrowth.

Using fine cut CT data from the patient’s femur and the ORTHODOC® (Integrated Surgical Systems, Sacramento, CA) software program, a surgeon is able to place a 3D template of a chosen femoral component into the correct position in the medullary canal (using AP, lateral, and axial slice data). Once in the operating room, the surgeon performs a standard posterior approach. The acetabulum is prepared in the usual fashion; a neck cut is performed and a femoral fixator is applied. The system is then registered to the patient’s femoral position.

The sterile draped ROBODOC® arm is brought into the field and an additional feedback sensor is then attached to the femur. Once the accuracy of the system registration is re-confirmed, the robotic manipulator arm “machines” the femoral cavity to the desired dimensions. The surgeon holds an emergency stop button at all times. Any excess motion detected by the connection between the robotic arm and the femur will immediately stop the machine, and the system is re-registered. The surgeon may stop the arm at any time and re-register or complete the procedure using traditional hand broaches. Once the...
cavity has been prepared, the femoral component is placed into the cavity. CT scans performed on an average of 312 days postoperatively show a deviation in height of the implant between 0.4 and 0.1 mm and maximum angular deviation of 1 degree.\textsuperscript{10}

**CAOS in Total Knee Replacement Alignment**

One of the major goals of total knee replacement is to create a stable knee while recreating the patient’s mechanical axis to restore limb alignment.\textsuperscript{11} After exposure, a great percentage of time is spent developing a local reference system for alignment. This is usually based on the intra-medullary canal of the femur and/or tibia on which to reference further cuts. These intra-medullary anatomic axes are used as a surrogate for the patient’s mechanical axes which extend from the femoral head to the mid talus, passing thru the medial aspect of the plateau.\textsuperscript{12,13} Using the KneeNav\textsuperscript{®} system (The Robotics Institute, Pittsburgh, PA) can aid with this process. Attaching an LED array rigidly to a point on a patient’s ilium, femur, tibia, and ankle allows their position in space to be registered and tracked. To determine the center of the hip, a range of flexion, extension, abduction, adduction, and rotation is performed. This movement generates a cloud of points on a sphere. The center of the sphere (i.e., the femoral head) that created this array of points can then be input to within 1 mm.\textsuperscript{14} Similarly, the centers of knee and ankle motion can be calculated. This information is displayed as a line drawing of the patient’s current axes as well as an idealized mechanical axis in both the coronal and sagittal planes. By then tracking the position and orientation of a cutting guide, and overlaying this onto the line drawing, the surgeon can readily create or recreate the desired mechanical axis of each long bone. Once the trial implants have been placed, the desired alignment can be confirmed before placing the final components. Again, the precise intra-operative axis alignment can be recorded for comparison with later clinical and radiographic follow-up data for accurate outcomes analysis stratification.

The above system saves the surgeon from using intra-medullary guides, but still requires standard cutting blocks for the five distal femoral surfaces as well as the tibia. Combining the same alignment system with an intra-operative milling arm would allow precise bone surface preparation without as many unique steps. The ACROBOT: Active Constraint ROBOT (Mechatronics in medicine group, Imperial College, London, UK) is based on this principle.\textsuperscript{15} Alternatively, shapes other than the standard five surfaces could also be devised to further limit loss of bone stock, while improving contact area and implant stability. As surgeons and operating rooms become comfortable with the robotic milling capability, other indications for precise bone surface preparation based on either pre-operative CT data or intra-operative reference points will undoubtedly be developed.

**CAOS in Spine Surgery**

Pedicle screw placement is well suited to computer assistance, as the complex anatomy is not well visualized in either the AP or lateral planes.\textsuperscript{16} Errors in hardware placement can have devastating consequences.\textsuperscript{5}

One device that addresses this problem is the Stealth system (Medtronic Sofamor Danek, Minneapolis, MN). Pre-operative CT data is obtained for the levels of planned instrumentation. Intra-operatively, each vertebral segment is individually registered. Once registered, the system can act as a surgical navigator to show the precise location of a probe relative to the CT data. The system can simultaneously display the vertebral levels on both the AP and lateral planes. More powerfully, oblique sagittal images parallel to the plane of the pedicle, or any other reconstruction can also be displayed. By attaching an LED array to a drill, drill guide, hand probe, or other instrument, a smart tool is generated. Overlaying the drill orientation as well as trajectory onto images along the pedicle allows complex screw placement to be performed with increased confidence. By simultaneously viewing an axial cut to determine screw length without violating the anterior vertebral body\textsuperscript{16} as well as the generation of the “axis of the pedicle view,” the surgeon can precisely locate the starting point, orientation, and length for the screws.

The development of an intra-operative CT scanner could greatly simplify implementation of this system by eliminating the need for placement of tracking spheres prior to the planned CT scan. Alternatively, improved surface registration techniques\textsuperscript{4} could also eliminate the tracking spheres and the need for a repeat scan on the day of surgery.

**CAOS in Trauma and Osteotomies**

Intra-operative fluoroscopy is invaluable for many orthopaedic procedures. The ability to visualize hardware and bones in real-time without extensive surgical exposures has allowed the development of many percutaneous techniques such as slipped capital femoral epiphysis fixation, hip fracture care, external fixators, intra-medullary nails, safer pedicle screw placement, sacroiliac percutaneous stabilization, complex osteotomies and many others. However, images are generally limited to a single plane at a time. In order make a correction in another plane, or to switch to an alternative or orthogonal view, someone must move the machine. They must do so while maintaining the sterile surgical field, not move the surgeon or instruments, choose a field of view without radiopaque interference, and rapidly obtain the precise view desired. All this must be accomplished while the surgeon maintains the orientation in the prior plane while attempting correction in the new
plane. Additionally, each image exposes the patient and surgical team to ionizing radiation. While specialty devices for simultaneous orthogonal views exist, they are bulky and not applicable to generalized orthopaedic applications.

The FluoroNav™ system by (Medtronic Sofamor Danek, Memphis, TN) eliminates many of these limitations. When used as a surgical navigator for a complex peri-acetabular osteotomy, a tracking array is first attached to the bone of interest. A second array is fitted to the hospital’s existing C-Arm. Prior to beginning surgery, the technician or surgeon can obtain the precise views needed for later navigation such as combined inlet and Judet views for the Berne peri-acetabular osteotomy.17 Multiple images can be saved for later recall during navigation. The C-arm can then be removed from the operative field. The system records the 3D position of the machine and bone at the time of image acquisition, and can then overlay the position and orientation of a smart tool onto this display. The surgeon performs a standard approach, places a calibrated osteotome or probe against the pelvis and can view the instrument on any and all of the saved fluoroscopic images. This allows real time, multi-planar corrections without any additional radiation or C-arm positioning. As the operation proceeds, different views can be selected as appropriate. The registration data remains accurate as long as there is no relative movement between the array attachment site and the bone segment of interest. At any time the surgeon may bring the sterile covered C-arm into the field to obtain and save updated images. By attaching an array to the peri-acetabular fragment prior to completion of an osteotomy, the correction in position and orientation can be precisely tracked. This information can be compared to numbers from a pre-operative plan, and also be recorded for postoperative evaluation of clinical and radiographic outcome studies and surgical simulations.18

This system can also be used for situations where the pre-operative data for the Stealth system would no longer be valid. For example, a pre-operative CT of a sacroiliac (SI) dislocation would not help surgical guidance once an adequate reduction had been performed. By acquiring images in the operating room as the anatomy is manipulated, and then displaying multiple simultaneous views, this system can be invaluable for decreasing radiation exposure, and improving surgical training. It can help prevent joint penetration by showing multiple oblique views simultaneously.18

Summary
These are just a few representative applications of the synergistic use of computer and robotic technology assisting the orthopaedic surgeon. While the individual systems are certain to change over time, the basic principles of correlating radiographic and anatomic data through a registration process, and displaying additional instrument or implant information through smart tools and surgical navigation are certain to become an increasingly important aspect of joint arthroplasty, deformity correction, and spinal and trauma surgery.

Only the orthopaedic surgeon who clearly understands the goals, applications, and limitations of these systems can decide which are appropriate for his patients, his hospital, and his practice. Determining the cost and time benefits, both before and after an obligatory “learning curve” requires a complex interaction of capital investments, time savings, and outcome research on both safety and efficacy issues. The orthopaedist who understands and applies these technologies will help his patients to achieve the best possible care.


Products Discussed
1. ROBODOC® system (Integrated Surgical Systems, Sacramento, CA)
2. HipNav® (Center for Medical Robotics and Computer-Assisted Surgery at The Robotics Institute, Pittsburgh, PA) http://www.mrcas.ri.cmu.edu/projects/hipnav.html
3. Flash-Point™ system (Image Guided Technologies, Boulder, CO)
5. Optotrak®Optotrak (Northern Digital Imaging, Waterloo, Ontario, Canada)
6. Active Constraint ROBOT (Mechatronics in medicine group, Imperial College, London, UK)

References