An Integrated Approach to Medical Robotics and Computer Assisted Surgery in Orthopaedics

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Abstract

There is great potential for medical robotics to have a positive impact upon surgical techniques, particularly in orthopaedics. Joint replacement procedures occur frequently, are very expensive, and depend upon the accuracy and precision of surgical cuts to insure a successful clinical outcome. Robotic systems are emerging to address this need; however, there are still key components that are missing to insure the clinical utility of surgical robots in orthopaedics. The paper describes a more integrated approach to this task that includes: 1) biomechanics-based preoperative planning, 2) less traumatic surgical robotics techniques, and 3) standardized postoperative clinical tracking. The authors argue that such a system will improve current medical robotic systems and provide the long term feedback necessary to evaluate the clinical consequences of these systems. The paper concludes by outlining the ongoing work on this project, with an emphasis on biomechanics.

1 Introduction

Surgical practice, and orthopaedics in particular, presents excellent opportunities for robotic and computer-based technologies to improve clinical techniques. Procedures such as total joint replacements are performed in large volumes and at significant cost. Nearly 200,000 total hip replacements and 190,000 primary total knee replacements are performed in the U.S. each year [5] at a cost of greater than $15,000 each. The short and long term clinical success of these procedures is very dependant on the proper placement and fit of the implants within bony structures[4]. The clinical importance of precision and accuracy, along with the high volume of the surgical procedures, indicates that important contributions can be made by surgical robots and pre-operative planners that utilize computer simulations.

Given the potential contribution, it is not surprising that robotic surgical devices are beginning to emerge in orthopaedics. Several commercial systems exist which allow a surgeon to use a computer to pre-operatively plan the placement of an implant within a view of CT data. This plan can then be executed intraoperatively through a precise robotic device[8]. These systems are technical successes; however, there is potential to improve the clinical utility of such systems by improving preoperative planning capabilities, surgical execution techniques, and long term clinical feedback.

2 Problem Definition

There are several improvements that will help insure the clinical use of medical robotics and computer assisted systems within orthopaedics.

First, meaningful preoperative feedback must be provided to the surgeon through realistic surgical simulations. In traditional joint replacement surgeries, a surgeon makes many decisions intraoperatively, based upon the "feel" of the tools and years of experience. In robot-assisted surgery, the surgeon uses a computer to plan the surgery so there is no longer any intraoperative feedback that can used for guidance. The robot will accurately carry out a given surgical plan, but how will the surgeon decide what is an appropriate plan?

A surgical simulator that incorporates biomechanics-based analyses can do much to improve current preoperative planning and address this issue. Existing planners do allow the surgeon to template the implant based upon 3D geometry[1], but give no indication of the consequences of the proposed surgery on the initial stability of the system, the presence of implant-bone interface gaps, and the changes in the mechanical environment that are induced in the bone.

Little attention has been directed to providing the surgeon with such useful preoperative feedback. Without any biomechanical feedback, and with very little experience in the medical community at planning robot-assisted joint replacement procedures on a computer, it is very difficult to insure a successful surgical plan. The inclusion of biomechanical simulations would permit the surgeon to make appropriate changes in the surgical plan. This may include changing such parameters as the implant placement, specifics of the bone preparation, and type and size of the implant.

Ideally a surgeon would be able to create a preoperative plan that would be optimized for the particular geometry and bone density of an individual patient. Biomechanical analyses would provide the surgeon with feedback concerning the distribution of strain in the bone, and the amount of bone-implant contact for a given surgical plan. Biomechanical analyses should consider both the implantation process (for cementless components) as well as the long term bone remodeling effects due to joint loading and varying load transfer mechanisms. Such an approach would be a great enhancement over current capabilities and would provide the surgeon with some guidance as to the clinical significance of a proposed operation.

Second, improvements in the surgical robotic techniques will also enhance clinical utility. For example, new intraoperative registration methods are needed to allow "pinless" or "frameless" determination of the pose (position and orientation) of a bone with respect to a robot. Current approaches suffer from the use of surgically implanted fiducial frames or pins to register the bone intraoperatively. These markers are visible in medical images and are still attached to the patient at the time of surgery. By locating the markers intraoperative, a transformation between the reference frame of the preoperative plan and the reference frame of the actual patient can be made.

This technique exposes the patient to additional trauma and risk associated with the implantation of markers, and tends to lengthen the duration of the surgical procedure over standard surgical techniques.

New techniques are needed that use "surface-based" registration to determine the bone's pose. Such a technique would eliminate the need to implant pins, and instead rely on the intraoperative collection and processing of bone surface data to locate the bone accurately.

Finally, the clinical results must be quantitatively analyzed to help evaluate the success of robot-assisted procedures. There is a need to both predict the long term biologic response of clinical procedures, as well as to prospectively track the actual clinical results of all procedures. Due to the nature of joint replacement failures, clinical tracking will not be able to convincingly demonstrate the long term success of the procedure until at least 10 years in the future. However, without a method for obtaining valid data for comparisons, there may never be a valid method for judging how successful the planning and execution components have been.

Currently there is no nationally standardized software or methodology for accomplishing this task, although attempts have recently been made to define the information all surgeons should collect [3]. Clinical studies are often designed many years after the surgery and can vary greatly in the information collected. It is therefore difficult to compare results. A standardized approach would facilitate evaluation of the clinical results. In addition, technology assessment, including cost/benefit analyses, will need to be coupled with these clinical outcome studies.

3 Proposed Integrated Approach

For the potential of computer assisted surgery to be fully realized in orthopaedics, we believe that it is important that several component technologies are effectively integrated. As illustrated in Figure

1. An indication of relative bone density can also be displayed.

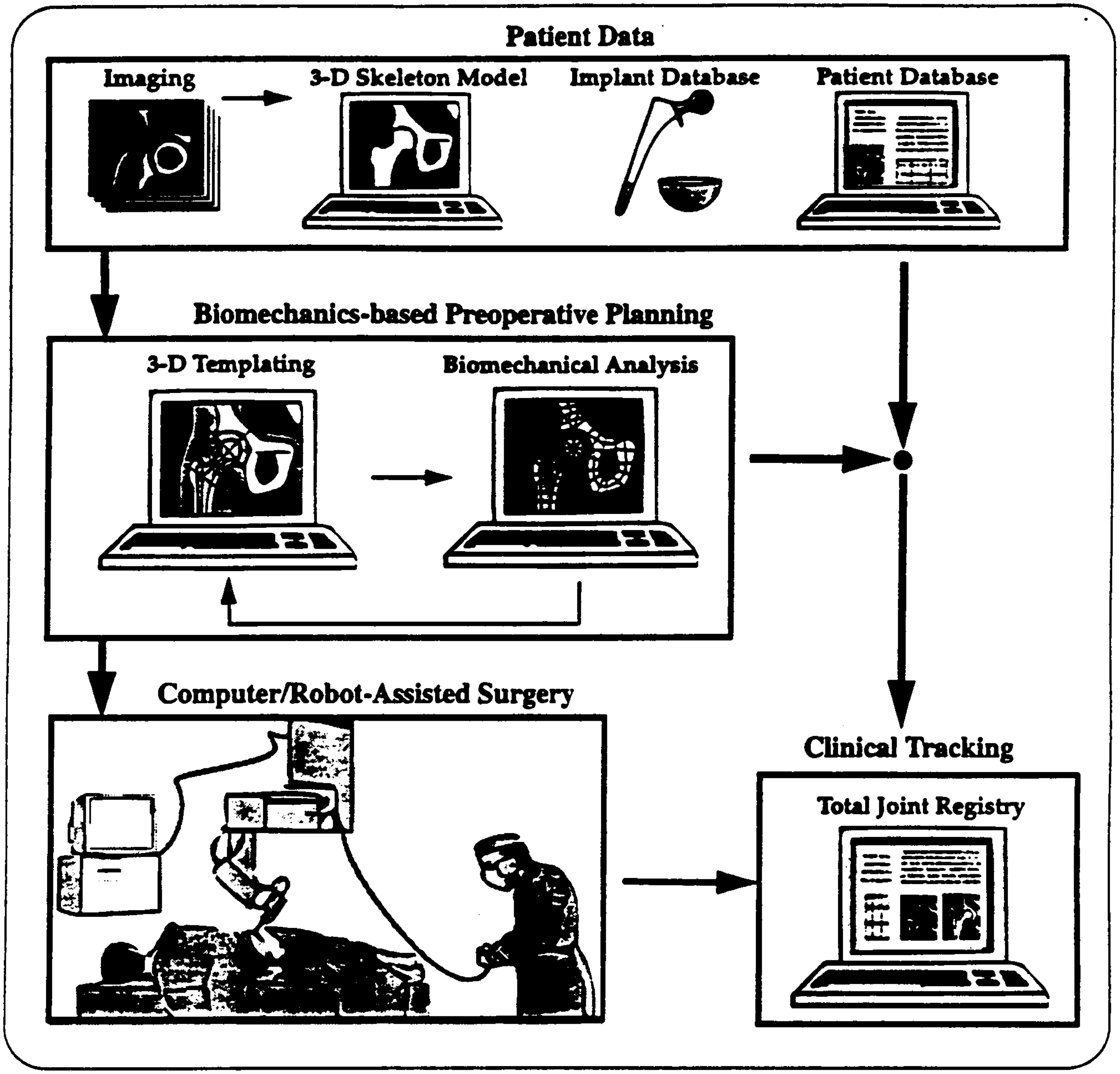

Figure 1. Component technologies combine to improve surgical technique.

1, these include patient data (medical imaging, implant databases, pre-operative patient evaluations) biomechanics-based preoperative planning, intraoperative robotic assistants, and long term clinical evaluations.

As described in Section 2, there is an individual need for improvements in each of the component areas: preoperative planners, surgical robots, and clinical tracking. There is additional gain to be had by effectively linking each of the components together.

A tight symbiotic relationship exists between surgical simulators and surgical robots. Improvements to either component greatly affects the clinical efficacy of the other.

Improved preoperative planning capabilities are of value even without a robot. It would be useful for a surgeon to realistically simulate a surgery beforehand to help determine what implant size to use.

However, without a robotic tool, there is no method for a surgeon to accurately implement a preoperative plan. For example, the simulation may help indicate an "optimal" bone cavity shape and implant location, but the surgeon will be unable to accurately perform this plan without a robotic device. In this manner, surgical robots actually improve the clinical usefulness of realistic surgical simulations.

Just as surgical robots impact the usefulness of preoperative planning, surgical simulations also increase the utility of surgical robots. A surgical robot is a useful tool for executing a surgical plan, but the outcome will only be as good as the original plan. For this reason, sophisticated preoperative planners are needed to fully develop the potential of robotics in orthopaedics.

Long term improvement in surgical technique will be expedited by careful quantitative clinical analysis. For this reason it is important to couple the surgical execution and planning with clinical outcome studies. Only by carefully tracking the clinical results of robotic (and traditional) procedures will it be possible to optimize the planning and surgical execution phases of these systems.

All of the pre-operative patient data and post-operative evaluations can be combined in a clinical database to allow long term evaluations of these new techniques. By combining engineering analysis, with robotic tools, and clinical databases, significant gains can be made in medical robotics.

4 Current Work

We currently are pursuing our vision of the integrated approach to medical robotics with research that focuses on total hip replacements. Work has focused on three component areas.

4.1 Biomechanics and Surgical Simulations

Our research concentrates on the finite element analyses of the implantation procedure for cementless acetabular and femoral components [1][4][6][9].Cementless procedures require tight coupling between the implant and bone. Our results have shown the importance of considering the implantation procedures and modeling friction effects with contact-coupled finite element models as illustrated in Figure 2.

Axisymmetric models have been examined to gain better understanding of forceful insertion of the implant into prepared bone cavity. These models

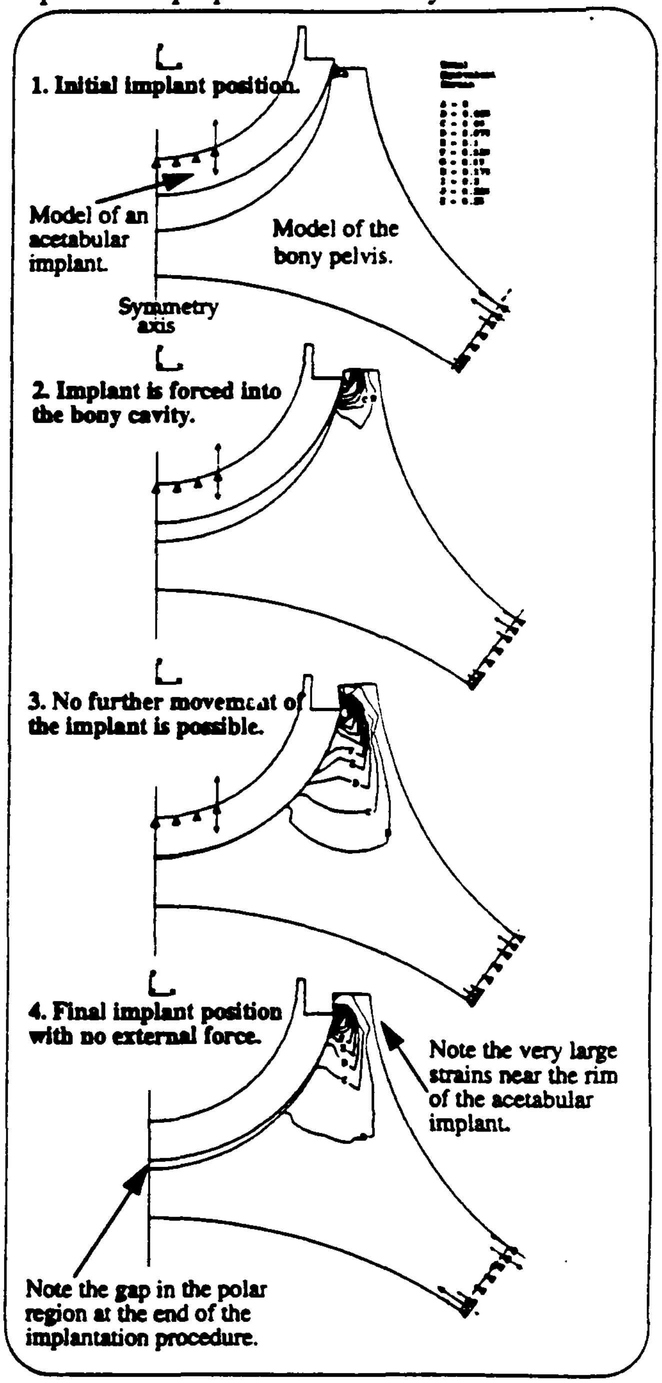

Figure 2. Axisymmetric model of the insertion of a cementless acetabular cup into a prepared acetabular cavity.

idealize the geometry of the implant and the bone by assuming axial symmetry, but they include most of the complex characteristics of the problem, such as frictional contact, large deformations, large strain and nonlinear material model. Further-more, they are convenient for parametric studies because they allow for the effects of any parameter (implant size, implant oversizing, material properties, friction, etc.) to be easily studied independently.

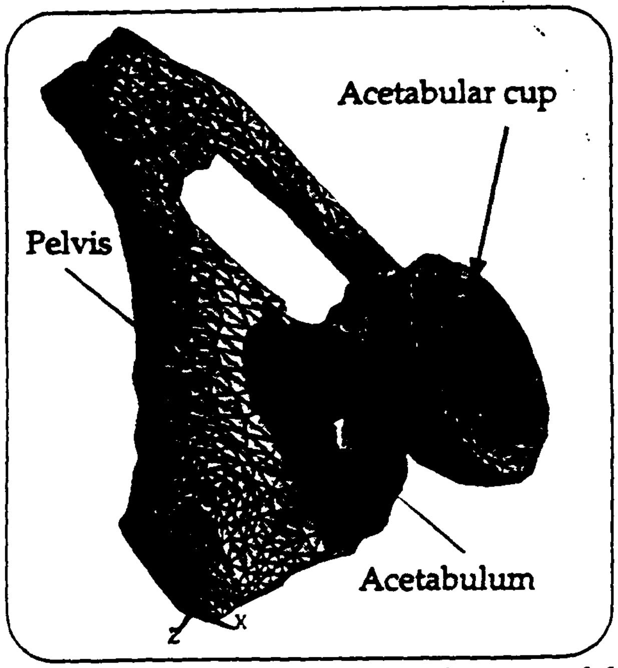

Figure 3. Three-dimensional finite element model of the acetabulum and cementless acetabular cup.

Currently, we are developing full three-dimensional models (of both the femur and acetabulum) based upon CT scan data. An example acetabular model is shown in Figure 3. We want to verify the results of the axisymmetric studies and to further the study of basic biomechanics phenomena associated with the press fit implant insertion. In addition, we are working toward developing of an automatized procedure that will include biomechanical simulation as a component of a preoperative surgical planner.

4.2 Surgical Robotics

We are investigating "frameless" registration methods for surgical robotics in orthopaedics. Our technique is initially aimed at the robotic preparation of the pelvis for the insertion of cementless acetabular components, but it is our goal to extend this approach to other procedures.

We are demonstrating cutting of accurate cavities in bone analogs using an industrial robot. Preoperative planning code is being developed with a data visualization package. Additional custom code has been written to create surfaces from the CT data. We are initially concentrating on acquiring intraoperative surface data using a digitizing probe to touch exposed surfaces of the bone; however, there is potential to expand this approach to many other data acquisition methods. Currently our research focuses upon integrating existing surface-based registration algorithms [9] into our overall system.

4.3 Clinical Database

We are addressing this component through the creation and use of a database we refer to as the "Total Joint Registry." This prospectively collected data will be used to examine the long term clinical success of joint replacement procedures. We use a research software package and a standardized, third-party data collection called "consensus information" and endorsed by the American Academy of Orthopaedic Surgeons, SICOT and The Hip Society. Patients have already enrolled in the registry and data is currently being collected. The incorporation of cost-benefit analysis and technology assessment into this process is a long term goal that may yield the ultimate measure of the impact on the health care system.

5. Conclusion and the Future

Our research endeavors to integrate all the components illustrated in Figure 1 into one complete system. We have made progress in many of the component technologies, but work remains to develop robust clinically practical tools and then to incorporate these technologies into an overall system. It is our belief that the development of the described approach will represent a significant improvement for the field of medical robotics. Our current work strives to make this goal a reality.

6. References

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