Pergamon

Comput. Biol. Med. Vol. 25, No. 2. pp. 183–191, 1995

0010-4825/95 $9.50 + 0.00

0010-4825(94)00043-3

BIOMECHANICS FOR PREOPERATIVE PLANNING AND SURGICAL SIMULATIONS IN ORTHOPAEDICS

ROBERT V. O'TOOLE III, BRANISLAV JARAMAZ, ANTHONY M. DIGIOIA III, CHRISTOPHER D. VISNIC and ROBERT H. REID

Center for Orthopaedic Research, Shadyside Medical Center. 5200 Centre Ave., Suite 309, Pittsburgh, PA 15232, U.S.A.

(*Received 21 September* 1994; *received for publication* 19 *October* 1994)

Abstract — Surgical simulations are particularly appropriate for the large volume and expense of joint replacement procedures in orthopaedics. A first generation surgical simulator has been developed to model the implantation procedure for cementless acetabular and femoral components in total hip replacement surgery. The simulator is based upon finite clement analysis and predicts the early postoperative mechanical environment that results from a proposed surgery. Since the short- and long-term clinical success of cementless hip replacement components is very dependent upon the initial mechanics of the bone–implant system, such simulations can help orthopaedic surgcons to develop better preoperative plans.

Surgical simulation Total hip replacement Orthopaedics
Biomechanics Preoperative planning Computer-assisted surgery

1. INTRODUCTION

Surgical training and practice present many opportunities for computer-generated simulations and environments to improve clinical techniques. Other researchers have already proposed the use of virtual environments to improve the practice of training surgcons [1–3]. There is additional clinical benefit to be gained from developing patient-specific computer simulations for exploring the biomechanical consequences of surgical options before making the first incision on the actual patient.

Procedures such as total joint replacements in orthopaedics are especially well suited for realistic surgical simulators. Joint replacements are expensive procedures and performed relatively frequently. Nearly 200 000 total hip replacements in the U.S. [4] and over 800 000 worldwide [5] are performed each year at significant expense. The substantial volume and cost of these procedures warrant efforts to optimize surgical results through computer simulations.

The short- and long-term clinical outcomes of a total joint replacement are very dependent upon the postoperative mechanical environment of the bone–implant system [6]. It is very difficult to generalize this environment because there is wide variation between patients. Such parameters as the bone geometry, the mechanical properties of the bone, the implant design and cutting system, and the nature of the clinical situation can vary widely. Furthermore, the specifics (such as fit. fill and micromotion) of the surgical implantation procedure can have a profound effect upon the initial biomechanics of the bone–implant system.

To develop a realistic mechanical simulation of a joint replacement procedure. it is therefore necessary to model both the surgical procedure and the mechanics of the resulting bone–implant system. Only through the creation of such biomechanics-based models can realistic surgical simulators be developed that will allow clinicians to explore and optimize the biomechanical consequences of a surgery in a computer environment before stepping into the operating room.

2. BACKGROUND

Total hip replacement involves the replacement of the body's defective joint with a new artificial joint. The new implant consists of an acetabular component (cup) and a femoral component (ball and stem). Currently in the U.S. almost all of the acetabular components and about half of the femoral components are affixed to the bone without using cement. This cementless technique relies on bone growing into a porous implant surface to achieve long-term stability. The initial stability is provided by "press-fitting" the component into an undersized cavity in the bone. Screws are also often used to provide additional stability for the cups.

The short- and long-term clinical success of the cementless procedure is very dependent on the proper placement and fit of the implants within the bone [7–10]. Too loose a fit and the implant may begin to migrate. Gaps as small as 0.25 mm can also prevent bone ingrowth [11, 12] and lessen implant stability. Conversely too tight a fit can induce large strains in the bone that lead to intraoperative fractures [13, 14]. Currently, hemispherical reamers are used to prepare the acetabulum (hip socket) and hand-held broaches are used to prepare the femur (thigh bone). Surgeons utilize their intraoperative experience *to* decide upon the amount of press-fit that is appropriate for a given patient.

New clinical robotic tools are beginning to emerge which provide the surgeon with a more accurate method for preparing the bone to implant cementless femoral components [15]. Robotic systems remove the inaccuracies of the current cutting tools. by allowing the surgeon to plan the procedure in a computer environment and then execute this plan with a precise robot. In addition to the Preoperative planner for the currently used robotic tool [16] other orthopaedic systems exist which allow medical imaging and implant data to be read in and manipulated [17, 18].

One weak link in current computer preoperative planners for orthopaedics is that no feedback is given to the surgeon concerning the biomechanical consequences of a proposed procedure. This capability is certainly important for hand-held procedures, but it is vital for emerging robotic procedures where the surgeon is given no feedback from the "feel" of the cutting tools during the surgery to help evaluate the proposed plan.

Although there have been many finite element models of implant systems, the literature presents relatively few biomechanical analyses of cementless hip replacement systems which examine the press-fit implantation procedure. Researchers tend to neglect the implantation procedure and begin their analysis with a "line-to-line" fit between the implant and the bone [19, 20]. This initial condition assumes that no significant assembly strains are created during the implantation procedure and that load can be transferred from the implant **to** the bone along the entire surface of the implant. In most cases, a realistic surgical simulator cannot utilize either of these assumptions with implants that utilize an initial press-fit to achieve the initial stability.

3. PROBLEM STATEMENT

The ideal simulator for total hip replacement should allow the surgeon to investigate the consequences of surgical options (specific manufacturer's implant designs, implant placement, implant size, amount of press-fit, etc.) before performing the operation. Such a simulator provides the surgeon with clinically meaningful feedback concerning the proposed surgery through such measures as the stress–strain distribution in the bone, the per cent surface contact between implant and bone, the force required to press-fit and dislodge the implant and other biomechanically relevant metrics.

A simulator which predicts the postoperative biomechanical environment, requires finite element analysis capabilities **because** of the complex, patient-specific nature of the hip replacement procedure. The bone–implant system exhibits highly nonlinear behavior with spatial and directional variations of material properties and geometry, a nonconservative implantation process, and nonlinear material properties (21,221. Such complexity insures that the analytical results are not always intuitive and can be difficult to generalize.

Surgical simulators should also allow any surgeon to evaluate the mechanical consequences of a procedure without requiring any particular expertise in computational mechanics. In keeping with this philosophy, emphasis must be placed upon developing a human computer interface that is simple to use for the surgeon.

The first of three primary technical hurdles in developing a simulator is the creation of the computational physical model. A balance must be struck between the accuracy of the simulation and the computational time required to analyze the model. Accurate **3D** finite element models can be generated from a patient's **CT** scan data [23]; however, the more degrees of freedom that are contained in these models the longer it will take to perform the analysis. Smaller idealized models can be used to speed the calculations but must not misrepresent the nature of the surgical procedure. As today's supercomputers become tomorrow's desktop machines this issue will lessen in importance.

Once the model has been created, the next technical task is the actual analysis of the surgical implantation procedure. The simulation should include the implantation procedure and examine the press-fit nature of the system which inserts an implant into a cavity that is smaller than its volume. By modelling this process, the simulation can examine such issues as the consequences of the amount of press-fit on the mechanical environment induced in the bone.

Finally, the simulation must be iterated in an attempt to optimize the mechanical outcome of the procedure. This procedure may initially occur by hand as a parametric study where a surgeon simply examines various surgical options. Ideally, a more automatic procedure would optimize the parameters of the procedure based upon an objective function. The parametric studies may help determine a reasonable objective function if combined with clinical outcome studies.

4. RESULTS

As a first step in developing a more realistic surgical simulator for total hip replacement. we have analyzed the implantation procedure for cementless acetabular and femoral implants. The implantation procedure was simulated through an incremental procedure. in which the implant is gradually driven toward its planned position in the bone. This mimics the surgeon inserting the implant into a prepared cavity in the bone. These simulations use idealized axisymmetric finite element models, as shown in Fig. 1(a and b). to describe the implantation-related mechanical phenomena. The simulation includes large displacement elements with contact coupling and nonlinear material properties to capture the complex nature of the bone–implant interface. The details of the biomechanics models are described elsewhere [24–26].

The finite element models are the first to allow a press fit implantation procedure to be simulated. For example, Fig. 2 shows a simulation of the implantation of an acetabular cup into the acetabulum. The implant is forcefully driven into place and then comes to rest at a final position (with no external forces or joint loads applied), just as it does in the clinical implantation. The figure shows radial strains (on the left) and hoop strains (on the right) in the bone for four steps of the implantation procedure. This particular simulation predicts significant strains in the bone and a large gap between the cup and the bone in the polar region. Such analyses can yield valuable information concerning the immediate postoperative state of the bone–implant systems.

Our initial parametric studies using these simulations have predicted the existence of substantial assembly strains in the bone that are due to the implantation procedure prior to the application of joint forces [24, 25]. These strains can lead to fractures of the bone if the yield strength in the cortical region is exceeded. Furthermore, gaps of various magnitudes have been demonstrated to exist in the polar region of the acetabular cups. These gaps inhibit bone ingrowth and substantially change the load transfer mechanism from that of the natural hip [26]. Confidence in the validity of the simulations has been bolstered by cadaver studies that have verified the existence of fractures and gaps in the pelvis as predicted by the simulations [14].

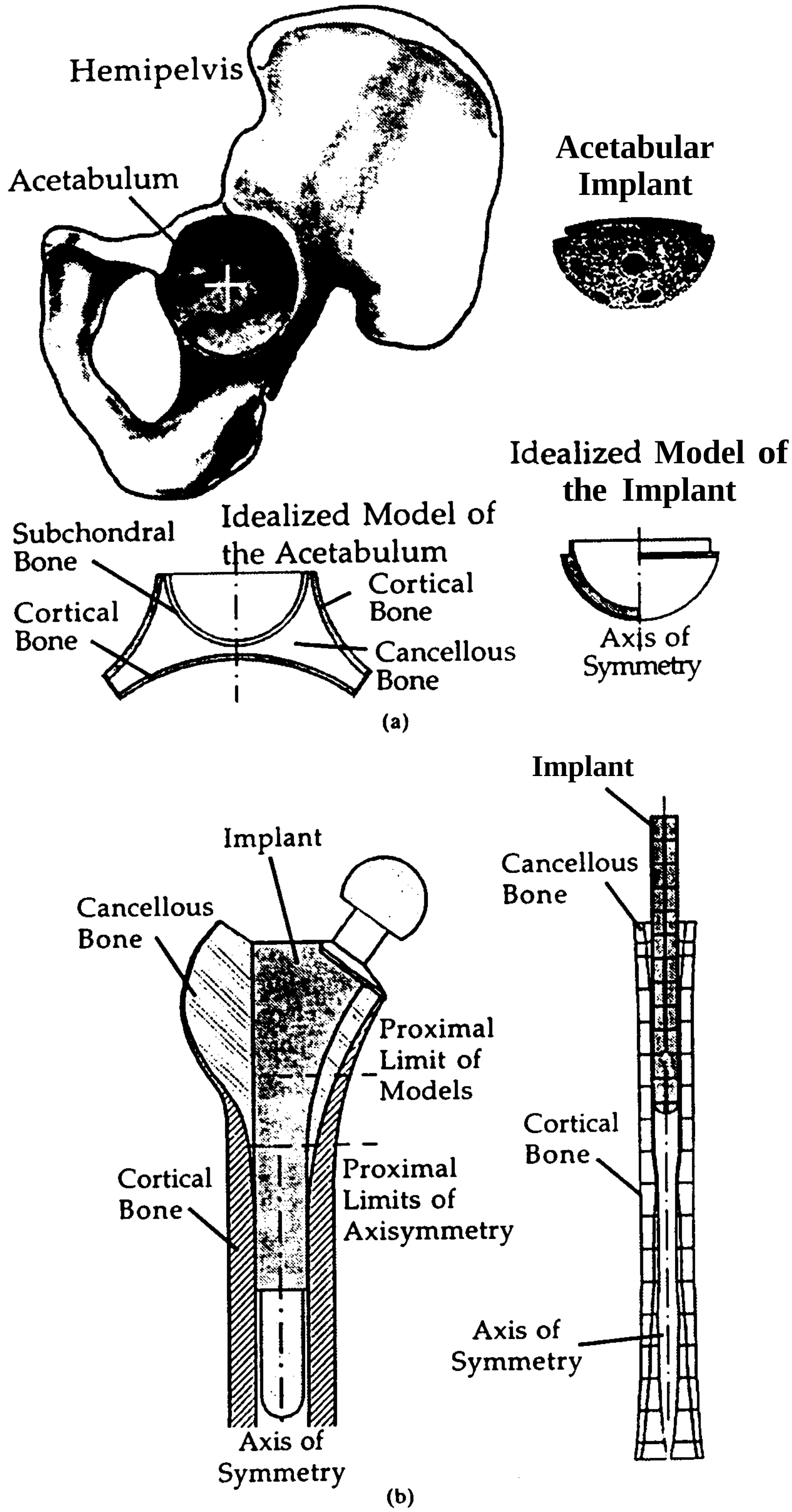


Fig. 1. Real and idealized geometries of (a) acetabulum and implant; and (b) femur and femoral implant.

These same models that were used to reach the above conclusions form the basis for a surgical simulator. The surgeon is able to select a specific implant, an implant size, the

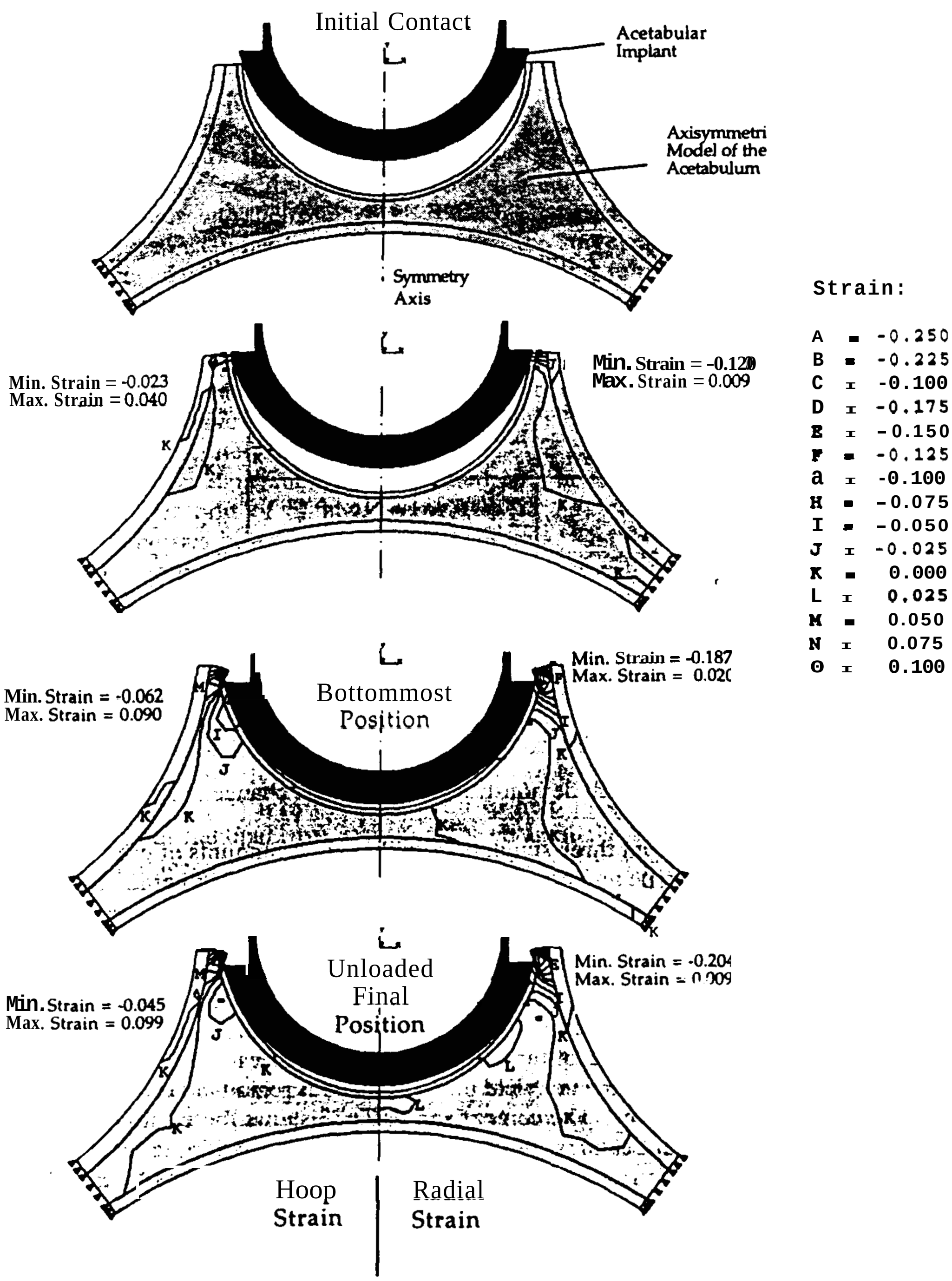
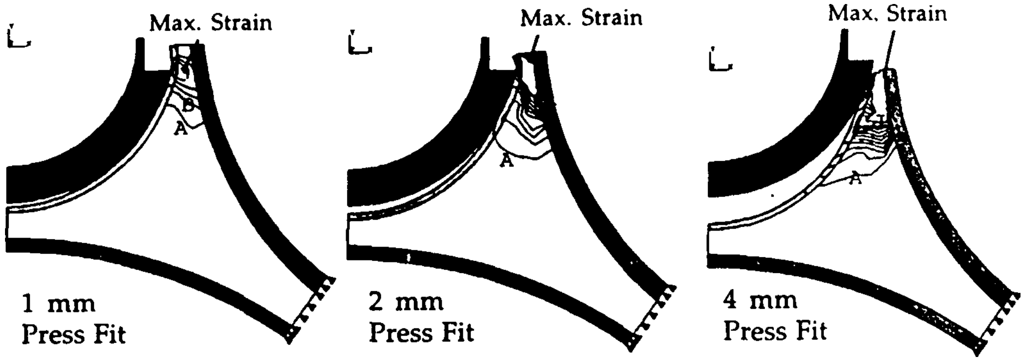


Fig. 2. Example surgical simulation for the implantation of an acetabular cup into the acetabulum in total hip replacement surgery. The implant is driven into place and comes to rest at a final position with no external forces. The figure shows radial strains (on the left) and hoop strains (on the right) in the hone at each of four steps of the implantation procedure.

amount of press-fit, and the appropriate size of the bone. These parameters can be selected for both the femur and the acetabulum and a simulation performed.

The output of the acetabular simulations yield such parameters as the stress/strain fields in the bone, the percent contact between bone and implant. the size of gaps between the implant and the bone in the polar region, and indicates if the limit strength in the cortical bone has been exceeded (which indicates cracking of the bone). An



	Area of Yield in Cancellous Bone	Area of Implant/ Bone Contact	Radial Interfacia Force	Exceeded Limit Strain in Cortical Bone
1 mm Press Fit	0.54 cm^2	24%	3.5 kN	No
2 mm Press Fit	1.15 cm^2	21%	4.8 kN	No
4 mm Press Fit	1.43 cm^2	9%	4.3 kN	No

Total Equivalent Strain:

A = 0.02
B = 0.04
C = 0.06
D = 0.08
E = 0.10

J = 0.20
K = 0.22

Fig. 3. Output of the surgical simulator comparing 1, 2, and 4 mm press fit for the same size **bone and implant.**

animation is also produced which demonstrates the dynamic change in stress state as the implant is pressed into place.

Figure 3 shows output from three simulations with various amounts of press fit for the same acetabular implant type and bone size. There are four feedback parameters in Fig. 3: the area of yield in the cancellous bone, the per cent surface contact between implant and bone, the radial force the bone transmits to the implant. and whether the ultimate yield limit in the cortical bone has been exceeded. Yield in the cortical region is unacceptable as it indicates bone cracking. Increasing the contact area is beneficial as it promotes bone ingrowth and therefore long term implant stability. The force required to dislodge the implant is a function of the radial force, so this gives some indication of the implant stability. The relative area of yield in the cancellous region indicates the amount of stress placed upon the bone. The comparison in Fig. 3 shows the trade-offs between these metrics as the amount of press fit increases.

The femoral simulation presents the same information to the user as the acetabular simulation, except that the percent contact area is not included. Since the current models are idealized as axisymmetric, the femoral bone and implant are in contact all the way along the periphery. This is not the case for the acetabular component, which bottoms out and only allows a certain region of the implant to contact the bone. For future 3D models, however, per cent surface contact will be an important measure for both implants.

5. DISCUSSION

As discussed above, this project is a first-generation surgical simulator and as such it uses a very crude human–computer interface. Surgeons are required to be quite familiar with computers, stress analysis, and computational mechanics to interpret the results of the studies. This is a limitation of the current system as any surgical simulator must be easy for a physician to use and to interpret the clinical significance of the results. Work is needed to produce a system that performs well in this respect.

A second limitation is the amount of time required to run each simulation. Each of the example simulations shown above required approximately 1 day of run-time and human interaction to generate results on a DEC 5000/240 using ANSYS 5.0 (Swanson Analysis Systems Inc., Houston, PA) as the finite element analysis software. The current hardware precludes the surgeon from interacting in real-time with the simulation.

The limitations in the current simulation result in the system being used vicariously by surgeons. The surgeon describes the desired simulations to an engineer who returns several days later with the results. This is useful, but the system may be more practical if a surgeon could examine the consequences of the surgery in real-time. With the ever-increasing speed of workstations this should be possible in the future. An improved user interface should also allow direct interaction between any surgeon and the surgical simulator.

We are currently developing an automatized surgical simulation from patient-specific full-scale biomechanical models that are based upon CT scan data. The goals of this approach are to have a more accurate computational model and to develop a robust algorithm to generate a finite element mesh. We have successfully made the bridge between CT scan data and geometric models. The remaining technical issue is the automatic generation of a finite element mesh and the appropriate assignment of material properties based upon the CT scan data. The raw scan data and the elastic properties of the bone will be stochastically related, so a probabilistic approach to determine the properties from the data may be most appropriate. This would allow a simulator that could show not only areas where the bone will crack or yield, but also the associated probability of such an event.

Ultimately, the surgical simulation might be improved if the analysis suggested a clinical plan automatically after examining the surgeon-selected options. This capability is years in the future as it is very uncertain what objective function should be maximized to help model a clinically successful surgery. A shorter term goal is the inclusion of bone remodelling work [27] into the simulation to help predict the long-term remodelling consequences of the operative procedure. Such an analysis may give valuable insight to the surgeon concerning the likely mechanical results of a surgery 10 years into the future.

6. CONCLUSION

Surgical simulators have great potential to improve preoperative planning capabilities for total hip replacement surgery. This potential will only be realized if the simulators realistically model the mechanics of the procedure. This work presents a first-generation surgical simulation for total hip replacement that utilizes computational mechanics to provide a more realistic prediction of the mechanical consequences of the surgery. Although there are limitations of the current approach, this is a first step towards a surgical simulator that allows the orthopaedist to explore the biomechanical consequences of a proposed surgery. Surgical simulators that incorporate biomechanical modelling have potential to improve the clinical outcomes of total hip replacement surgeries by improving surgeons' preoperative planning capabilities.

7. SUMMARY

A first-generation surgical simulator is described for cementless total hip replacement in orthopaedics. This simulator is based upon finite element analyses that allow the implantation process to be simulated realistically. The surgeon is able to investigate the consequences of variations in implant type, implant style. size of the bone cavity, and size of the patient's bone. The simulation presents the results in the form of stress–strain distributions in the bone. per cent surface contact between the implant and the bone, and the radial force that can be correlated with initial implant stability.

Limitations of the current simulator involve the human computer interface and the speed of the process. The interface requires significant computer literacy and is therefore not yet appropriate for the typical surgeon. Additionally, the simulations take in the order of one day to run using current hardware. Work is underway to improve the interface. and new generations of computer hardware should reduce the simulation time so that it may be run in real time in the not too distant future.

This work is a first step in producing a preoperative planner for orthopaedics that provides the surgeon with clinically meaningful feedback. This biomechanical feedback can help guide the surgeon to plan a surgery that is best for the patient.

Acknowledgements—This work was partially supported hy the Competitive Rcscarch Fund at Shadyside Hospital and the Albert B. Fcrguson Jr. Orthopaedic Research Foundation.

REFERENCES

1. R. M. Satava, The role of virtual reality in medicine of the 21st century, *Virtual Reality Syst.* **2**, 64–67 (1993).
2. A. C. M. Dumay. Cyhcrsurgcry, *Proceedings of Medicine Meets Virtual Reality II*, 42–44. Aligned Management Associates, San Diego (1994).
3. R. B. Loftin, D. Ota, T. Saito and M. Voss, A virtual cnvironmcnt for laparascopic surgical training, *Proceedings of Medicine Meer Virtual Reality. II*, 121–123. Aligned Management Associates, San Diego (1994).
4. E. J. Graves, 1988 Summary: national hospital discharge survey, Advance data from vital health and statistics, *National Center for Health Statistics*, p. 185, Hyattsvillc, MD (1990).
5. H. Malchau, P. Herberts, L. Ahnfelt and O. Johncll, Prognosis of total hip rcplaccmcnt. *Scientific Exhibition America Academy of Orthopedic Surgeons.* p. 61. Fchruary (1993).
6. V. C. Mow and W. C. Hayes, *Basic Orthopaedic Biomechanics,* pp. 375–380. Kavcn Press, New York (1991).
7. J. D. Bohyn and C. A. Engh. Human histology of bone-porous metal implant interface. *Orthopaedics* **7**. 1410–1421 (1984).
8. W. H. Harris and M. Jasty. Bone ingrowth into porous coated canine acetabular replacements: the effect of pore size, apposition. and dislocation. *Hip,* pp. 214–234, Moshy. St Louis (1985).
9. P. M. Sandborn, S. D. Cook. W. P. Spires and M. A. Kcstcr. Tissue response to porous-coated implants lacking initial bone apposition, *1. Arthroplasty* **3**, 337–346 (1988).
10. K. A. Thomas, S. D. Cook. K. L. Thomas and R. J. Hadad, Tissue growth into retrieved noncemented human hip and knee components. *Proceedings of the 5th Southern Biomedical Engineering Conference.* Pergamon Press, New York (1986).
11. R. D. Bloebaum, D. M. Rhodes, M. H. Rubman and A. A. Hoffman. Bilateral tibial component of different cementless designs and materials: microradiographic backscattered imaging. and histologic analysis. *Clin. Orthop.* **268**, 179–187 (1991).
12. J. T. Schwartz. C. A. Engh. M. R. Forte, Y. Kukita and S. K. Grandia, Evaluation of Initial surface apposition in porous-coated acetabular components. *1. clin. Orthop. Rel. Res.* **293**, 174–187 (1993).
13. R. H. Fityerald, G. W. Bringley and B. F. Kavanagh, The uncemented total hip arthroplasty: intraoperative femoral fractures, *Clin. Orthop.* **235**, 61–66 (1988).
14. T. Brown. Y. Kim. J. Callaghan and P. Ahn. Factors influencing acetabular fracture during insertion of oversized .hemispherical components, *40th Annual Orthopaedic Research Society Conference in New Orleans* (1994).
15. H. Paul. W. L. Bargar. B. Mittlestadt, B. Musits. R. H. Taylor. P. Kanzanzides. J. Zuhars. B. Williamson and W. Hanson, Development of a surgical robot for cementless total hip arthroplasty, *Clin. Orthop.* **285**, 57–66 (1992).
16. R. H. Taylor. H. Paul. B. Mittlestadt. W. Hanson. P. Kanzanzides. J. Zuhars. E. Glassman, B. L. Musits, W. Williamson and W. L. Bargar. An image-directed robotic system for precise orthopaedic surgery, *IEEE Engng Biol. Soc.* **12**, 1928–1930 (1990).
17. L. Kcmpfer, Medical imaging and CAD unit. *Comput. Aided Engng* **13**, 20 (1994).
18. T. Yasuda. X. Zhou. S. Yokoi. J-i. Toriwaki and R-i. Izumida, Computer-aided Surgical Simulation System for Hip Joint Plastic Surgery, Computers in Biomedicine: *Proceedings of the First International Conference.* South Hampton, UK, Sept 1991, Computational Mechanics Publishing, Boston, MA, pp. 271–281 (1991)
19. D. J. Rappaport. D. R. Carter and D. J. Schurman, Contact finite element stress analysis of porous ingrowth acetabular cup implantation, ingrowth. and loosening. *J. orthop. Res.* **5**, 548–561 (1987).
20. D. R. Pedersen, R. D. Crowninshield, R. A. Brand and R. C. Johnston, An axisymmetric model of acetabular components in total hip arthroplasty, *1. Biomech.* **15**, 305–315 (1981).
21. A. L. Yettram, Effect of interface conditions on the behavior of a Freeman hip endoprosthesis, *1. biomed. Engng* **11**, 520–524 (1989).
22. W. C. Hayes and V. C. Mow, *Basic Orthopaedic Biomechanics,* pp. 419–437. Raven Press, New York (1991).
23. Y. K. Kang, H. C. Park, Y. Youm, I. K. Lee. M. H. Ahn and J. C. Ihn, Three dimensional shape reconstruction and finite element analysis of femur before and after the cementless type of total hip replacement, *J. biomed. Engng* 15.497 (1993).
24. C. D. Visnic, Mechanical consequences of press fitting an uncemented acetabular implant in total hip replacement. Master's Thesis, Carnegie Mellon University, Pittsburgh, PA (1994).
25. C. D. Visnic. A. M. Digioia III, B. Jaramaz and O. Ghattas, Contact-coupled axisyrnmetric model of a cementless acetabular implant, *Proceedings of the 6ih International Ansys Conference & Exhibition*, Pittsburgh, PA. May. Swanson Analysis, Houston, PA (1994).

26. C. D. Visnic, R, H. Reid. A. M. DiGioia III, B. Jaramaz and O. Ghattas. Finite element pre-operative simulation of cementless hip replacement. *Proceedings of the 1994 Winter Simulation Conference.* Lake Buena Vista, FL, December. Braun-Brumfield, Ann Arbor, MI (1994).
27. D. R. Carter and N. J. Giori, Effect of mechanical stress on tissue differentiation in the bony implant bed, *The Bone–Material Interface*, pp. 367–379. University of Toronto Press. Toronto (1991).

About the Author—ROBERT O'TOOLE received his B.S. in Mechanical Engineering in 1991 from Carnegie Mellon University. After spending one year in CMU's Fifth Year Scholar program. he completed his M.S. in Mechanical Engineering at Stanford University in 1993. He currently works at the Center for Orthopaedic Research. Shadyside Medical Center and has an appointment with the Robotics Institute within Carnegie Mellon University.

About the Author—BRANISLAV JARAMAZ received his Dipl. Ing. in Civil Engineering in 1979 and a M.S. in Computational Mechanics in 1987 both from the University of Split. He obtained his Ph.D. degree in Civil Engineering/Computational Mechanics from Carnegie Mellon University in 1992. Dr Jaramaz currently works at the Center for Orthopaedic Research, Shadyside Medical Center and is a Visiting Scientist at Carnegie Mellon University's Robotics Institute.

About the Author—ANTHONY DIGIOIA earned his M.D. degree from Harvard Medical School in 1986. He completed his medical training in Orthopaedic Surgery at the University of Pittsburgh Medical Center from 1986 to 1991, and completed a fellowship in Adult Reconstructive Surgery at Massachusetts General Hospital in 1992. Dr DiGioia is currently the Director of the Center for Orthopaedic Research at the Shadyside Medical Center and a practising orthopaedic surgeon. He also serves as co-director for the Center for Medical Robotics and Computer Assisted Surgery within the Robotics Institute at Carnegie Mellon University.

About the Author—CHRISTOPHER VISNIC obtained his B.S. in 1992 in Civil Engineering and his M.S. in 1994 in Computational Mechanics, both from Carnegie Mellon University. He is continuing his research at the Center for Orthopaedic Research, Shadyside Medical Center while preparing for medical school.

About the Author—ROBERT REID received his B.S. in Civil Engineering from University of Pittsburgh. and his M.S. from the Illinois Institute of Technology. He is a Ph.D. candidate in Computational Mechanics from Carnegie Mellon University.