Minimally invasive 3D data registration in computer and robot assisted total knee arthroplasty

P. F. La Palombara M. Fadda S. Martelli M. Marcacci
Laboratorio di Biomeccanica, Istituti Ortopedici Rizzoli, via di Barbiano 1/10, 40136 Bologna, Italy

Abstract—Computer and robot assisted surgery is concerned with the improvements achievable by using computer methods and robotic devices to plan and execute surgical interventions. The registration of different coordinate frames, often achieved through the matching of 3D data sets, represents a crucial step connecting planning and execution. Orthopaedic surgery already features a number of functioning applications which include registration routines relying on presurgically implanted fiducial markers. Replacing such invasive routines with non-fiducial registration procedures is regarded as a necessary step towards a minimisation of surgical invasiveness. A minimally invasive registration technique based on the iterative closest point algorithm is presented and conceived for a specific computer and robot assisted orthopaedic reconstructive intervention, namely total knee arthroplasty. The whole surgical protocol is examined in detail and the experimental results, relative to tests performed on synthetic and animal specimens, are thoroughly reported and discussed. The authors indicate that the proposed registration approach is well-suited for the relevant application and appropriate for in vivo testing.

Keywords—Registration, Iterative closest point, Computer assisted surgery, Total knee arthroplasty, Joint replacement


1 Introduction

Computer assisted surgery (CAS) is becoming a widely popular technology and is now leaving laboratories and universities and entering surgical rooms. The application of computer techniques in the simulation, planning and execution of surgical interventions, aimed at increasing the rate of surgical success, is CAS’s primary target.

The advantages of CAS systems are widely recognised and orthopaedic surgery, in particular, can already feature a number of operative implementations. This is mostly due to a compelling need for high geometric accuracies and to some coexisting inherent characteristics of the skeletal system such as relative rigidity and fairly differentiated visualisation in standard diagnostic imaging technologies. Computer and robot assisted joint replacements (Ho et al., 1995; Kazanzides et al., 1995), osteotomies (Caponetti and Fanelli, 1993), screw and nail placements (Lavallée et al., 1994; Nolte et al., 1994; 1995; Viant et al., 1995) and ligament reconstructions (Ort i et al., 1993) have been investigated in recent years. Our group has already contributed to the ongoing debate by submitting a computer integrated approach to total knee arthroplasty (TKA) (Marcacci et al., 1995).

The implant of knee prostheses, specifically TKA, is among the surgical procedures which would principally benefit from a computer integrated approach. A computer based planning system reduces the number of decisions the surgeon has to take intraoperatively by enabling them to be taken preoperatively. As a consequence, it ensures a larger degree of safety in the surgical procedure and a reduction of the intraoperative time (Rand, 1993). Conversely, robotic assistance during the execution phase is a means for improving the absolute accuracy in positioning and guiding surgical tools. The latter is an important point of importance for implant fixation and long-term stability in TKA (Peters and Rosenberg, 1994).

Successful implementation of CAS protocols requires a coherent integration of spatial data relative to a broad variety of imaging, sensing and actuating devices, each with its own coordinate system. This is why an accurate estimation of the geometric relationships between different coordinate frames and 3D data sets, normally referred to as ‘registration,’ plays a crucial role in virtually all CAS applications. In computer and robot assisted TKA (CRA-TKA) the registration step is a critical link between the planning and execution phases, because attainment of the same high geometric accuracy achieved during preoperative planning in the actual surgical execution is extremely important.

Most of the current high accuracy protocols employ artificial markers—fiducials—which need to be implanted before surgery. The fiducials are both identifiable in the preoperative images and accessible intrasurgically by means of a position transducer. Registration is then generally performed through fast and robust point-to-point matching algorithms (Taylor et al., 1994; Mittelstadt et al., 1995; Kienzle et al., 1995a; 1995b; Lea et al., 1995). Following a widespread trend towards a reduction in surgical invasiveness, intensive investigation of non-fiducial registration techniques is currently in progress. Such effort concerns computer assisted orthopaedic surgery as well as other related fields (Simon et al., 1995a;...
The aim of this study is to present a non-fiducial, minimally invasive registration method based on the Iterative Closest Point (ICP) algorithm (BESL and MCKAY, 1992; ZHANG, 1994) within the framework of a CRA-TKA procedure. The distinctive role played by the registration phase and its synergism with the other steps of the relevant protocol are taken into account. This is to provide a comprehensive outlook on the specific CAS application analysed and to stress its influence over the material and methodological constraints that the registration routine must comply with. Though widely adopted, non-fiducial registration techniques are, in fact, highly application-dependent. No implementation concerning TKA has yet been divulged and very few results on 'close-to-reality' testing have been disclosed regarding the whole field of computer assisted orthopaedic surgery. In this paper, particular emphasis is given to the dependence of the routine's accuracy standard on input data features. This issue has already been addressed by SIMON et al. (1995a) in their work on registration techniques for computer assisted total hip replacement. We have tried, however, to include the physical constraints which existed during an actual intervention in the laboratory trials that we performed on synthetic and animal specimens. This element is, in our opinion, very important to increase the reliability of the reported experimental results and assess the actual applicability of the described protocol.

2 System overview

TKA is the principal reconstructive procedure for patients suffering from severe knee arthritis. Progress in implant design and surgical technique lead to success rates close to 85% (CALLAHAN et al., 1994). During the intervention, the articular surfaces of the femur and tibia are replaced with two prosthetic components. Alignment errors of such components, particularly those exceeding 1° in orientation or 1 mm in position, can severely affect the kinematic and kinetic functionality of the operated limb and might eventually lead to implant failure. Hence the usefulness of careful presurgical planning (RAND, 1993; BARNES et al., 1993). A robotic execution of the planned bone resections can ensure further improvement to the procedure because of the higher intrinsic geometric accuracy of a robot as compared to that of a human operator. Moreover, recent studies on bone remodelling following cementless joint replacement show that the adhesion of the prosthetic components due to bone ingrowth, which is a key condition for surgical success, is strongly related to the structural features of the bone/prosthesis interface (PETERS and ROSENBERG, 1994; CARLSSON et al., 1988). Also from this viewpoint a robotic execution could be advantageous.

Our system for CRA-TKA is composed of a surgical planning toolbox, a robotic assistant and a registration protocol, which will be described in detail in the following paragraphs.

The planning toolbox runs on an Indigo2 workstation®. It incorporates OpenGL-based graphic tools, uses a 3D model of the patient's joint, as reconstructed from computed tomography (CT) scans, and allows the surgeon to:
- analyse the patient's anatomy and the pathological alterations;
- determine the geometric and mechanical characteristics of the subject's limb interactively with the help of computational and graphic facilities;
- choose the most appropriate model and size of prosthesis;
- assess the best placement for the femoral and tibial prosthetic components based on the above mentioned anatomical, geometric and mechanical features;
- simulate bone resections and prosthetic implantation so as to check the compliance with biomechanical constraints;
- include circumstantial refinements in the surgical approach or decide to change some of the components.

The planning system yields as output a spatial dataset describing the resection planes—five relative to the femur and one to the tibia—in the CT reference frame.

Laboratory tests on robotic bone cutting have been performed using a Puma 560 industrial robot® equipped with a force sensor for manual guidance, safety system™ and an air powered motor with milling tools®. Resections were executed through incremental steps along the axial direction of the bone. Bone slices 2–3 mm thick were removed at each crossing of the milling tool until the whole of the planned surface was covered. As far as the geometric characteristics of the resected bony surfaces were concerned, robotic machining gave better results than manual cutting (FADDA et al., 1996). Design and manufacture of a new dedicated custom-built robot is in progress.

Once the intervention has been carefully planned, since the robotic system ensures a high standard of intrinsic preciseness and reliability, the outcome of the entire procedure depends on how accurately the robot will execute the planned tasks. This strongly depends on how accurately the reference frames of the robot, preoperative model and intraoperative patient anatomy can be registered with one another. In the past, this task was accomplished by locating preoperatively implanted artificial markers with the robot's end-effector. The detection of such markers in the preoperative environment also permitted the computation of the transformation between the two reference systems with a satisfying degree of accuracy. The new, less invasive technique described below, tries to eliminate the need for artificial marker implantation while retaining the good accuracy level of the previous approach.

3 Registration protocol: theory and implementation

Broadly speaking, registration is the assessment of the affine transformations linking different coordinate frames. In fact, the problem is often stated in terms of the matching of spatial data sets embedded in the relevant frames. Non-fiducial registration techniques generally exploit the geometric characteristics of such data sets in order to find a correlation between them, as pointed out in the extensive review published by LAVALLÉE (1995).

The basis of our registration protocol is the ICP algorithm (BESL and MCKAY, 1992; ZHANG, 1994), which provides a simple approach to the solution of the two point sets matching problem. Neither point-to-point correspondence nor extraction of any specific geometric feature—axes, curves, ridges, etc.—is required. Although the algorithm was not expressly proposed for biomedical applications, several research groups...