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Robotic surgery: from autonomous systems to intelligent tools

Ferdinando Rodriguez y Baena†* and Brian Davies‡

†*The Mechatronics in Medicine Laboratory, Department of Mechanical Engineering, Imperial College, Exhibition Road, London, SW7 2AZ, UK*
‡*The Italian Institute of Technology (Fondazione Istituto Italiano di Tecnologia), Via Morego 16163 Genoa, Italy*

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SUMMARY
A brief history of robotic surgery is provided, which describes the transition from autonomous robots to hands-on systems that are under the direct control of the surgeon. An example of the latter is the Acrobot (for active-constraint robot) system used in orthopaedics, whilst soft-tissue surgery is illustrated by the daVinci telemanipulator system. Non-technological aspects of robotic surgery have often been a major impediment to their widespread clinical use. These are discussed in detail, together with the role of navigation systems, which are considered a major competitor to surgical robots. A detailed description is then given of a registration method for robots to achieve improved accuracy. Registration is a major source of error in robotic surgery, particularly in orthopaedics. The paper describes the design and clinical implementation of a novel method, coined the bounded registration method, applied to minimally invasive registration of the femur. Results of simulations which compare the performance of bounded registration with a standard implementation of the iterative closest point algorithm are also presented, alongside a description of their application in the Acrobot hands-on robot, used clinically for uni-condylar knee arthroplasty.

KEYWORDS: Computer-assisted surgery; Robotic surgery; Surgical navigation; Intelligent tools; Smart tools; Registration; Bounded registration method; Iterative closest point.

1. Introduction

In recent years, medical robotics has seen a transition from systems that have been initially proposed and developed by enthusiastic technologists towards those that are cost-effective systems that are essential for surgeon application. This change from technology 'push' to surgeon 'demand' has resulted in a different approach to medical robotics, which will hopefully result in a greater use of these systems. This paper presents robotic technologies that had been developed in the past, and also attempts to consider what is needed to ensure their widespread application in the operating room. Many of the obstacles to their use are non-technological, related to the needs of surgeons, patients and hospital trusts. The focus is on practical robots that are being used in the operating room, rather than the more exaggerated claims, such as those of nanorobots that are assembled inside the body and freely rove around the blood stream. These more speculative research concepts, whilst exciting, are likely to be less relevant to patient needs in the next few decades.

* Corresponding author. E-mail: f.rodriguez@imperial.ac.uk

2. History of Robotic Surgery

It is perhaps strange to speak of a history of technology when it has only been applied in the last 20 years. However, some general trends can be observed. The earliest use of robots in medicine was in the mid-1980s with the use of the Unimation Puma 560 robot to hold a fixture at a specified location and orientation next to the head, so that a surgeon could manually conduct neurosurgical procedures.[1] By using the robot as a positioning fixture, with all intervention carried out manually by the surgeon, they were able to perform accurate resection of deep-seated brain tumours which had previously been inoperable. However, permission to use these robots for surgery was withdrawn when Westinghouse purchased the company, on the basis that such robots were not designed for use adjacent to people. It is sad to think that a life-saving procedure was not possible because of safety concerns and possible litigation for the company. Subsequently in the early 1990s industrial robots, modified for safety, were used for hip and knee replacement orthopaedic surgery. Because the leg could be rigidly clamped in position, it was thought that the bones could be machined in a way similar to a computer numerical control (CNC) manufacturing process, and this made orthopaedics an easier option for robotics. This view proved over-optimistic, as the variability in humans, and the inability to rigidly clamp, made the process much more difficult than CNC machining. These industrial robots were generally used autonomously, with little surgeon involvement. The cutter was positioned by the surgeon at a desired location, and the robot automatically carried out the procedure in accordance with a pre-operative plan that was based on a computer tomography (CT) scan of the leg. The surgeon had no further part to play other than to hold an emergency-off button. Two examples of this type of robot were the Robodoc (ISS, USA)[2] (Fig. 1) and Caspar (URS, Germany)[3,4]. For reasons mostly unrelated to the technology, the Caspar system went into liquidation in 2004 and Robodoc in 2005.[5] However, in August 2006 the Robodoc group was given enough funds by a Korean investor to conduct clinical trials in an attempt to obtain FDA clearance in the United

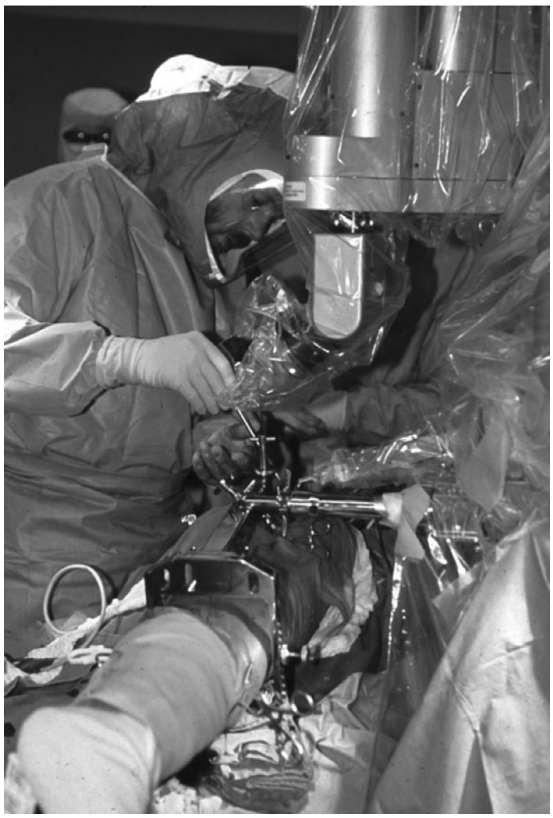

Fig. 1. Robodoc Hip surgery robot (ISS, USA).

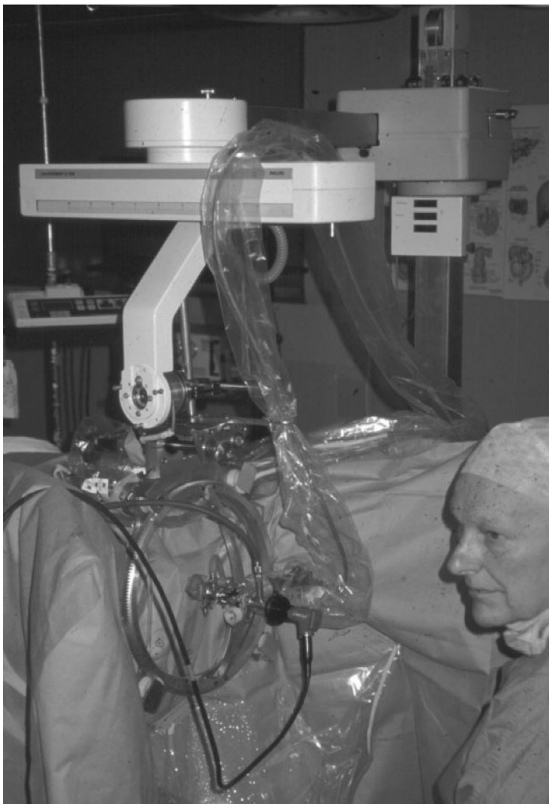

Fig. 2. Probot for prostate resection (Imperial College London, UK).

States. In 2007, ISS transferred all of its assets to Curexo Inc., and the product is now referred to as Robodoc, a Curexo Technology Company, which obtained FDA approval in August 2008.[6] Since their first use, medical robotic systems that have been used clinically have evolved substantially. The basic rules and approaches to the use of robots in medicine had to be invented. For example industrial robots were not intended for use near people, so the whole strategy to ensure the safety of patients and medical personnel had to be worked out from first principles (such as the use of duplicate position measurement sensors and the emergency shut-down of power from prime movers, rather than cascading through layers of software). As in the early days of computing, much of the early promise of medical robotics failed to materialise; only recently have more reliable, better targeted, clinical implementations achieved medical and commercial success.

The senior author's initial experience of the clinical implementation of a medical robotic system was with a robot called Probot, specially developed for trans-urethral resection of the prostate in 1991. This was the first time that a robot was used actively to remove tissue from a human patient,[7] (Fig. 2). Following preliminary laboratory studies using a motorised framework added to a standard six-axis industrial robot at Imperial College London, it was decided that a special-purpose robot was needed to ensure the safety of both patients and medical personnel. The robot was designed using a framework that had a remote centre of motion that constrained cuts to the desired region and could also hold an ultrasound probe to provide measurements for a pre-operative plan as part of an integrated system. This autonomous robot could be positioned at the *veru-montanum* and traverse into the prostate, automatically removing conical segments of tissue whilst the surgeon had no further part to play, other than to hold an emergency-off button. Although surgeons had thought that this autonomous feature was desirable, their unease at being just observers of a procedure that was largely in the control of the robot programmer soon became apparent. Also, the surgeon was continually reaching through the robot mechanism in order to push the patient's bladder. This need to continually interact with the patient is part of surgeon training, which led to the concept of a hands-on robot in which the surgeon interacted with the robot as if it were an intelligent tool under his direct command. As a result of this experience, the Mechatronics in Medicine Group at Imperial College London started in 1991 to develop a new type of special-purpose robot for orthopaedic surgery which was called the Acrobot (for active-constraint robot), in which the robot actively constrains the surgeon to cut accurately within a safe region.[8] This was designed to be a 'hands-on' robot, in which a force-controlled handle is placed near the end of the robot arm. The handle is held by the surgeon and is moved around under servo-control to compensate for friction and gravitational forces. The refinement of this system has benefited greatly from the clinical collaboration with Professor Justin Cobb, who is now professor of orthopaedic surgery at Imperial College London, and resulted in us forming a spin-off company, the Acrobot Company limited, in 1999. Acrobot has been developed into a system that can accurately achieve minimally invasive surgery, for example for uni-condylar knee replacement.

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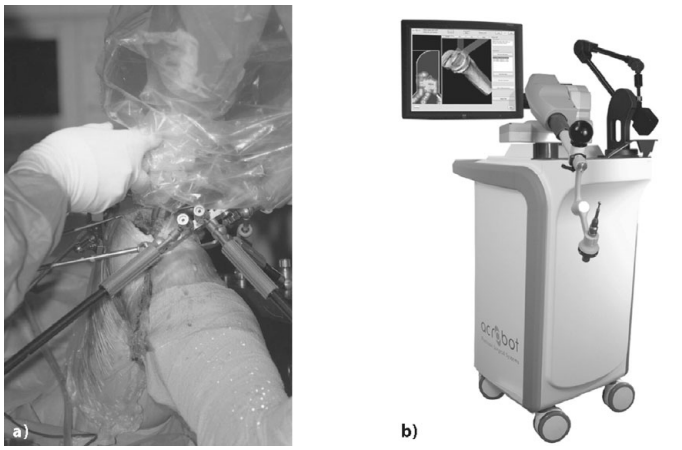

Fig. 3. The Acrobot robot for uni-condylar knee replacement (Acrobot Ltd): (a) Clinical trials on an early system; (b) and the improved Acrobot Sculptor System.

Randomised clinical trials have shown that the robot can achieve much better accuracy for this procedure than experts using conventional jigs and fixtures. In a small study, 15 conventional and 15 robotic uni-condylar procedures were undertaken. All had a pre-operative plan. Whilst all robotic cases achieved a varus/valgus leg alignment within 2° of that planned, only 40% of conventional procedures achieved this target[9,10] (Fig. 3a). More recently, the robot has been reduced in size and cost and made into a trolley mounted system called 'Acrobot Sculptor' to perform the specific task of minimally invasive orthopaedic surgery (Fig. 3b). A separate navigation arm is used to dynamically track the position of the knee, thus avoiding the time-consuming necessity of locking down the leg.

2.1. Telemanipulators

Autonomous robots are less suited to soft-tissue surgery, since the tissue can change shape as it is pushed or cut. For this a telemanipulator (master/slave) robot is best. One of the most successful commercial robots has been the daVinci robot (Intuitive Surgical, Sunnyvale, CA, USA), which was originally implemented for heart surgery[11] (Fig. 4). In this master/slave robot the surgeon sits at a master console next to the patient, who is operated on by the slave arms. The surgeon views the internal organs through an endoscope and by moving the master manipulator can adjust the position of the slave robot. The surgeon compensates for any soft-tissue motion, thus closing the servo-control loop by visual feedback. Robotic heart-surgery procedures are carried out by means of tools passing through small incisions in the chest wall between the ribs. However, the number of suitable procedures was small, and the very high cost of the robot (typically UK£1.2 million with £100,000 annual maintenance and £1,500 consumables per procedure) has limited the number of implementations to those which are life-saving. One of the founders of intuitive surgical, Dr Moll, has now founded Hansen Medical, which produces a simpler and lower-cost heart surgery robot, which is currently undergoing FDA approvals (www.hansenmedical.com). More recently, the daVinci robot has been used to carry out trans-pubic radical prostatectomy with reduced risk of incontinence and impotence. The excellent three-dimensional images and micromanipulation ability of the robot make it ideal for this procedure. As a result of publicity, patient demand has increased, and 10% of urology hospitals in the United States now have daVinci robots.

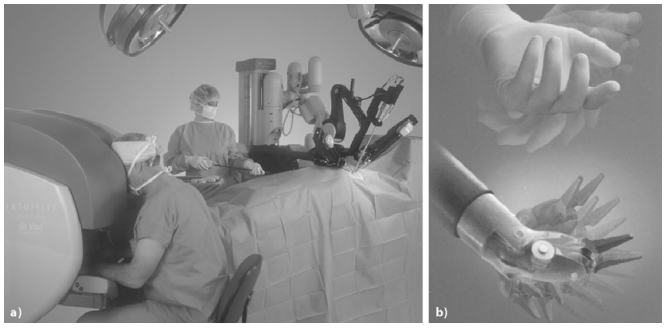

Fig. 4. The daVinci telemanipulator (Intuitive Surgical).

3. Non-Technological Barriers to the Use of Surgical Robots

The use of autonomous robots has caused concerns about who is in charge of the procedure: the surgeon or the computer programmer. The move towards a 'hands-on' type of robot, such as the Acrobot Sculptor, removes many such concerns because the robot is seen to be an intelligent tool that is under the direct control of the surgeon. This has an impact on the uptake of robots for surgery in a number of ways. Because it is essential for the surgeon to be present during the procedure, he has fewer fears that he will be made redundant and so is more likely to adopt this new technology. Also, the public can be reassured by the continued presence and involvement of the surgeon in his traditional role. This continued involvement of the surgeon makes it less likely that robotic procedures will be the subject of adverse litigation, which can be very costly to a company and can prevent hospitals from using the robot whilst litigation is in progress, a situation which occurred in Germany for the Robodoc orthopaedic surgery robot.

4. Cost Effectiveness of Robotics in Surgery

The importance of a clear cost-benefit analysis for robotic surgery has only recently been recognised. One difficulty in demonstrating benefit is that the required accuracy for a particular procedure can be unclear. Even in orthopaedic arthroplasty, where bone is machined and does not distort or change its location during cutting, error by the surgeon can produce a huge variability in the result. However, it is often unclear how accurate the surgery needs to be. In uni-condylar knee replacement surgery, for example, there is no consensus on how accurate the varus/valgus alignment of the prosthetic knee centre should be with respect to the hip. Whilst it is generally agreed that 2° would be excellent and 6° will cause problems, it is not clear how bad the alignment can be before a poor outcome will result. To demonstrate post-operative results, the accuracy of planar radiographs is also

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very suspect. For this reason the uni-condylar replacement study undertaken by Acrobot compared a CT-based pre-operative plan with subsequent CT of the achieved alignment in order to make an objective comparison. With the correct software protocol, a full modern spiral three-dimensional CT scan takes only 10 seconds and has the same dose as three X-rays, so CT cost and radiation dose is no longer a significant barrier.[12] Poor post-operative performance of prostheses can be due to incorrect fixation caused by surgeon error. This error, since it is usually not measured at all, implies that the accuracy necessary for prostheses to last for a long time without causing pain is largely unknown. A further reason for this is that the body is very adaptive and will compensate over a period of time so that the subjective judgements of hip and knee scores is suspect. These scores are also a gross measure; e.g. if the change in leg length from hip replacement surgery is less than 2 cm it is not recorded. Thus objective studies of accuracy, both achieved and required, are needed for robots to deliver their full potential. One benefit from robotic procedures is that they are sufficiently consistent that investigation of the importance of variables such as prosthesis alignment and rotations will be possible; furthermore, researchers will be able to identify the crucial features of a prosthesis design, without being confused by the variability of surgeon error. For the patient, there are clear cost benefits from the robot's ability to achieve minimally invasive surgery with less patient time confined to bed and fewer days off work and with an accuracy that will give a long pain-free prosthesis life, minimising the need for subsequent revisions. However, hospitals will need to judge these benefits of a robotic procedure against the possibility of a slightly increased operating time in the early days of a robotic implementation, with a consequent adverse effect on operating room lists. There is a tendency in the United Kingdom owing to current National Health Service (NHS) pressures to emphasise the equipment cost and the number of procedures carried out by the surgeon in a day, rather than the quality of the patient outcome. This implies that in the shorter term, it is more likely that the private sector will be the area of rapid deployment of surgical robots. In spite of concern that the surgeon is no longer in charge of the choice of a procedure, there is some evidence from both Germany and the United States that patients are querying if a particular hospital uses a robot or computer-aided surgery (CAS) navigation system and that if they do, then the patient will elect to be treated there. This has resulted in some hospitals using robot systems as a marketing tool. An example of this is in Germany, when the Caspar robot went into liquidation and it was no longer possible for it to be used in hospitals, there was less disruption than had been expected, indicating that the robots were purchased for marketing purposes rather than for regular use in the operating room. Early implementations of medical robotics were difficult because engineers require a very precise specification of the task. Surgeons, however, are trained in an apprenticeship system, which places little value on precise measurement of displacements, velocities and forces. Engineers must visit the operating room and infer the measurements of physical parameters they think appropriate to a procedure. This very iterative and time-consuming task is necessary to ensure that the design of the robotic system is correct and that the task is universally recognised as one difficult to carry out manually, justifying robotic implementation. Universities can research medical robotics relatively easily in the laboratory by means of well-motivated students using industrial robots and simulations; however, clinical application is very much more demanding. When robotic systems are to be used on patients, an ethics committee approved study is required for the research group and the hospital to work together. Patient safety is of course of prime concern. In the United Kingdom, the medical device directives of the European Union have been interpreted in such a way that once two or three patients have successfully undergone the robotic procedure, if further data are required for statistical evidence, then either the equipment must have a CE mark or a trail approved by the Medicines and Healthcare products Regulatory Agency (MHRA) must be undertaken. This makes clinical implementation of robotic systems extremely difficult and expensive in the United Kingdom and has an adverse effect on research. In the early days of implementation of the medical device directives, a special amendment allowed a research consortium in the United Kingdom to conduct widespread investigations under ethics committee approval, but in recent years the possibility of adverse legal action has resulted in a much more conservative approach.

5. CAS Navigation Systems

CAS navigation systems are seen as one of the main competitors to robots in surgery. A number of CAS navigation systems have been used clinically for surgery, in which cameras are used to track a series of light-emitting diodes attached to tools and to the patient (e.g.www.brainlab.com). These enable the tool locations to be tracked whilst being manually positioned by the surgeon. The tool locations can then be positioned relative to the patient and displayed on a computer. When the tool is correctly aligned, a display shows a green light and the tool can be inserted. Such systems give greater accuracy than conventional surgery. A variation on this approach is that of the Acrobot Company, UK, that utilises a pair of tracked arms to locate the position of tools relative to the patient,[13,14] (Fig. 5). This avoids many of the problems associated with camera-based systems in which the surgeon can obstruct the line of sight between the tool and camera. The success of navigation systems means

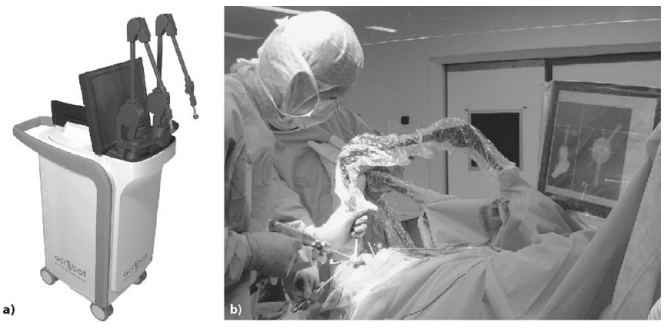

Fig. 5. Computer-assisted hip resurfacing using Acrobot navigation (Acrobot Ltd).

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that when robots are used for surgery, their benefits must be compared with those obtained from navigation rather than those from conventional surgery. It is inevitable that robots, which contain prime movers and control systems, will be costlier than navigation systems. In addition to greater accuracy than navigation systems, robots can provide a physical constraint that prevents the surgeon from cutting into critical areas, as well as providing the ability to cut complex shapes with great accuracy.

6. Registration

One of the major sources of error, both for CAS navigation systems and robotic surgery, is that of the registration of the robot and patient to the pre-operative computer-based model and plan. CAS generally involves patient to modality registration,[15] as in any CAS application that involves planning, the relationship between the modelled space, where the procedure is planned, and the patient's workspace, where the procedure is executed, needs to be established. Identifiable features, such as fiducial marker screws[16] or anatomical landmarks, are first extracted from the model and then 'sensed', or located, in the operating theatre. This process provides the system with enough positional information for the modelled space and patient's space to be registered against a ground.

When access to the registration surface is restricted, such as in minimally invasive surgery, registration accuracy can degenerate. This is due to the poor quality of the information collected in real space, in terms of both positional accuracy and surface covered, which results in poor correlation between the surfaces to be co-registered. Since any such inaccuracy has a direct impact on the outcome of the robotic or computer-assisted procedure, accurate and robust registration methods are of paramount importance. As such, significant efforts have been invested to identify those technologies and techniques which can help mitigate the effect of a limited access on surgical outcome. Among these, a new registration method was developed at Imperial College, in collaboration with the Acrobot Company Ltd, where a remote set of paired correspondences is used to bound registration outcome. This method, as applied to minimally invasive registration of the femur, is briefly described in the following sections.

During minimally invasive unicompartmental knee arthroplasty (UKA), regions I–III in Fig. 9 are accessible for registration, without the need for additional stab wounds. However, a poor quality of point set, in terms of both point touching accuracy and point spread, can cause the registration result to quickly degenerate, resulting in large rotational errors, which are unacceptable for computer-assisted UKA. The bounded registration method binds the outcome of model-based registration by means of a remote set of paired correspondences in the two spaces to be co-registered.

As illustrated in Fig. 6, let leg placement be defined according to anatomical notation, using the medial, lateral, posterior, anterior, proximal and distal nomenclature. Also, let correct varus/valgus and anterior/posterior (AP) alignment of the mechanical axis be specified by defining the position of the knee, which can be approximated by a single

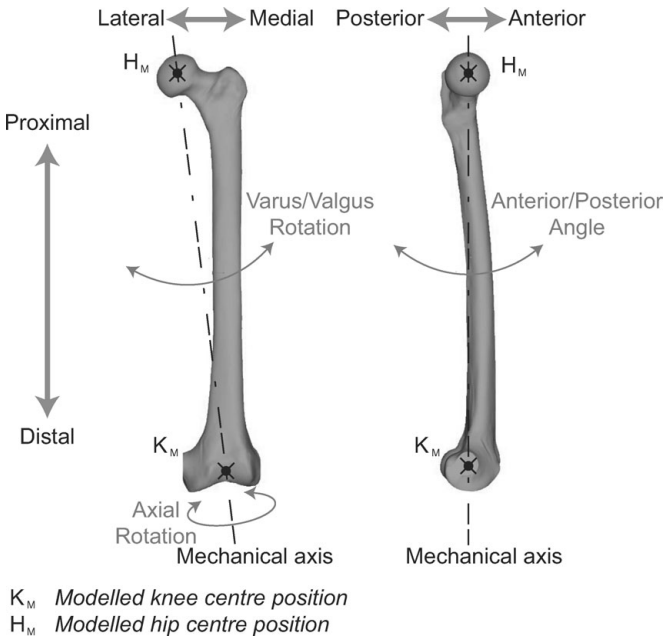

Fig. 6. Leg alignment in terms of knee and hip centres.

set of three-dimensional co-ordinates situated anywhere on the distal femur, and the centre of the femoral head.

Accurately estimating the centre of the femoral head provides a three-dimensional point that is very far from the distal femur where the dataset for registration is collected. A medial displacement error of 1 cm in the true hip centre to an estimate will result in 1.2° of varus/valgus misalignment, assuming a 40 cm average length of femur and correct distal alignment. Therefore, correctly locating the position of the functional centre of the hip has the potential to guarantee correct AP and varus/valgus alignment of the leg.

The bounded registration method is designed to harvest the full potential from the hip centre, without impairing correct registration of the degrees of freedom, such as axial rotation and medial, lateral, posterior, anterior, proximal and distal translations.

6.1. Locating the hip centre

Estimation of the functional centre of the hip has been well documented over the years in a number of applications, for instance in biomechanics[17] and in CT free registration of the knee joint[18]. As the hip joint can be approximated to a "ball and socket' joint, its functional centre can be obtained by fitting a sphere on points measured about a fixed distal location on the femur, whilst pivoting the leg around the hip with the pelvis immobilised. Although a least squares Gauss–Newton method was used for the implementation described in Section 6.3, a number of alternative methods are available in the literature.

6.2. The method at a glance

The method is based on pre-operatively acquired data, and it assumes that both modelled and estimated hip centres can be defined accurately. A 'physical' model for the convergence process is used for illustrative purposes (Fig. 7).

Initially, the modelled and estimated hip centre positions (which are in model and real space respectively) are

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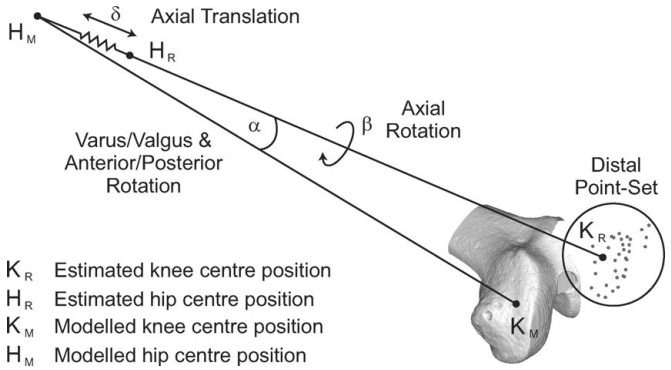

Fig. 7. 'Physical model' for the bounded ICP convergence theorem.

considered to be coincident. All points measured on the distal femur are regarded as a whole, by referring to them in terms of their centroid – the 'knee centre estimate'. Finally, the knee centre estimate is connected to the modelled hip centre with a virtual spring or slider, able to extend and compress but not bend. Each point has a corresponding representation on the modelled surface, which needs to be correctly identified for the best solution to be found. Pairs of points and respective closest points provide the measure to be minimised, which can be expressed in terms of the root mean square (RMS) of their relative distance and is used in the error minimisation process until a solution is found (e.g. the error falls below a specified threshold). The distal point set is allowed to oscillate about the modelled hip centre (α), to move away or towards the modelled hip centre (δ) and to rotate about the axis defined by the knee centre estimate and modelled hip centre (β). In the embodiment used for the clinical implementation (Section 6.3), a possible solution, or local minimum, is obtained for the position of the point set on the modelled surface, where the error distance between points and closest points is minimum. As in ref. [19], convergence is achieved by iterating upon closest points, although the transformation matrix used to map the points on to the surface at every iteration is calculated by applying rotations about and translations along the axis generated by the hip centre and centroid of the point set. Successive transformations applied to the original point set are therefore bound at one end whilst free to move at the other, giving the bounded registration method its name. A mathematical description of the implementation used for the clinical trials described next is beyond the scope of this review; however further details can be found in ref. [20].

6.3. Clinical implementation

An implementation of the bounded registration algorithm was incorporated in the software of a hands-on robot for UKA, namely the Acrobot System.[8]

During the pre-operative planning phase, the functional centre of the hip joint is identified by inspecting the three-dimensional reconstruction of the femoral head generated from CT data. Frontal and AP views are used to find the outer edges of the femoral head, which are then used to overlay a spherical shape on the screen. The schematically depicted sphere, shown as two circles in the frontal and AP views, is placed on the reconstructed leg anatomy so that its centre

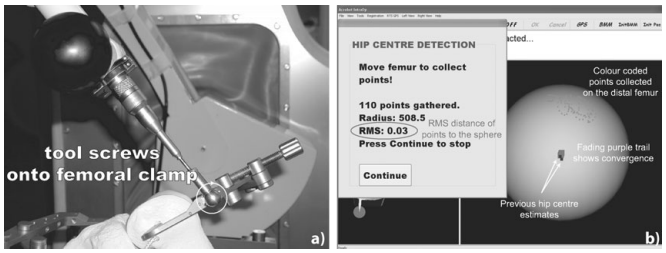

Fig. 8. (a) Cutter insert used to generate a set of measurements for the distal femur location during hip centre estimation and (b) the intra-operative GUI used during the hip centre estimation process.

coincides with the anatomical centre of the femoral head. The three-dimensional co-ordinates of the sphere centre are then stored as the co-ordinates of the modelled hip centre.

Intra-operatively, the hip centre estimation process is aided by a graphical user interface (GUI), which directs the surgeon through the acquisition process and provides visual and quantitative feedback on the convergence process. A set of auxiliary bed clamps are tightened to the side rails and pushed against the patient's iliac crests, effectively pinning the pelvis down on to the operating table, throughout the procedure.

The functional centre of the hip can be obtained by fitting a sphere on points measured about a fixed distal location on the femur as the leg is moved in a grid whilst pivoting about the hip with the pelvis immobilised. In order to identify a unique point on the distal femur, a custom cutter insert was devised for use with the hands-on robot, which enables the femur to be moved whilst connected to the robot's end effector. The insert, illustrated in Fig. 8, has a spherical ball joint which, allowing complete freedom in three dimensions, enables the surgeon to move the leg through an adequate range of its working envelope.

The intra-operative GUI illustrates the acquisition process by plotting the points harvested on the distal femur against a circle of radius 1 cm centred about the last successful estimate. The display (illustrated in Fig. 8) enables the surgeon to visually inspect the current progress to ensure coverage of all areas on the leg's available workspace. Points are collected by the software automatically at regular intervals, as the surgeon slowly moves the leg through as much of the available space as possible whilst making sure the hip joint is not over-stretched.

Hip centres of all successful runs are plotted against each other on the same GUI. Visual inspection of the position and spread of different hip centre estimates can provide the surgeon with a confidence factor for the quality of the result.

Point collection on the distal femoral surface is carried out through the conventional UKA incision, with an emphasis on the front of femur, the femoral notch and the medial side of the medial femoral condyle. A typical pointset covering the three main regions of interest is illustrated in Fig. 9. For successful and robust registration of the femur, 15–20 points are sufficient.

The quality of the hip centre estimate is a robust indicator of performance for the bounded registration method. Since points collected on the distal femur are only used to bound the distal end of the femur, large distance errors between the points and the surface may describe poor correlation

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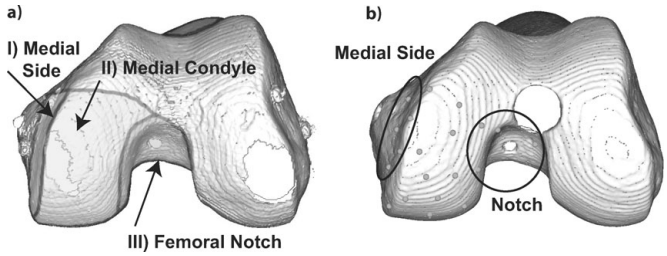

Fig. 9. (a) Accessible surfaces on the femur during conventional UKA and (b) a typical femoral point-set for the Bounded Registration method.

between the point set and the surface but may not reflect the registration quality for the two important varus/valgus and AP components. For instance, a 1-cm lateral translation of the hip centre will result in approximately 1.2° of varus/valgus misalignment. Consequently, points on the distal femur will settle in the minimum position allowed by the fixed hip centre, which may have a significantly higher RMS value than that obtained if the same points were used with an 'unbound' implementation. Similarly, for a perfect hip centre, varus/valgus and AP angles are very likely to have near-zero misalignment, even though the RMS value may be relatively high because of poor correlation between the probe points and the surface. Therefore, accurate registration can be ensured by a careful analysis of the quantitative and qualitative feedback produced by the GUI during hip centre estimation, which is repeated twice to ensure that the least squares spherical fit systematically converges to a similar minimum.

6.4. Results

The performance of the bounded ICP method, as applied to minimally invasive femoral registration, was evaluated by means of simulation, laboratory and clinical trials. Details are given here of a comparative study between the bounded ICP algorithm and of a standard implementation of the ICP algorithm, for a number of randomly generated point sets, using a custom-developed simulation platform. A population size of 100 sets was chosen to represent each point-set size, for five different levels of maximum random noise applied to each point between 0 mm and 2 mm. Random perturbations of 5° and 5 mm in magnitude, in random directions, were used to displace each point set away from the surface during initialisation. For the bounded ICP algorithm, the simulated hip centre error was chosen to be in a random direction with constant 1-cm magnitude. The two resulting sets of point sets are therefore identical, with the exception of a realistic hip centre estimate being added to bounded ICP dataset.

Figure 10 illustrates results for the average rotational error, in terms of leg alignment components, and overall translational error for different point-set sizes and maximum noise values, for the two algorithms.

Clearly, registration outcome, in terms of varus/valgus and AP alignment, drastically differs between the two charts. In the bounded registration method, charts for these two components of the error matrix can be approximated to a plane regardless of point-set size and maximum noise applied. More specifically, the two planes lie at approximately 0.5° rotational error, which coincides with the average rotational error generated by a 1-cm translational offset of the hip centre estimate, if the random direction for the offset follows a normal distribution.

A comparison between the performance of the bounded registration algorithm and of a standard ICP algorithm implementation highlights a substantial improvement in terms of leg axis alignment for identical point sets. Even for exceptionally poor correlation between the points collected on the distal femur and the corresponding modelled surface, the bounded registration method produces consistently accurate results given a reasonable hip centre estimate. Therefore, by carefully estimating the position of the functional centre of the hip joint intra-operatively, it is possible to bound registration outcome. Worst case scenarios can also be readily estimated by pre-operatively evaluating the contribution of each phase of the algorithm, from pre-operating planning to the intra-operative point collection method.

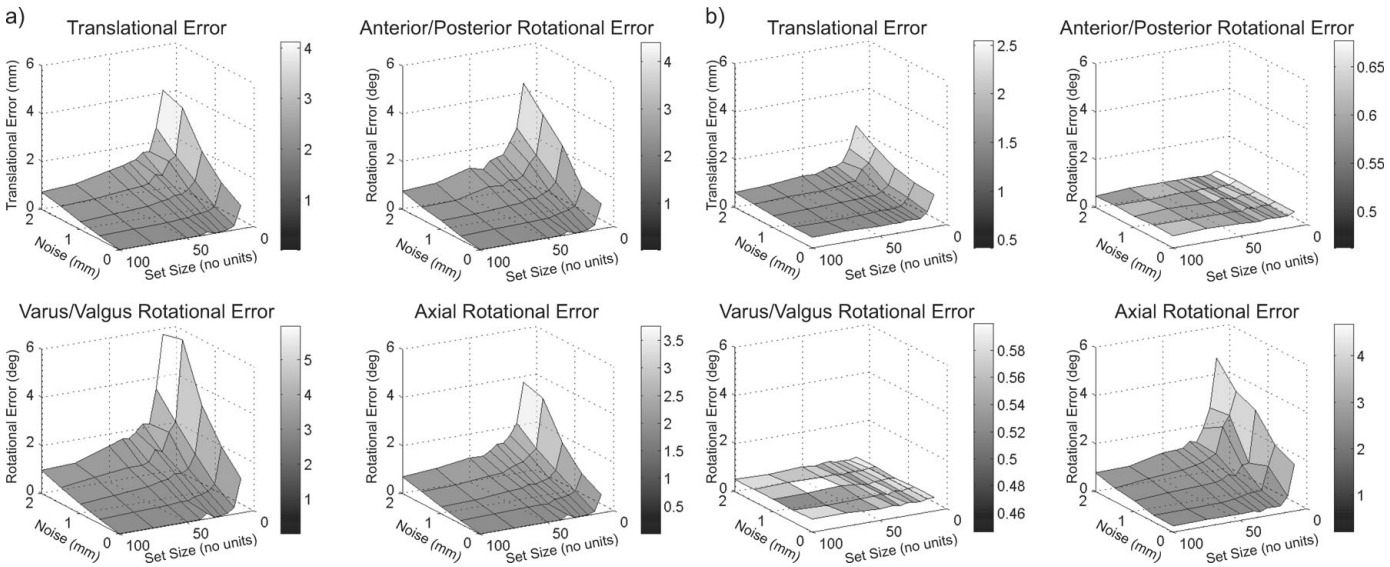

Fig. 10. (a) Registration accuracy for a standard implementation of the ICP algorithm and (b) the bounded registration algorithm.

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7. Conclusion

In the early days of the application of robots in surgery, enthusiasts drove their implementation. Now systems have to be clinically relevant with benefits for patient and surgeon. This has meant that robots are unlikely to be applied to surgical procedures which are straightforward. It is in tasks that surgeons find very difficult or currently impossible that robots have had their greatest success. The move towards smaller, lower-cost systems that utilise smart sensing is resulting in their widespread application. These intelligent tools, that allow the surgeon to have hands-on control, tend to be applied to specific applications. In some ways this is a move away from the concept of the robot as a universal re-programmable tool. However, the particular requirements of a specific procedure in an operating room imply that the robot will be limited to a few similar applications. A typical example is in orthopaedics, where the same robot may be used for both hip and knee surgery, but it is unlikely to be also made available to another operating room for, say, spine surgery, and certainly will not be available for such different procedures as soft-tissue surgery or neurosurgery. This implies that the concept of a multi-axis, costly and complex robot that can be justified by its use for a wide number of procedures is flawed. The cost of the single robot system must be justifiable by its application to a restricted number of procedures. This has led to the development of simpler, lower-cost system that are quick to set up and deliver shorter procedures, as well as improved accuracy and outcomes. One of the major sources of error in both CAS navigation and robotics is that of registration. This is particularly relevant to orthopaedic surgery. The bounded registration method presented here has been shown to give considerable benefit in achieving the planned leg alignments, and thus holds considerable promise for accurate registration in robotic surgery in general. The current implementation has proved to be a very robust means for femoral registration performed through a conventional UKA incision, is suitable for minimal access surgery (as a few inaccurate distal points are sufficient to bound the registration outcome for a reasonable hip centre estimate) and has been fully tested within a clinical setting. In fact, the bounded registration method, incorporated in the software of the Acrobot System, was part of the MHRA approved clinical evaluation described in ref. [10], with excellent results.

After a very mixed start, which did not live up to its exaggerated expectations, it is now accepted that robots can deliver clear clinical benefits at an acceptable cost. The move towards safe, simpler, low-cost intelligent tools promises a bright future for medical robots.

References

1. Y. Kwoh, J. Hou, E. Jonckheere and S. Hayati, "A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery," *IEEE Trans. Biomed. Eng.* **35**(2), 153–160 (1988).
2. A. Bauer, "Total hip replacement – robotic assisted technique," **In**: *Computer and Robotic Assisted Knee and Hip Surgery* (A. DiGioia, ed.) (Oxford University Press, 2004) pp. 83–96.
3. W. Siebert, S. Mai, R. Kober and P. F. Heeckt, "Technique and first clinical results of robot-assisted total knee replacement," *Knee*, **9**(3), 173–180 (2002).
4. W. Siebert, S. Mai, R. Kober and P. Heeckt, "Total knee replacement: Robot-assistive technique," **In**: *Computer and Robotic Assisted Knee and Hip Surgery* (A. DiGioia, ed.) (Oxford University Press, 2000) pp. 122–135.
5. B. L. Davies, F. Rodriguez y Baena, A. R. W. Barrett, M. P. S. F. Gomes, S. J. Harris, M. Jakopec and J. P. Cobb, "Robotic control in knee joint replacement surgery," *Proc. Inst. Mech. Eng. H, J. Eng. Med.* **221**, 71–80 (2007).
6. U.S.A. Food and Drug Administration, "Digimatch Robodoc surgical system receives U.S. FDA 510(k) marketing clearance," NO: K072629 (6 Aug. 2008).
7. S. J. Harris, F. Arambula-Cosio, Q. Mei, R. D. Hibberd, B. L. Davies, J. E. A. Wickham, M. S. Nathan and B. Kundu, "The Probot – an active robot for prostate resection," *Proc. Inst. Mech. Eng. H, J. Eng. Med.* **211**(4), 317–326 (1997).
8. M. Jakopec, S. Harris, F. M. Rodriguez y Baena, P. Gomes, J. Cobb and B. Davies, "The first clinical application of a 'hands-on' robotic knee surgery system," *Comp. Aid. Surg*. **6**(6), 329–339 (2001).
9. M. Jakopec, F. M. Rodriguez y Baena, S. J. Harris, P. Gomes, J. Cobb and B. L. Davies, "The hands-on orthopaedic robot 'Acrobot': Early clinical trials of total knee replacement surgery," *IEEE Trans. Rob. Automat.* **19**(5), 902–911 (2003).
10. J. Cobb, J. Henckel, P. Gomes, S. Harris, M. Jakopec, F. Rodriguez y Baena, A. Barrett and B. Davies, "Hands-on robotic unicompartmental knee replacement," *J. Bone Joint Surg.* **88**, 188–197 (2006).
11. G. S. Guthart and J. K. Salisbury, "The Intuitive telesurgery system: Overview and application," *IEEE Int. Conf. Rob. Automat.* **1**, 618–4102 (2000).
12. J. Henckel, R. Richards, K. Lozhkin, S. Harris, F. M. Rodriguez y Baena, A. R. W. Barrett and J. P. Cobb, "Very low-dose computed tomography for planning and outcome measurement in knee replacement," *J. Bone Joint Surg.* **88**, 1513–1518 (2006).
13. A. R. W. Barrett, B. L. Davies, M. P. S. F. Gomes, S. J. Harris, J. Henckel, M. Jakopec, V. Kannan, F. M. Rodriguez y Baena and J. P. Cobb, "Computer-assisted hip resurfacing surgery using the Acrobot navigation system," *Proc. Inst. Mech. Eng. H, J. Eng. Med.* **221**, 773–786 (2007).
14. A. R. W. Barrett, B. L. Davies, M. P. S. F. Gomes, S. J. Harris, J. Henckel, M. Jakopec, F. M. Rodriguez y Baena and J. P. Cobb, "Preoperative planning and intraoperative guidance for accurate computer-assisted minimally invasive hip resurfacing surgery," *Proc. Inst. Mech. Eng. H, J. Eng. Med.* **220**, 759–774 (2006).
15. J. Maintz and M. Viergever, "A survey of medical image registration," *Med. Image Anal.* **2**(1), 1–36 (1998).
16. R. E. Ellis, S. Toksvig-Larsen, M. Marcacci, D. Caramella, and M. Fadda, "Use of a biocompatible fiducial marker in evaluating the accuracy of computed tomography image registration," *Invest. Radiol.* **31**(10), 658–667 (1996).
17. A. Leardini, "Validation of a functional method for the estimation of hip joint centre location," *J. Biomech.* **32**(1), 99 (1999).
18. K. MyungJin, H. Sadri, L. Moccozet, N. Magnenat-Thalmann and P. Hoffmeyer, "Accurate simulation of hip joint range of motion," **In**: *Computer Animation, 2002. Proceedings* (2002) pp. 215–219.
19. P. Besl and N. McKay, "A method for registration of 3-d shapes," *IEEE Trans. Patt. Anal. Mach. Intell.* **14**(2), 239–250 (1992).
20. F. Rodriguez y Baena, Improving accuracy in robotic assisted orthopaedic surgery *Ph.D. Thesis*, (London: Imperial College London, 2004).

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