Computer-assisted hip resurfacing surgery using the Acrobot® Navigation System

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Abstract: The authors have previously reported on the laboratory development of the Acrobot® Navigation System for accurate computer-assisted hip resurfacing surgery. This paper describes the findings of using the system in the clinical setting and including the improvements that have been made to expedite the procedure. The aim of the present system is to allow accurate planning of the procedure and precise placement of the prosthesis in accordance with the plan, with a zero intraoperative time penalty in comparison to the standard non-navigated technique.

At present the navigation system is undergoing final clinical evaluation prior to a clinical study designed to demonstrate the accuracy of outcome compared with the conventional technique. While full results are not yet available, this paper describes the techniques that will be used to evaluate accuracy by comparing pre-operative computed tomography (CT)-based plans with post-operative CT scans. Example qualitative clinical results are included based on visual comparison of the plan with post-operative X-rays.

Keywords: hip resurfacing, computer-assisted surgery, pre-operative planning, post-operative analysis, surgical navigation, surgical outcome, surgical accuracy

1 INTRODUCTION

Osteoarthritis of the hip has traditionally been treated operatively by the replacement of the worn articulating surfaces with a total hip replacement (THR) prosthesis. While this has been a successful procedure, the long-term outcome for younger or more active patients is unacceptably poor, leading to early implant failure and/or repeated revision surgery [**1–5**]. Hip resurfacing (HR) surgery has significant potential for these younger and more active patients [**6**, **7**]. The HR prosthesis has several advantages when compared to the THR prosthesis. The HR prosthesis more closely resembles the underlying anatomy, since the diameter of the femoral component is large when compared to the small head of a THR prosthesis, leading to a reduction in the likelihood of dislocation of the joint post-operatively. The femoral neck is not sacrificed during the HR operation, so that bone stock is maintained and subsequent revision surgery is facilitated. The loading of the joint is more akin to the normal physiological loading, so that stress shielding is less prevalent, leading to a reduction in the degree of bone resorption post-operatively.

There are, however, several disadvantages when comparing the HR operation to a standard THR procedure. The operation is more technically demanding and there is a significant learning curve for surgeons [**8**]. The skin incision is generally larger than that required for a THR operation (since the femoral head and neck are not removed and access to the lateral cortex of the femur is required), leading to increased patient morbidity and a longer hospital stay. This

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runs against the current trend of minimally invasive surgery, which has been particularly prevalent in THR during recent years [**9–11**]. However, the reduction in incision size has led to additional problems for the surgeon in trying to prepare the bone surfaces and place the implants accurately, requiring intra-operative fluoroscopy with its associated risks [**12**, **13**]. Moreover, component positioning for HR is more crucial than in THR; in particular, notching of the femoral neck or varus placement of the femoral component can lead to fracture of the neck [**14**, **15**].

The goal of this paper is to present the Acrobot® Navigation System for computer-assisted HR surgery. At present the system is being used through a conventional incision, but there is significant potential for the surgery to be performed in a minimally invasive manner in the future, while maintaining the accuracy of the implant position, without the need for fluoroscopy during the procedure. The system is controlled directly by the surgeon using a draped touchscreen and a footswitch; therefore an additional technician is not required in the operating theatre. The paper describes the steps involved in generating a plan for the surgery and achieving this plan in the operating theatre, and presents initial qualitative results.

2 PRE-OPERATIVE PLANNING

In contrast to the majority of surgical navigation systems available, the Acrobot® Navigation System uses a pre-operative plan based upon computed tomography (CT) scans of the patient. Use of a CT scan allows accurate models of the patient's bones to be produced and presented to the surgeon for precise planning of the implant position. There is a threefold benefit to this pre-operative plan.

1. The surgeon has a clear understanding of the specific anatomy of the patient's hip prior to the operation. This allows accurate sizing of the implants so that the smallest acceptable femoral component can be used without the worry of femoral notching, thus conserving bone stock on the corresponding acetabular component. This additional bone stock is beneficial should a revision be required for the patient in the future.

   The impact of the implant position and size can be explored so that the surgeon can understand how the joint will function post-operatively, i.e. what the range of motion will be before impingement will occur, since the planning software allows the reconstructed joint to be visualized and manipulated to simulate post-operative joint motion. The plan also allows the surgeon to decide which osteophytes must be removed during the surgery so that the range of motion is optimized. Initial feedback from surgeons is that there is significant benefit from using this type of planning technique even for conventional non-navigated hip resurfacing and especially for the more complex cases.
2. Since the planning occurs before the operation, the time impact of navigating the surgery in the operating theatre is minimal. The interaction with the navigation system is only to define where the patient's bones are and then navigating the surgery can commence. Without the pre-operative plan, intraoperative time must be spent on trying to define what the shapes and sizes of the bones are, where those bones lie within the patient, what prosthesis size is best suited for the patient, and what is the optimal position of those implants on the bone. These additional steps consume a considerable length of time, leading to a navigated procedure that is significantly longer than the conventional procedure. In addition, there are uncertainties regarding the ability of navigation systems to produce accurate patient models based upon intraoperative point touching alone. Figure 1 shows some typical examples of patient bone models, highlighting the variation that is routinely encountered.
3. The pre-operative plan provides a benchmark against which the true performance of the navigation system and surgery can be judged by taking a second scan post-operatively and comparing planned against achieved result. CT provides the only means for an accurate assessment of implant position in the patient. While much of the literature gives results that have been measured using post-operative X-rays, there have been several studies (e.g. reference [**16**]) that have highlighted the inadequacy and inaccuracy of X-ray based measurements for implant position. Section 5 describes the techniques employed to match the pre-operative plan to the post-operative result.

2.1 CT scanning

The surgery is planned pre-operatively on three-dimensional computer models derived from computed tomography (CT) scans of the patient's hips and upper femur [**17**]. To reduce the radiation dose to the patient, the scan is separated into two regions, the first at 4 mm slice intervals from just above to just below the left and right anterior superior iliac spines (ASISs) and the second at 1 mm slice intervals

Fig. 1 Patient-specific femoral bone models constructed from CT data. From left to right: stage IV avascular necrosis, femoral head collapse, cam-type impingement with an anterior boss and a retroverted head, and severe osteoarthritis secondary to achondroplasia

from just above the acetabulum down to the lesser trochanter of the femur. Figure 2 is a schematic of the scanning arrangements.

2.2 Segmentation and bone model generation

CT images in Digital Imaging and Communications in Medicine (DICOM) format are imported into the planning program, which checks for data anomalies on loading. To be accepted as a valid dataset, all slices must be labelled in the DICOM data as having a CT scanning modality and every slice must contain identical information identifying the patient, institution, scanner, and study, ensuring that (a) the data are in a format that the planning software can process and (b) two or more different patients or studies have not accidentally been combined into the imported data. The slices are presented to the user (typically a radiographer) for visual inspection to assess aspects such as image quality and patient motion artefacts. Once imported, the segmentation process is performed.

Segmentation is a semi-automated procedure that allows the computer to assign different parts of the model to the different bones. Each slice is thresholded using a dual-threshold function with upper and lower levels set by the user, resulting in a binary image that can also be filtered to reduce speckle. Each discrete unconnected white region (blob) in the binary image is assigned a unique value and the black areas are considered to be background.

For the first segmented slice, the threshold image is presented to the user, who assigns the blobs with the appropriate bone types (in the HR planner the bone types are pelvis and femur) or as ignored (for artefacts, extraneous features such as the scanner bed or unnecessary bones such as vertebrae). The user is also provided with basic painting tools (line drawing, region filling, and region assignment) which enable correcting of the computer's segmentation

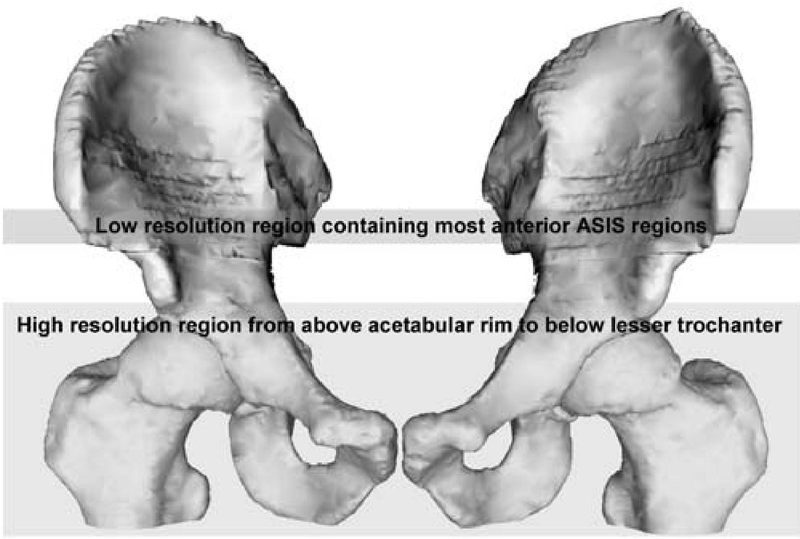

Fig. 2 CT scanning regions: upper band, low resolution; lower band, high resolution

or, where bones are touching, to divide the image between the bones and assign them their correct labelling. On screen the different segmented regions are colour coded and overlaid on to the original CT images.

On subsequent slices, the computer performs an initial assignment of the blobs to bone types based upon the previous segmented image. This allows automatic marking of a particular bone through the dataset. Where a blob does not have anything touching it in the previous slice, it is assigned as unknown, and it is the responsibility of the user to teach the system the new bone region that is appearing.

Once the slices have been segmented, three-dimensional surface models are generated using a matching cubes algorithm [**18**]. The output is smoothed and two models are created for each bone, a fine resolution model for registration and a decimated version for display. (The reconstruction accuracy has been verified using plastic models to within 1 mm. It is generally considered that accuracy to ± 2 mm is adequate.) The segmentation process typically takes 10 to 15 minutes per case, but can be longer when there are significant artefacts in the data (e.g. an existing implant on the contra-lateral side).

2.3 Coordinate frame definition

There are four coordinate frames defined for HR planning, two for the pelvis and two for the femur.

2.3.1 Pelvic coordinate frames

The overall pelvis frame of reference (FOR) is based on the anterior pelvic plane (APP). This is defined by the most anterior points on the left and right ASISs and a point midway between the most anterior points on the left and right pubic tubercles. The user marks the two ASISs and pubic points, and the computer determines the transformation between this plane and the CT coordinate system, with the origin at the centre of the pubis. The Z axis is aligned with a vector between the centre point of the pubis landmarks and the centre point of the ASIS landmarks. The X axis is aligned with a vector between the two ASIS landmarks. Thus X and Z axes form the APP, with Y normal to it. The APP and FOR are shown in Fig. 3(a).

The acetabular FOR is based around the acetabulum, but is referenced back to the APP. Thus, if the pelvis position is transformed, the acetabulum FOR will move with it. Two aspects of the acetabulum are used to determine its FOR. First a set of at least eight points is picked on the surface of the acetabulum (which is assumed to be approximately spherical) and a sphere-fitting algorithm determines the centre point, which becomes the origin of the acetabular FOR. Next a set of at least eight points is picked on the acetabular rim and a plane-fitting algorithm is used to determine the best-fit plane (making the assumption that the rim points are approximately planar). The normal to this plane pointing outwards from the acetabulum defines the anteversion and inclination angles of the acetabulum, and the combination of these with the origin determines the acetabular FOR (Fig. 3(b)).

2.3.2 Femoral coordinate frames

The main femur FOR is defined around the *piriformis fossa* at the top of the femur which is set as the origin. A point is chosen at the bottom of the femoral scan at the centre of the shaft. The vector from the *piriformis fossa* to this point defines the angular orientation of the femoral shaft in the anterior–posterior and medial–lateral views. For planning HR, the exact axial orientation of the shaft is not as important as it would be for a THR, so the axial orientation of the femur is aligned with the CT FOR. At present, with the small amount of femur available in the scans, axial orientation is difficult to assess. Features such as the lesser trochanter have been considered, but the position of this is too variable to obtain an accurate angular measurement [**19**, **20**]. If a precise measure of femoral head anteversion is required then additional scans of the distal end of the femur are added to the scanning protocol and additional points are taken on the posterior condyles at the knee [**21**]. These additional scans have a minimal impact on radiation dose.

The second FOR is for the femoral head which originates at the head centre. The head is assumed to be approximately spherical and surface points are used in a sphere-fitting algorithm to determine the centre and diameter. Typically with arthritic patients, the upper surface of the head is worn so this region is avoided during point picking. The femoral neck centre is found by fitting a plane passing through the greater trochanter, lesser trochanter, and anterior tubercle. The neck centre is picked from a view of the CT data at the projection of this plane and a vector is formed between the neck and head centres. This vector gives the head–neck angle and a relative anteversion angle. The femoral head FOR is referenced to the femur, so the femoral head can be transformed when the femur is transformed. The femur and femoral head FORs are shown in Figs 3(c) and (d).

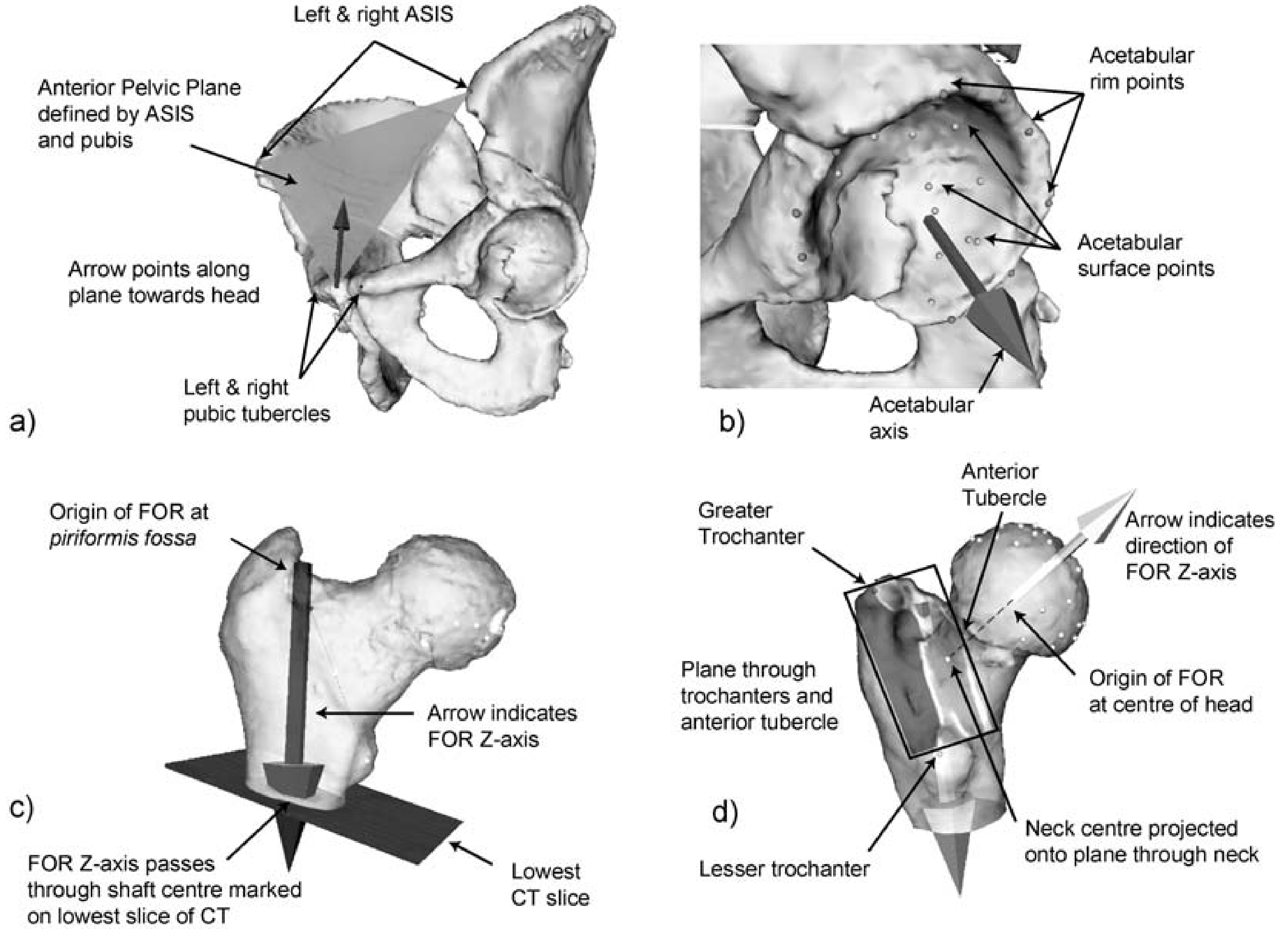

Fig. 3 (a) APP and pelvis FOR; (b) acetabulum FOR; (c) femur FOR; and (d) femoral head FOR

The point selection process within the coordinate frame definition stage has an impact upon the clinical measurements of joint position and orientation (both for the native joint and the reconstructed prosthetic joint), and particularly for cases of deformed anatomy. This is of particular importance for the neck centre and femoral shaft points since the femoral neck shaft angle is determined by these. It is essential for the surgeon to verify the point selections and to factor in aspects of abnormal anatomy when deciding upon the implant size and position. The plan should be tailored to the specifics of the patient rather than aiming for target clinical measurements (e.g. aiming for a cup implantation at 45° inclination and 15° anteversion is not ideal for every patient).

2.4 Implant positioning and visualization

The femoral and acetabular prosthesis components each have their own FOR, which are relative to the femoral head and acetabular FOR respectively. The default FOR for each component initially places the component at the position and orientation of the appropriate anatomical feature. The default size of the femoral head is chosen based on the closest match to the computed femoral head diameter. Changing a component's FOR will move it relative to its respective anatomical feature. The user moves a component to the desired location by pressing on-screen buttons to change its position and orientation.

The components are visualized on the three-dimensional bone models and both the bone and component transparencies can be adjusted, allowing the user to view the bone through the prosthesis or the prosthesis through the bone (the femoral component position is shown in Fig. 4(a)). In addition, the CT voxel data can be projected on to the three-dimensional model (Fig. 4(b)). Slices are shown along orthogonal axes aligned with the prosthesis, and the slices viewed can be moved along these axes. Notching of the femoral neck can occur in HR when the component is placed such that the cuts to accommodate it leave a lip around the base of the

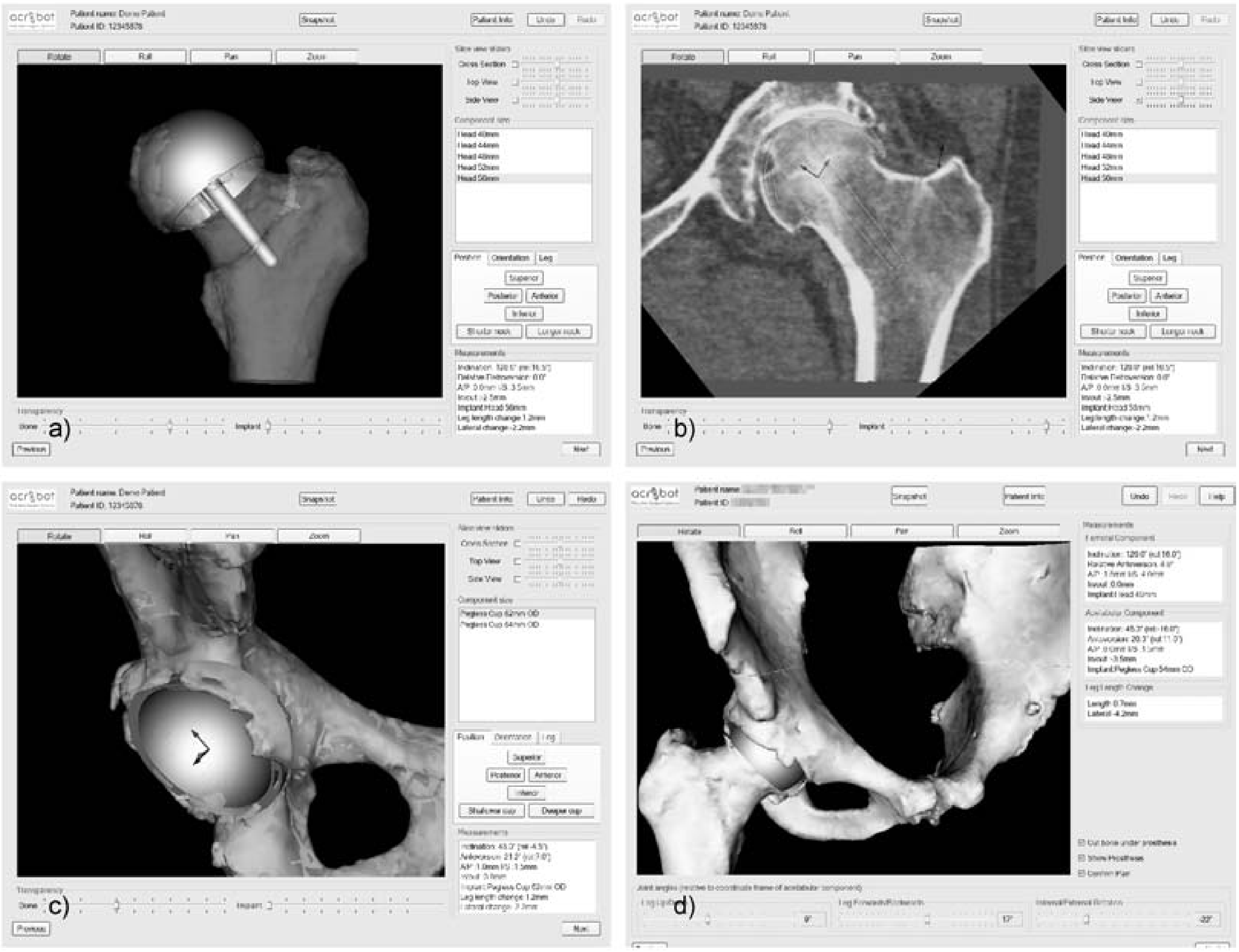

Fig. 4 (a) Femoral component planning; (b) femoral component outline on a slice reconstructed from the CT data in the AP plane; (c) acetabulum component planning; (d) joint motion view and impingement checking with excess bone removed. The joint can be moved manually in three orientations controlled by on-screen sliders

head giving rise to stress points. To avoid this, the slice views are used to ensure that no bone overlaps the head component at the component's base. The bone models may also be displayed in their prepared form, i.e. without the excess, which is removed during the surgical preparation of the bone.

The acetabular component is adjusted in the same way as the femur, but only two sizes are available (since these must match the chosen femoral component size). Again, CT cross-sections and the transparency feature help the user to ensure that the component is seated correctly (Fig. 4(c)).

Ideally, the leg length and lateral position of the femur remain unchanged in comparison to the pre-operative case. While the components are being positioned, changes in vertical and horizontal displacement of the femur are computed and displayed. Finally, once the prosthesis components are in place, the user can preview the motion of the joint (Fig. 4(d)).

3 REGISTRATION

The process of registration provides the missing link between the coordinate system where the procedure is planned and the coordinate system where the plan is executed. The intraoperative system incorporates a registration algorithm that uses a set of points measured with a mechanical digitizer on the exposed surfaces of the bone and the three-dimensional model surfaces produced during the planning stage [**22**]. As the accuracy of registration has a direct impact on the outcome of the navigated procedure, a novel point acquisition protocol has been developed to ensure consistently accurate registration.

3.1 Region-based acquisition protocol

The aim of any registration method is to establish accurately the transformation of one coordinate system to another. A robust registration method is one where this relationship can be derived with a high degree of confidence, irrespective of the environmental conditions (registration robustness being defined in this case to within ± 2 mm and $\pm 2^\circ$). For an algorithm that uses a set of points measured in one coordinate system and a surface measured in another coordinate system, the quality of both the point-set and the surface has a direct effect on the registration outcome. In the region-based point-touching protocol point-set quality is used as a direct measure of the registration outcome.

The quality of a point-set is defined in terms of three factors.

1. Accuracy of the points. Point accuracy is a representation of the extent to which the point-set fits the surface and is affected by a number of factors, which include point collection inaccuracies, the accuracy of the digitizing method, and the quality of the registration surface. The latter is affected by the quality of the bone and the accuracy of the CT scanner, scanning process, and segmentation.
2. Distribution of the points on the surface available for registration. Point distribution provides a direct measure of how accurately a set of points identifies a surface. Poor distribution would result in a poor representation of the surface, as a number of key features that give a surface its shape would not be located.
3. Number of points in the point-set. As point collection is time consuming, the number of points required for registration is important and should be minimized.

The regions shown in Fig. 5 highlight the areas where points should be acquired so that the registration is robust. These regions and the corresponding point totals (given in Table 1) needed in each region have been extensively validated on a simulation platform and *in vitro* experimentation [**1**], and have shown excellent results in intraoperative use.

4 INTRAOPERATIVE GUIDANCE

The intraoperative system is an Acrobot® Navigation System [**23**], which differs from other surgical navigation systems through the use of two mechanical tracking devices (Microscribe, Immersion Corporation) rather than optical tracking used by the majority. The use of two arms allows tracking of two objects simultaneously, namely the bone and the tool that is being used to prepare the bone. While optical tracking provides the ability to track more than two objects, the accuracy of mechanical tracking is greater, with a faster, realtime update rate and no line-of-sight issues; with optical tracking

Table 1 Numbers of points in each registration region

Femur		
Head	Greater trochanter	Lesser trochanter
20	5	5
Acetabulum		
Rim	Floor	Fovea
10	10	10

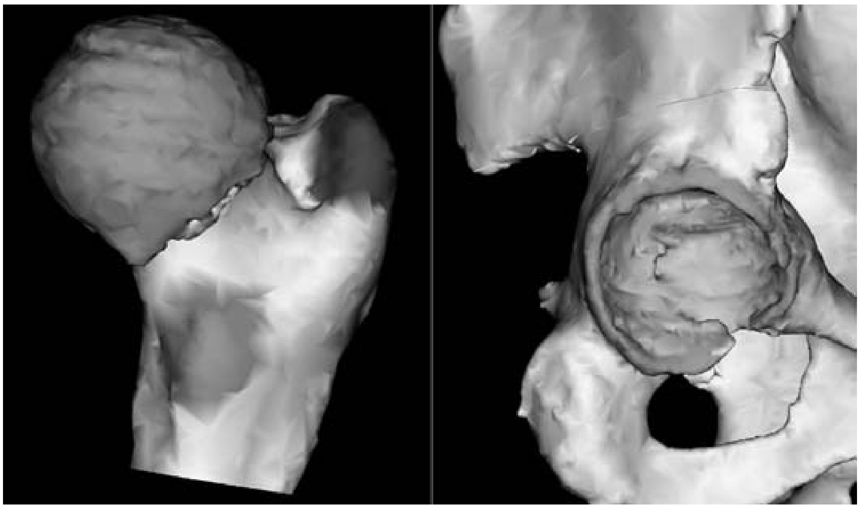

Fig. 5 Regions for point acquisition to give robust registration

the surgeon's head or other obstacle can obscure the infrared markers on the tool and cause loss of positional information. For hip resurfacing, and many other orthopaedic surgeries, tracking of more than two objects simultaneously is not required.

The plan prepared during the pre-operative planning stage is transferred to the intraoperative system. The intraoperative system is shown in Fig. 6.

4.1 Surgical approach

There are a number of standard surgical approaches to the hip, including antero-lateral, posterior, and anterior incisions. The Acrobot® Navigation System can be used with any of these approaches and there is significant potential for the system to be used with minimal incisions while maintaining accuracy.

Fig. 6 Acrobot® Navigation System incorporating mechanical tracking arms and touchscreen display

4.2 Patient positioning and bone reference interlock

The patient is placed on the operating table in the lateral position. The approach to the hip is made and the hip dislocated in the standard manner. A bone reference interlock is attached to the bone to be prepared (either femur or acetabulum, depending on the surgeon's preference of preparation order) using conventional cancellous bone screws. One of the tracking arms is connected to the bone reference interlock to allow realtime tracking of the bone position without the requirement to clamp the bone. The bone reference interlock is attached to the bone through the main incision, i.e. no additional stab wounds are made, in contrast to optical navigation systems.

4.3 Registration

The region-based acquisition protocol (section 3.1), which is iterative in nature, is enforced intraoperatively by the graphical user interface (GUI), which visually guides the surgeon through the point collection process. As illustrated in Fig. 7, the GUI shows the number of points still to be touched in each region before the registration phase is completed. As each point is collected a registration computation is performed so that the best estimate registration is shown on-screen. The registration's accuracy is checked by manual verification of the match between the probe position on-screen and in reality by touching on features of the anatomy (e.g. running the probe along the edge of the fovea and dropping off the edge – the on-screen probe should match the reality). As long as a valid registration estimate has been produced, it is always possible to override the acquisition process before the complete set has been acquired and proceed to the next step of the procedure.

4.4 Tool tracking and on-screen guidance

Information regarding the position of each surgical tool is provided by attaching the tools to the mechanical tracking arm. The appropriate tool is selected on the GUI, and the display shows the current and desired positions of the tool. The desired position is calculated according to the pre-operative plan. Examples of the guidance screens are shown in Fig. 8, where (a) shows the tool out of position and (b) shows the tool at the desired position. The desired position is achieved by moving the tool so that the cross-hair

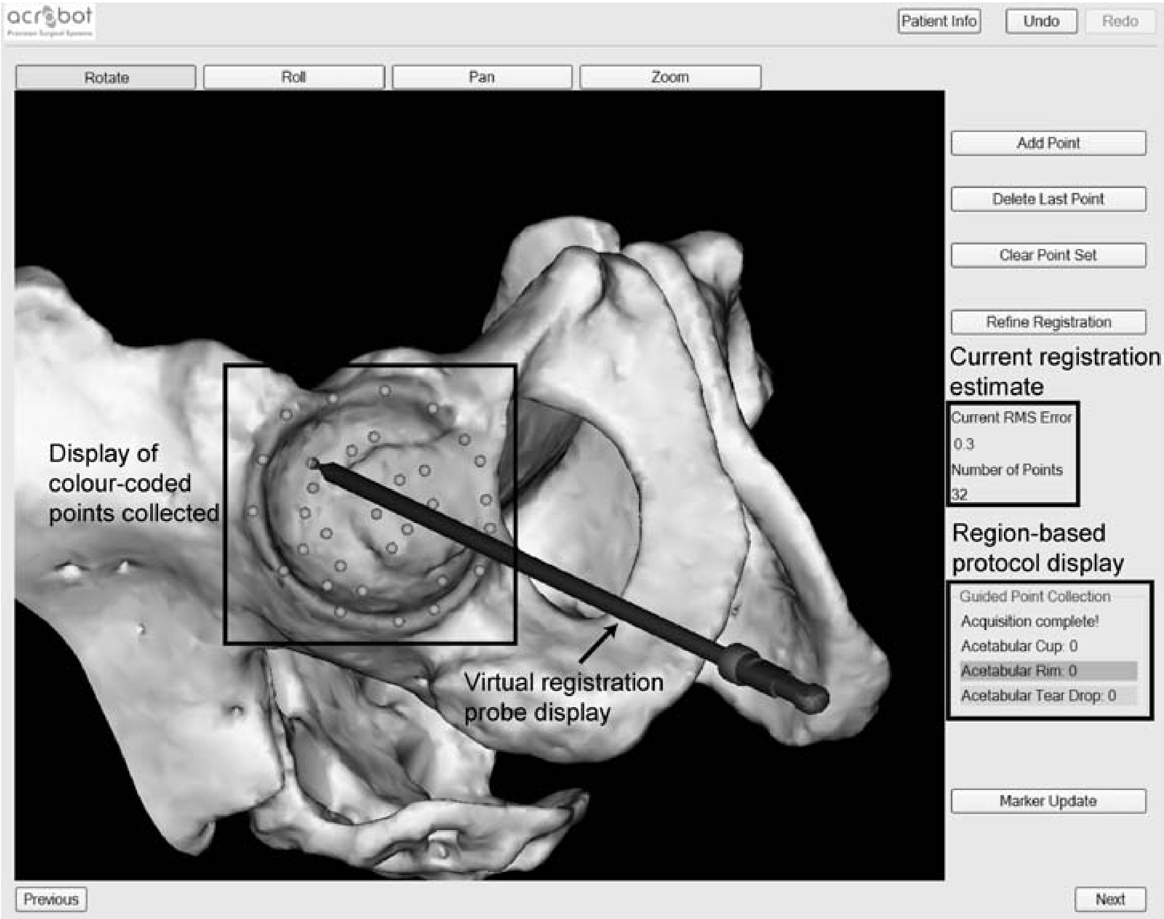

Fig. 7 Snapshot of the intraoperative registration GUI showing different elements of the display (highlighted with black rectangles)

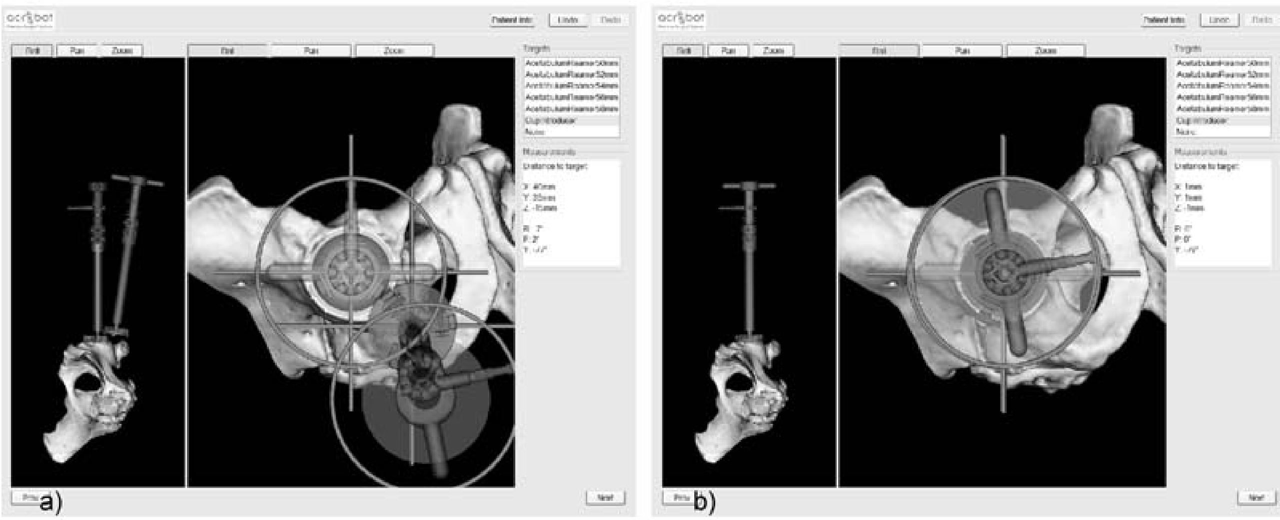

Fig. 8 Tool tracking and targeting: (a) off-target and (b) on-target

pairs (which coincide with the working tip of each tool) and the circle pairs (which coincide with the distal end of each tool) are matched. The depth to the desired position is shown as a dilating disc, which expands to the diameter of the guidance circle as the correct depth is reached. The colour of the disc also changes to green once the correct depth is attained; proceeding beyond the correct depth causes the colour to change through orange and then red, giving a visual warning to the surgeon. The GUI also shows the offset values for distance and orientation between the current position and the desired position. The tool tracking occurs in realtime, so there is no lag between on-screen motion and reality.

5 CT-BASED EVALUATION OF OUTCOME

The outcome measure of an orthopaedic arthroplasty operation has traditionally been an angular measurement of joint alignment based upon post-operative X-rays. However, there have been a number of studies showing that accurate measures of position and orientation on X-ray films are not possible (e.g. reference [**16**]) since they provide very little information outside their plane of view. The approach adopted in this paper provides a true measure of procedure outcome by measuring precisely what was achieved against what was planned in all three dimensions. This measure includes all the sources of error that are present within the procedure protocol, namely:

(a) errors inherent in the CT scanning process;
(b) discrepancies between the generated surface models and the actual patient bones (due to thresholding, segmentation inaccuracies, etc.);
(c) accuracy of the mechanical tracking arms;
(d) errors in the registration process;
(e) deviations of the achieved position of a tool from the displayed correct position of a tool;
(f) unintended motion between the arm tracking the bone and the bone itself;
(g) difficulties in impacting the prostheses into the planned positions.

The post-operative CT scan is thresholded at a high Hounsfield number so that only the metal of the prosthesis remains and a three-dimensional model is produced of the two components (Fig. 9(a)). Surface models of the actual components are matched to this model using a surface-to-surface registration algorithm [**25**], as shown in Figs 9(b) and (c). Figure 9(d) shows the computed position of both components while Figs 9(e) and (f) show the residual errors following the surface matching for the acetabular and femoral components respectively. The residual surface error maps extend from −0.8 mm to 0.8 mm.

The CT scan is re-thresholded and segmented at a lower Hounsfield number so that the bone surface is included in the model. The surface-to-surface registration is used to match the bone surface in the post-operative scan to the corresponding surface in the pre-operative plan. At this point, the pre- and post-operative implant positions are in the same coordinate system, so direct measurements of the implant error can be made in six degrees of freedom (three translational errors and three rotational errors). Figure 9(g) shows the planned versus achieved position of a non-navigated cup implantation, while Fig. 9(h) shows the corresponding image for a

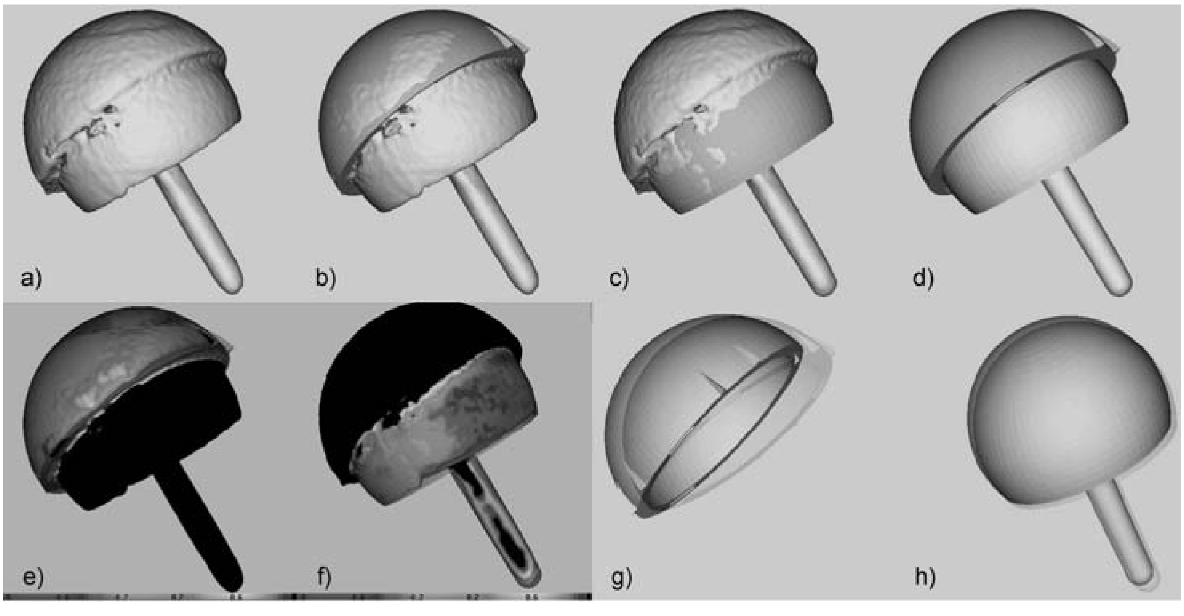

Fig. 9 CT-based comparison of planned versus achieved position for a navigated femoral component and conventionally implanted (non-navigated) acetabular component

navigated femoral component (planned positions are shown as solid and achieved positions as transparencies).

6 RESULTS

Figure 10 shows the navigation system being used in the operating theatre by the senior author (JPC) for drilling the guide wire into the femur. The mechanical tracking arm in the background is clamped on to the femur and tracks the bone position in realtime, so there is no requirement to clamp the bone. The tracking arm in the foreground navigates a drill guide whose relative position can be observed on the touchscreen.

Figure 11 shows some sample post-operative X-ray outcomes in comparison to the pre-operatively planned positions. While no quantitative information can be derived from these data, the qualitative results show a good visual match between the plan and the outcome.

Table 2 shows the quantitative errors in planned versus achieved positions for the femoral and acetabular components shown previously in Fig. 9 for one case (note that the components are symmetric around their central axis so a value for the axial rotation is not applicable).

7 DISCUSSION

While CT scanning and pre-operative planning does extend the time required to process a patient, the knowledge of the three-dimensional bone geometry before the procedure gives significant benefits to the surgeon since the full procedure can be visualized in virtual reality prior to the operating theatre. Inside the operating theatre, the plan is already determined and therefore the time required for navigation is solely to describe the position of the bones, at which point the surgery can proceed directly. It is the belief of the authors that this will allow the navigated procedure to be conducted without an intraoperative time penalty in comparison to the conventional procedure, and with a far greater degree of confidence about the positioning of the components on the bone.

Fig. 10 The Acrobot® Navigation System in use in the operating theatre

Table 2 Angular and linear displacement errors in planned versus achieved component placement

	Angular displacement (deg)		Linear displacements (mm)		
	Varus/valgus	Anterior/posterior	Medial/lateral	Anterior/posterior	Proximal/distal
Acetabular component (conventional)	8.3	−5.7	4.1	−3.4	3.6
Femoral component (computer-assisted)	−0.4	−1.8	0.8	−0.4	−2.2

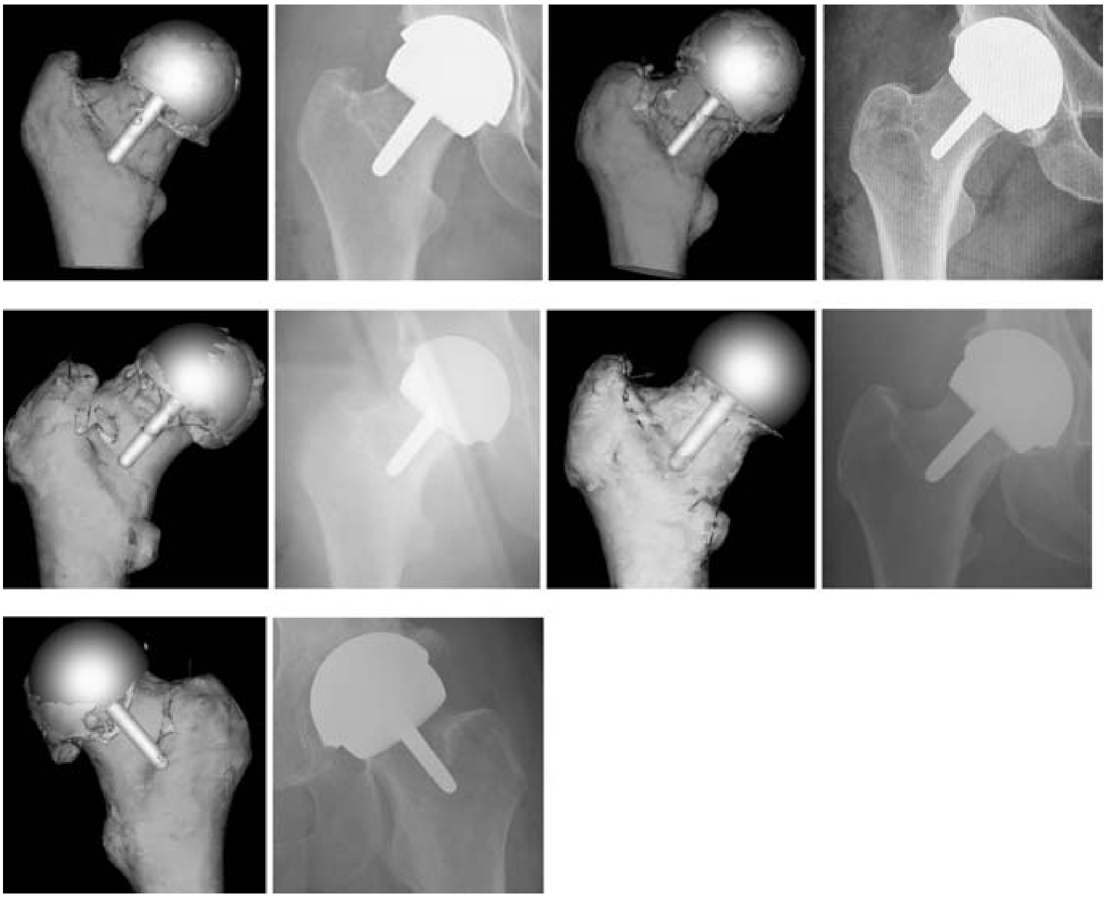

Fig. 11 Pre-operative images showing the planned position of the femoral component and the actual positions on the post-operative X-rays

The comparison of planned versus achieved results using CT data pre- and post-operatively gives an accurate measure of procedure outcome. This allows a true evaluation of the benefits of the navigation system on the full procedure level. In addition, accurate knowledge of achieved implant position coupled with future long-term patient outcome will drive the definition of the rules for optimal placing of the implants – something that has yet to be determined. This method has been used previously in computer-assisted knee replacements [**24**, **25**], but this is the first time it has been used for metal-on-metal components, which are much more difficult to distinguish in the CT data owing to excess artefacts.

8 CONCLUSION AND FURTHER WORK

This paper has presented the initial clinical use of a system for performing accurate hip resurfacing surgery using computer assistance based upon patient-specific CT data. These early results show that the system has the potential to allow surgeons to achieve good clinical outcomes without the intra-operative time penalty traditionally associated with computer navigation in orthopaedics. The system is currently undergoing final clinical tests prior to formal clinical studies.

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REFERENCES

1 **Barrett, A. R. W., Davies, B. L., Gomes, M. P. S. F., Harris, S. J., Henckel, J., Jakopec, M., Rodriguez y Baena, F. M.,** and **Cobb, J. P.** Preoperative planning

and intraoperative guidance for accurate computer-assisted minimally invasive hip resurfacing surgery. *Proc. IMechE, Part H: J. Engineering in Medicine*, 2006, **220**(H7), 759–773.
2 **Callaghan, J. J., Forest, E. E., Sporer, S. M., Goetz, D. D.,** and **Johnston, R. C.** Total hip arthroplasty in the young adult. *Clin. Orthop.*, 1997, **344**, 257–262.
3 **Chandler, H. P., Reineck, F. T., Wixson, R. L.,** and **McCarthy, J. C.** Total hip replacement in patients younger than thirty years old. *J. Bone Jt Surg. Am.*, 1981, **63**, 1426–1434.
4 **Dorr, D. L., Kane, J. T. III,** and **Conaty, P.** Long-term results of cemented total hip arthroplasty in patients 45 years old or younger. *J. Arthroplasty*, 1994, **9**, 453–456.
5 **Joshi, A. B., Porter, M. L., Trail, I. A., Hunt, L. P., Murphy, J. C.,** and **Hardinge, K.** Long-term results of Charnley low-friction arthroplasty in young patients. *J. Bone Jt Surg. Br.*, 1993, **75**, 616–623.
6 **Daniel, J., Pynsent, P. B.,** and **McMinn, D. J.** Metal-on-metal resurfacing of the hip in patients under the age of 55 years with osteoarthritis. *J. Bone Jt Surg. Br.*, 2004, **86**, 177–184.
7 **McMinn, D., Treacy, R., Lin, K.,** and **Pynsent, P.** Metal on metal surface replacement of the hip. Experience of the McMinn prosthesis. *Clin. Orthop.*, 1996, **329**(Suppl.), S89–98.
8 **Beaule, P. E., Amstutz, H. C., Le Duff, M.,** and **Dorey, F.** Surface arthroplasty for osteonecrosis of the hip: hemiresurfacing versus metal-on-metal hybrid resurfacing. *J. Arthroplasty*, 2004, **19**(8, Suppl. 3), 54–58.
9 **Berry, D. J., Berger, R. A., Callaghan, J. J., Dorr, L. D., Duwelius, P. J., Hartzband, M. A., Lieberman, J. R.,** and **Mears, D. C.** Minimally invasive total hip arthroplasty. Development, early results, and a critical analysis. *J. Bone Jt Surg. Am.*, 2003, **85**, 2235–2246.
10 **Berger, R. A.** Total hip arthroplasty using the minimally invasive two-incision approach. *Clin. Orthop.*, 2003, **417**, 232–241.
11 **Berger, R. A., Jacobs, J. J., Meneghini, R. M., Della Valle, C., Paprosky, W.,** and **Rosenberg, A. G.** Rapid rehabilitation and recovery with minimally invasive total hip arthroplasty. *Clin. Orthop.*, 2004, **429**, 239–247.
12 **Hungerford, D. S.** Minimally invasive total hip arthroplasty: in opposition. *J. Arthroplasty*, 2004, **19**(4, Suppl. 1), 81–82.
13 **Fehring, T. K.** and **Mason, J. B.** Catastrophic complications of minimally invasive hip surgery. A series of three cases. *J. Bone Jt Surg. Am.*, 2005, **87**(4), 711–714.
14 **Shimmin, A. J.** and **Back, D.** Femoral neck fractures following Birmingham hip resurfacing. *J. Bone Jt Surg. Br.*, 2004, **87**, 463–464.
15 **Shimmin, A. J., Bare, J.,** and **Back, D. L.** Complications associated with hip resurfacing arthroplasty. *Orthop. Clin. N. Am.*, 2005, **36**, 187–193.
16 **Thornberry, R. L.** Variability of digital X-ray measurement from CT measurement of mechanical axis of total knee arthroplasty. In Proceedings of the 4th CAOS, Chicago, Illinois, 2004, pp. 82–84.
17 **Harris, S. J., Barrett, A. R. W., Jakopec, M., Dandachli, W., Cobb, J. P.,** and **Davies, B. L.** Computer assisted planning for hip resurfacing replacement surgery. In Proceedings of the 5th CAOS, Finland, 2005, pp. 155–157.
18 **Lorensen, W. E.** and **Cline, H. E.** Marching cubes: a high resolution 3D surface construction algorithm. *Comp. Graphics* (*Proc. SIGGRAPH*), 1987, **21**, 163–169.
19 **Kingsley, P. C.** and **Olmsted, K. L.** A study to determine the angle of anteversion of the neck of the femur. *J. Bone Jt Surg. Am.*, 1948, **30**, 745–751.
20 **Murphy, S. B., Simon, S. R., Kijewski, P. K., Wilkinson, R. H.,** and **Griscom, N. T.** Femoral anteversion. *J. Bone Jt Surg. Am.*, 1987, **69**, 1169–1176.
21 **Dandachli, W., Richards, R., Harris, S. J., Barrett, A. R. W., Davies, B. L.,** and **Cobb, J. P.** A practical reference coordinate system for planning hip resurfacing surgery. In Proceedings of the 5th CAOS, Finland, 2005, pp. 78–80.
22 **Rodriguez y Baena, F. M.** *Improving accuracy in robotic assisted orthopaedic surgery.* PhD Thesis, Imperial College London, London, 2004.
23 **Barrett, A. R. W., Cobb, J. P., Jakopec, M., Harris, S. J., Rodriguez y Baena, F. M.,** and **Davies, B. L.** The tubes for minimally invasive computer-assisted hip resurfacing surgery. In Proceedings of the 5th CAOS, Finland, 2005, pp. 22–24.
24 **Henckel, J., Cobb, J. P., Richards, R., Harris, S. J., Jakopec, M., Rodriguez y Baena, F. M., Barrett, A. R. W.,** and **Davies, B. L.** Computer assisted arthroplasty; appropriate imaging for assessment of implant position. In Proceedings of the 4th CAOS, Chicago, Illinois, 2004, pp. 16–19.
25 **Henckel, J., Cobb, J. P., Harris, S. J., Jakopec, M., Rodriguez y Baena, F. M.,** and **Davies, B. L.** Accuracy in arthroplasty: a 3-dimensional CT based measurement study. In Proceedings of the 5th CAOS, Finland, 2005, pp. 165–167.

APPENDIX

Notation

APP	anterior pelvic plane
ASIS	anterior superior iliac spine
CT	computed tomography
DICOM	Digital Imaging and Communications in Medicine
FOR	frame of reference
GUI	graphical user interface
HR	hip resurfacing
THR	total hip replacement