Computer Assisted Hip Resurfacing Using Patient-Specific Instrument Guides

Manuela Kunz and John F. Rudan

Abstract Hip resurfacing is considered to be a viable alternative to total hip replacement in the treatment of osteoarthritis, especially for younger and more active patients. There are, however, several disadvantages reported in the literature, due to difficult surgical exposure and the technical challenges of the intraoperative procedure. Surgical errors, such as notching of the femoral neck, tilting of the femoral component in excess varus, or improper prosthesis seating, can result in early failure of the procedure. In this chapter we discuss the use of patient-specific instrument guides as an accurate and reliable image-guided method for the placement of the femoral and acetabulum components during hip resurfacing. The outcome of patient-specific guided procedures depends on many factors, starting with the accurate depiction of the anatomy in a preoperative image modality, the careful selection of registration surfaces for the guide, the accuracy of the guide creation, as well as the reliability of the guide registration intraoperatively. We will discuss in detail how current research is addressing these points in patient-specific instrument guided hip resurfacing applications.

1 Introduction

Total Hip Arthroplasty (THR) is considered the number one treatment choice for patients with advanced hip disease. However, when younger and more active patients started to seek hip replacement in an attempt to restore an active life style, disadvantages of THR—such as limited revision possibilities and partial range of hip motion—became a restrictive factor and accelerated research into more bone-preserved hip replacement options. In 1977, Amstutz et al. [1] first introduced

M. Kunz (✉)
School of Computing, Queen's University, Kingston, ON, Canada
e-mail: kunz@queensu.ca

J.F. Rudan
Department of Surgery, Queen's University, Kingston, ON, Canada

G. Zheng and S. Li (eds.), *Computational Radiology for Orthopaedic Interventions*, Lecture Notes in Computational Vision and Biomechanics 23, DOI 10.1007/978-3-319-23482-3_17

a method for total hip articular replacement, in which a cemented cobold (Co) and chromium (Cr) femoral component articulated with an all-polyethylene acetabulum component. However, with a 10-year survival rate of only 61.5 % [2], the prosthesis was far inferior to THR. In the early 90s it was established that increased polyethylene wear debris, generated by large femoral heads articulating with ultra-high-molecular-weight polyethylene (UHMWPE), was the main reason for failure of the early designs, and low-wear bearing metal-on-metal became the standard material for Hip Resurfacing Arthroplasty (HRA). Since then, 10-year survival rates of between 92.9 % [2] and 99.7 % [3] have been reported, making hip resurfacing arthroplasties a valuable alternative to total hip arthroplasies, especially for younger and active patients.

The advantages of HRA compared to THR include: preservation of femoral bone stock (ease of revision) [4], lower dislocation risk [5], as well as improved Range of Motion [6]. Studies measuring patient satisfaction found that the outcome of the procedure met patients' expectations in terms of pain relief and improvement of hip function [7, 8]. On the other hand, the literature reports a series of postoperative problems unique to HRA such as femoral neck fractures, adverse local tissue reaction, and increased blood metal-ion levels.

1.1 Femoral Component Positioning

Many studies have reported femoral neck fractures as the main reason for early failures of hip resurfacing procedures [9–11]. Notching of the femoral neck during preparation of the proximal femur, it was found, increases the risk for postoperative fractures [12]. Finite element analysis [13] has demonstrated that the stress riser created by the femoral component is due to the disparity of the high-stiffness CoCr prosthesis versus the low-stiffness femoral neck. The same study showed that superior femoral neck notching will further concentrate stress at the rim of the femoral component, increasing the risk of neck fracture even further.

Further, mal-alignment of the femoral component was also identified as a stress riser for the femoral neck, leading to greater risk for femoral neck fractures. Various studies have shown the importance of aligning the femoral component in a valgus orientation (with respect to the anatomical neck-shaft angle) for optimal postoperative outcome [3, 9, 11, 14].

Besides the alignment, the seating of the femoral component at the prepared proximal femur influences the postoperative fracture risk. For optimal stabilization of the trabecular bone, the femoral component needs to completely cover the reamed cancellous proximal femur bone [11, 15].

During the preparation of the femur, a minor amount of bone of the proximal head is resected (Fig. 1) to allow for the thickness of the femoral component. The under- or over-resection of the proximal femoral head can result in changes in the femoral

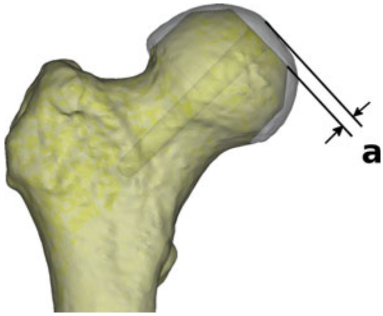

Fig. 1 Depth of the resection of the proximal head to allow for the femoral component thickness

offset[1] and leg-length postoperatively. The literature demonstrates that for an optimal functional outcome, leg-length restoration [16, 17] and femoral offset [18–20] play an important role. Recently, various studies have shown offset and leg-length changes after HRA. Silva et al. [21] found that compared to preoperative values, the postoperative offset significantly decreased by a mean of 0.8 mm, while the postoperative length of the treated leg significantly increased by a mean of 4.6 mm. In an in vivo study, Loughead et al. [22] found a significant reduction of offset from a preoperative average of 49.4 to 44.9 mm postoperatively. This reduction in postoperative femoral offset was also observed by Girard et al. [23]: they measured an average decrease of 3.3 mm. The authors of this study also observed an average shortening of leg length of 1.9 mm. In contrast, a study with 28 patients found an average postoperative leg length increase of 4.9 mm [24]. The authors of this study also observed a decrease of femoral offset by 1.3 mm on average.

Although the published results for offset and leg-length changes following HRA are often significantly smaller compared to THR studies, they still indicate non-optimal postoperative biomechanical reconstruction of the hip. In particular the decrease in femoral offset can negatively influence the hip's function.

1.2 Acetabular Component Alignment

Although the role of the femoral component alignment with respect to postoperative outcome is well known, the role of acetabulum component alignment is less certain. Recent studies suggest that improper alignment of the acetabulum component might be connected to increased metal ion levels, as well as unexplained postoperative pain. Abnormal periprosthetic soft-tissue lesions (also know as pseudotumor, or adverse reaction to metal debris) have been reported after metal-on-metal HRA with an incidence rate of up to 4 % [25] for asymptomatic hips and were linked to an increased blood, serum and hip aspirate level of cobold (Co) and chromium

[1]The femoral offset is defined as the distance between the center of rotation of the femoral head and the long shaft axis of the femur, measured perpendicular to the femoral long axis.

(Cr) [26, 27]. This correlation indicated that these abnormal periprosthetic soft-tissue lesions could have been the result of increased component wear, a hypothesis confirmed in retrieval studies [28, 29]. These studies also indicated that edge-loading[2] with the loss of fluid-film lubrication may be a likely reason for the wear. Follow-up studies have investigated this connection successfully [30, 31]. Various authors have found connections between acetabulum component alignment and the occurrence of edge-loading and high metal-ion levels [27, 31–34]. Recent publications investigate optimal acetabulum component alignment. Langton et al. concluded [27] as a result of an in vivo study that there is a correlation between acetabulum inclination angle and high levels metal ions, but that the maximum limits for inclination depended on the prosthesis type. In 2013 Liu and Gross [35] suggested that the "safe zone" for the acetabulum inclination angle varies depending on component size. In 2015 Mellon et al. [12] suggested that optimal acetabulum component alignment is patient-specific.

1.3 Image-Guided Hip Resurfacing

Most of the limitations and problems discussed above are controlled by the surgeon's actions intraoperatively, with only small margins of error. Therefore, it is not surprising that HRA is deemed a technically challenging procedure with a significant learning curve [11, 36]. Various authors have discussed the advantages of using image-guided, or computer-assisted systems to help surgeon improve the accuracy of HRA.

In 2004, the first clinical results using a fluoroscopy-based navigation system for positioning of the femoral component during hip resurfacing was published [37]. In this study, four intraoperatively registered fluoroscopy images of the hip were used to navigate the insertion of the femoral central pin. Deviation between the intraoperative targeted and the postoperatively achieved central pin alignment in 31 cases were measured using standard postoperative x-rays. The reported average was 2.6°, with no postoperative complications reported. However, the authors did identify an increase in operating time of 10–15 min in the last 10 cases of the series.

El Hachmi and Penasse [38] compared mid-term postoperative outcomes between patients where the conventional method for femoral guide pin placement was used and patients, in which the femoral guide pin was placed using the BrainLab Hip Essential navigation system (BrainLAB AG, Feldkirchen, Germany). In this imageless navigation system a point/surface acquisition is used to generate a three-dimensional (3D) model of the femoral head and neck and to measure the anatomical 3D neck-shaft angle. Although patients from both groups showed significant mid-term clinical improvement, the authors found a significant reduction of

[2]Contact between the femoral and acetabulum component at the edge of the acetabulum component.

outliers in femoral pin placement for the navigated group in both anterio-posterior (AP) and lateral postoperative x-rays.

In a similar study by Bailey et al. [39], 37 patients who underwent HRA, in which the femoral central pin was navigated using the imageless BrainLab Ci ASR navigation system (BrainLAB AG, Feldkirchen, Germany), were followed up with a 4-month postoperative CT scan. The measured average deviation between the targeted and postoperatively measured femoral component angle in the frontal plane was 0.5°.

In 2007, Hodgson et al. [40] reported improved repeatability in varus/valgus placement of the femoral central-pin when using a CT-based, opto-electronic navigation system versus manual technique. Further, there was no significant dependence on surgeon skill level (in contrast to the manual technique), and surgical time was significantly reduced in the navigated group. However, the authors of this in vitro study also noted a reduced reproducibility in version alignment of the central-pin of the navigated group, compared to the manual group.

The influence of using a navigation system on the learning curve for femoral central-pin placement during HRA was investigated in an in vitro study by Cobb et al. [41]. Students inexperienced in HRA performed central-pin placement, either with conventional methods or by using the CT-based, mechanically tracked Wayfinder system (Acrobot Co Ltd, London, UK). After each procedure the femur model was reregistered and a CT-based navigation system (Acrobot Co Ltd, London, UK) was used for 3D evaluation of the pin placement. The authors found that students using the navigation method performed the placement three times more accurately compared to the non-navigated group, and suggested that navigation may play a major role in reducing the length of the learning curve for HRA.

Similar observations about the reduction of learning curves using the imageless BrainLab navigation system were published by Romanowski and Swank [42], as well as Seyler et al. [43].

These published results suggest that computer assistance can help achieve higher accuracy and/or precision during the intraoperative process, and could reduce the learning curve for inexperienced surgeons in hip resurfacing. However, disadvantages with computer assistance include additional technical equipment in the operating theater; matching the intraoperative action to the imaging modality; and a time-consuming intraoperative registration process.

In 1994, Rademacher et al. [44] first described individual (or patient-specific) templates as an easy-to-use and cost-effective alternative for computer-assisted orthopaedic surgeries. The principle of the individualized templates was to customize surgical templates based on 3D reconstruction of patient-specific bone structures. Small reference areas of these bone structures were integrated into the template and an instrument guidance component (e.g., drill sleeve, etc.) was attached. By this means, the planned position and orientation of the instrument guide in spatial relation to the bone was stored in a structural way, which could then be reproduced intraoperatively by fitting the references areas of the template to the bone. Other authors subsequently published the results of various applications of individualized templates including pedicle screw fixation [45], computer-guided reduction of acetabulum fractures [46], and cervical pedicle screw placement [47].

Although this novel method was well-received in the research community, it did not transfer to clinical use, mostly due to the inaccessibility of the prototype technology used to create such templates. However, with the development of inexpensive and more accessible additive manufacturing technologies in the last 10 years, patient-specific templates have made a strong comeback in orthopaedic research and clinical use [48–52].

In the following sections, we describe how individualized templates, also known as patient-specific instrument guides, are currently used to navigate hip resurfacing procedures.

2 Patient-Specific Instrument Guides for Femoral Central-Pin Placement

Most published applications for patient-specific instrument guides in hip resurfacing are in the placement of the femoral central-pin. In the majority of hip resurfacing systems, the placement of the femoral central-pin (also know as the guide-wire) is a crucial step for the accuracy of femoral component alignment since it identifies the final femoral component orientation, as well as 2 of the 3 degrees of freedom for femoral component positioning. Only the position of the component along the central-pin axis is not directly determined during the central-pin placement.

Conventional instrument sets provide mechanical guides designed to help the surgeon to connect intraoperative actions to preoperatively planned pin alignment. However, the preoperative planning is often performed on a 2D x-ray, which may result in possible projection errors. Furthermore, the mechanical guidance tools are used in a very limited surgical exposure and are therefore challenging to use. Last but not least, mechanical guidance tools are designed to provide navigation for an average patient population, and are therefore not necessarily optimal for a specific patient.

Various research groups have published methods and results for patient-specific femoral central-pin guidance tools to replace general mechanical guidance tools. In a review of the literature it is apparent that the proposed methods can be split into two different groups of patient-specific femoral pin placement guides. They mainly differ in the anatomical area in which the guide is registered. While some authors choose the femoral head as a registration surface, other authors prefer the femoral neck area for registration of the guide. So far, published accuracy studies do not show a substantial difference between the two types of guides.

In 2013 Du et al. [53] published the result of a randomized study in which the accuracy of femoral central-pin placement using a patient-specific guide compared to conventional pin placement techniques was investigated. In this study, the guide was registered to the femoral head surface. In an postoperative radiographic analysis of 34 patients, the authors found that using the guide significantly improved the accuracy of the femoral component neck shaft angle with an average of 137° (targeted angle was 140°), compared to an average angle of 121° for the conventional surgical group. Using a similar design for the patient-specific instrument guide, Zhang et al. [54] also found a significant increase of accuracy in femoral component placement. In their randomized study of 20 patients, the conventional method for femoral pin placement was compared to the placement using a patient-specific guide, which was registered to the medial aspect of the femoral head. Measurements of postoperative x-rays showed, that the use of the guide in this study significantly reduced the average deviation between the neck-shaft angle and the actual implanted short neck-shaft angle from 10.2° for the conventional group to 1.3° in the navigated group.

In an in vitro study, Olsen et al. [55] compared the outcome of conventional, imageless optoelectronic-guided and patient-specific instrument-guided techniques. The guide in this application registered mainly to the femoral head, but it also contained a small registration area around the femoral head-neck junction. Pin placement accuracy was assessed by anteroposterior and lateral radiographs and was defined as the absolute mean deviation from the planned alignment values. Results of this study did not show an improvement in the femoral pin placement in the coronal plane using the patient-specific guide (average error of 6.4°) compared to the conventional method (average error of 5.5°). However, the authors found the average error of 1.3° for the imageless optoelectronic guided group was significantly smaller compared to both the conventional and patient-specific guided group. In contrast, when comparing the deviations in version angle, the patient-specific guided alignment was, with an average error of 1.0°, significantly better compared to the conventional group (5.6°). The same authors also compared the femoral component alignment error in the coronal plane using patient-specific guided and imageless optoelectronic guided procedure in a clinical study, and found no significant difference between methods.

All three groups—Du et al., Zhang et al., and Olsen et al.—suggested the use of a patient-specific femoral alignment guide, which was mainly registered on the femoral head. In comparison, Sakai et al. and Kitada et al. proposed the use of a patient-specific guide for femoral central-pin alignment, which was designed to fit on a small portion of the femoral head, to the posterior aspect of the femoral neck, as well as to the intertrochanteric region. Kitada et al. [56] tested the accuracy of femoral central-pin placement using the patient-specific guide in a laboratory study with synthetic femoral bone models, and compared the outcomes to errors in pin placement using both a CT-based optoelectronic navigation system and a conventional method. The analysis of postoperative CT obtained from the femoral bone models showed that the patient-specific guides had a significant influence in reducing the error of the stem-shaft angle: 2.4° compared to the stem-shaft angle error of −5.3° for the conventional method. No significant changes in the measurements of femoral pin placement were found between the patient-specific and optoelectronic guided methods. Using the same guide design, Sakai et al. [57]

investigated in an in vitro study the influence of the size of the surface for guide registration on the accuracy of femoral central-pin placement. The authors found that guides in which the contact area was approximately 25 % larger significantly reduced the absolute error of the insertion point for the central-pin compared to guides registering at the same anatomical surfaces, but with smaller contact areas. However, the authors did not see any significant changes in the orientation errors of the central-pin between the two guided groups, with absolute errors for neck-shaft angle of 2.6° in the smaller contact guides and 0.9° in the guides with larger contact areas.

Over a period of more than 6 years of research with patient-specific guides for femoral central-pin alignment, we changed our design from a guide that had an equal amount of femoral head and neck registration area to a design that relies mainly on the registration on the femoral neck (Fig. 2). In an early accuracy study [58] with 45 patients in which guides of the earlier design were used, we measured using a CT-based optoelectronic tracking system that in average, the intraoperatively achieved central-pin alignment deviated 1.1° in the frontal plane and 4.3° in the transverse plane, compared to the planned pin alignment. For the entrance point, we measured an average error of 0.1 mm in the frontal plane and 3.5 mm in the transverse plane. Analyzing our results, we suspected that a mis-registration of the guide on the femoral head was the reason for the substantially higher deviations in the version alignment and the anterior-posterior placement of the entrance point.

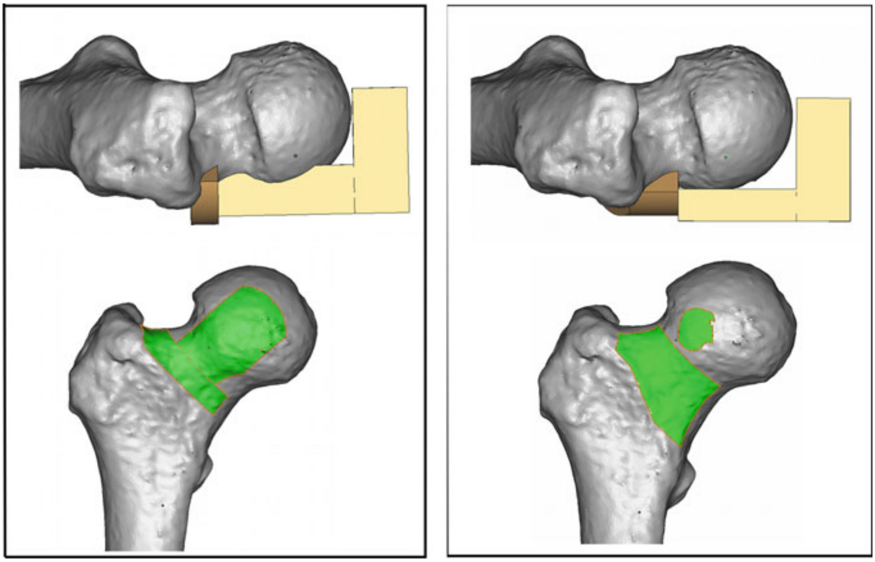

Fig. 2 Changes in patient-specific guide design for femoral central-pin placement. On the *left side* an older design, in which the guide registered to equal parts of the head and neck. On the *right side* the newer design, in which only a minor part of head is part of the registration surface. The *green areas* in the lower images represent the registration surfaces for each design (Color figure online)

Based on this hypothesis, we changed the design to minimize the involvement of the femoral head anatomy in the registration of the guide, and instead increased the contact area in the lateral aspect of the femoral neck. In 2011 [59], we reported on a consecutive study with 80 patients in which the alignment error for the central-pin was reduced to 0.05° in the frontal plane and 2.8° in the transverse plane. We found errors in the entrance point for the central-pin of 0.47 mm in the frontal plane and 2.6 mm in the transverse plane. Both alignment and positioning of the central-pin in the transverse plane seemed to have improved using the new guide design. However, we did not perform a direct comparison study in which we statistically evaluated the differences between the two guide designs.

From the 80 patients, 72 were operated with an anterolateral approach and 8 patients with a posterior approach. When analyzing our data with respect to approach, we found a tendency for the final pin alignment to be more retroverted and in valgus for the posterior approach and anteverted for the anterolateral approach. Also the direction for the deviation in the entrance point seem to be depending on the approach; as we found a more superior pin entrance for the posterior approach and more anterior for the anterolateral approach. A further investigation of the anterolateral approach cases revealed, that there was a significant correlation between increased anteversion deviation and anterior misplacement of the entrance point. This correlation, together with results from changes in error directions between both approaches, suggests that the errors in the anterolateral approach were the result of inaccurate registration of the patient-specific guide in the medial part of the anterior femoral neck and/or parts of the femoral head. Although we eliminated most of the articular surface from the registration, our data implies that there are still segmentation uncertainties in the femoral neck area. However, on the anterior femoral neck, especially on the junction between head and neck, there are often osteophytes (small bony protrusions), which might be the reason for the increased segmentation errors in this area. To investigate this relationship we performed further studies. The results of our investigation will be discussed in a later section of this chapter.

The following case report uses a patient-specific guide for femoral pin replacement, registered to the anterior aspect of the femoral neck.

2.1 Case Report

The patient, a 42-year-old male, presented in the orthopaedic clinic with a two-year history of right hip pain and a moderate degree of arthritic change in his hip. Once treatment options were discussed and the risks and benefits of hip arthroplasties reviewed, the patient decided on an HRA (Birmingham Hip Resurfacing System, Smith and Nephew, Memphis, USA) for the right hip, and consented to use of a patient-specific guide for femoral central-pin placement.

2.1.1 Preoperative Planning

A Computed Tomography (CT) scan of the patient's pelvis was obtained prior to the scheduled procedure. The scans were obtained in helical mode, with a slice thickness of 2 mm at 120 Kvp. During the scan, the patient was positioned as Feet-First-Supine. Using a commercially available software package Mimics (Materialise, Leuven, Belgium), three-dimensional surface models of the proximal femur and the acetabulum of the affected side were created (Fig. 3) and saved in steriolithography format (stl). For planning of size, position and orientation of femoral component, virtual 3D models were loaded into Mimics software and their position and orientation was manually manipulated until the surgeon was satisfied with the positioning.

The planned component size of 54 mm in diameter and the position of the femoral component were verified by virtual reaming of the femoral head (subtraction of the component model from the femur model) to identify any potential risk for notching. Furthermore, outlines of the planned component were superimposed onto orthogonal views of the CT dataset to identify any potential postoperative risk due to bone cysts in the femoral head (Fig. 3).

Based on the final planning for the femoral component, the central-pin orientation was determined with 134° varus and 4.05° anteversion.

For creation of the patient-specific guide, the virtual femur model, as well as the central-pin planning data, were loaded into custom-made software and displayed to

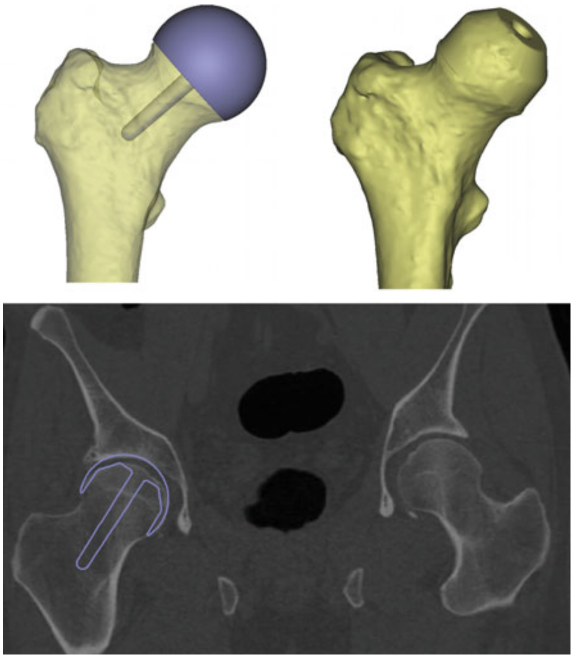

Fig. 3 Preoperative planning. *Top left* A model of the femoral component is superimposed onto the femur model. *Top right* Femur model is virtual reamed. *Bottom* Outlines of the femoral component are superimposed onto the CT dataset of the hip

the user. The user selected the size and position of the registration component of the guide. Bone surface for guide registration was chosen with respect to the following criteria:

- Surgical approach: The registration surface for the guide should be completely accessible. The chosen approach for this patient was anterolateral.
- Registration stability: A sufficient number of significant anatomical landmarks had to be covered to allow for unique positioning of the guide intraoperatively.
- Segmentation uncertainty: Anatomical surface areas with a higher potential for segmentation uncertainties (due to a missing joint gap between femur and acetabulum, or known region of osteophytes such as the femoral head-neck junction) must be avoided.

Based on these criteria, the registration part of the guide was constructed from two subcomponents. The first component was oriented along the anterior femoral neck, which ensured stable position and orientation of the guide along the neck axis. Because of the segmentation uncertainty in the articular surface of the head and head-neck junction, these regions were, as best as possible, eliminated from the registration surface, as shown in Fig. 2. The second registration subcomponent was a region oriented perpendicular to the neck axis, and positioned on the lateral aspect of the femoral neck. This ensured rotational stability around the neck (Fig. 4). To increase the overall stability of guide registration, this second registration component enveloped roughly 120° of the lateral femoral neck, measured with respect to the femoral neck axis.

Both registration subcomponents were united and a drill-guidance component was attached to the medial side of the guide. A drill guide channel was inserted into this guidance component, which was oriented along the planned central-pin trajectory as shown in Fig. 4.

A physical model of the patient-specific guide was created using a rapid prototype machine (dimension SST, Statasys, Inc., Eden Prairie, MN, USA). The material used for this 3D printing process was a thermo-plastic acrylonitrile

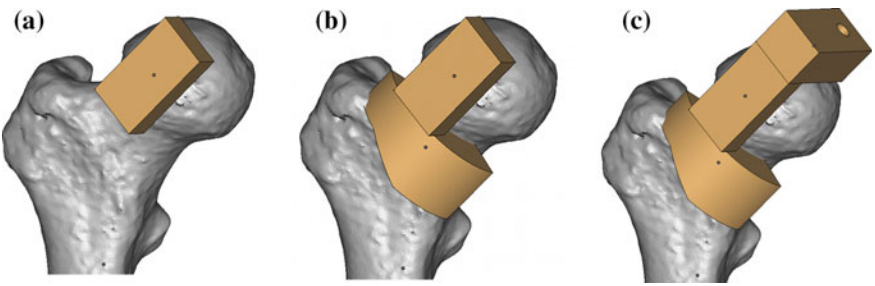

Fig. 4 Patient-specific instrument guide for femoral central-pin placement. **a** First registration subcomponent along the neck axis; **b** Second registration subcomponent on the lateral aspect of the anterior neck; **c** Attachment of the drill-guide component

butadiene styrene (ABS). Finally, the patient-specific drill guide and a plastic model of the patient's femur were gas plasma sterilized (STERRAD Sterilization System, Advanced Sterilization Products, a division of Ethicon US, LLC., Irvine, CA, USA), and labeled before being sent to the operating theater.

2.1.2 Intraoperative Procedure

After the patient was brought into the operating theater, a spinal anesthetic was administered and he was placed in a peg board in the left lateral decubitus position with the right side up. His right hip was prepped and draped in the usual fashion. An antero-lateral approach was performed and the femoral head was dislocated (Fig. 5a). Inspection of the femoral head and neck showed no significant osteophytes.

The surgeon fitted the patient-specific drill guide to the corresponding bone surface at the proximal femur (Fig. 5b) and a conventional metal drill sleeve was inserted into the drill guide channel (Fig. 5c). The central-pin was then drilled using a conventional power drill (Fig. 5d), after which the drill sleeve and the patient-specific guide was removed. In accordance with the conventional procedure,

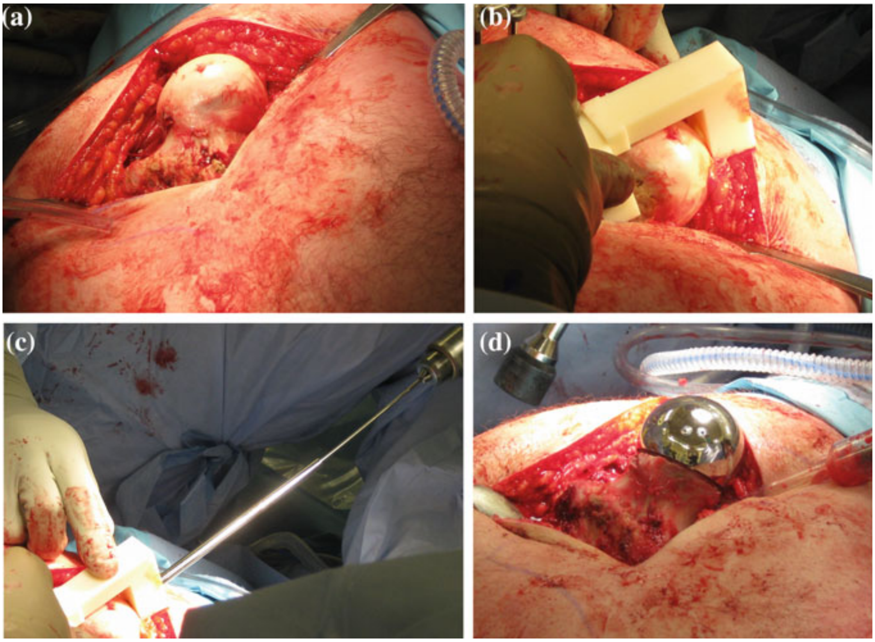

Fig. 5 Intraoperative procedure. **a** Surgical exposure of the proximal femur. **b** Registration of the patient-specific guide. **c** Drilling of the femoral central-pin, navigated by the patient-specific guide. **d** Final femoral component in place

Fig. 6 Accuracy measurement for achieved central-pin alignment. *Left side* After the attachment of an optoelectronic marker and successful registration a tracked pointing device was aligned inside the central-pin hole. *Right* Position and orientation of the tracked pointer were stored with respect to the CT coordinate system and deviation between planned and achieved central-pin alignment were determined

the central-pin was now overdrilled and the guide pin was removed. To measure the achieved central-pin alignment for the purpose of accuracy measurement, we utilized an optoelectronic tracking system (Certus Optotrak, Northern Digital Inc., Waterloo, Canada), with a company reported 3D accuracy of 0.1 mm and a resolution of 0.01 mm. After an optoelectronic marker was attached to the proximal femur, a registration between anatomy and CT model was performed, using a robust method for surface-based registration [60] with reported submillimeter root-mean-square error in the presence of spurious data. After successful registration a tracked pointing device was used to capture the 3D position and orientation of the femoral guide hole (Fig. 6) in the CT coordinate system. After storing this information, the optoelectronic marker was detached from the femur and the remaining steps for the preparation of the proximal femur were performed in the conventional manner. After final preparation and verification, the femoral component was filled with bone cement and impacted into position (Fig. 5, bottom right).

2.1.3 Results

The intraoperatively achieved central-pin alignment was 134.1° varus and 7.05° anteversion, only slightly more varus (0.12°) and 3° more anteverted compared to the planned alignment. When comparing the entrance point on the proximal head we found that the final central-pin position was 0.8 mm more distal and 0.2 mm more anterior compared to the planned positioning.

During the final steps of the proximal femur preparation, the surgeon chose to change the planned femoral component size from 54 mm diameter to a 52 mm diameter femoral head.

2.2 Discussion

The application of patient-specific instrument guides for the navigation of femoral central-pin placement during HRA procedures shows promising results in laboratory, in vitro and in vivo studies. So far, all studies that compared outcome between patient-specific guided to conventional methods have shown an increase in accuracy for pin placement using patient-specific instrument guides.

There seems to be so far no agreement about optimal registration areas for the guide, as both the femoral head as well as the femoral neck is used in the literature and similar results are measured with both guide designs. In any case, we believe that patient-specific guide for the navigation of femoral central-pin placement has the strong potential for routine clinical use, since it provides for a complex and challenging surgical action an easy-to-use and accurate solution. However, for the introduction into a clinical routine use, more research in the complete system, containing the preoperative preparation of the guide, as well as the intraoperative procedure, needs to be done. So far studies have only investigated the intraoperative procedure and have not taken time and complexity of the preoperative guide design into account. It might be from interest to review and develop procedure and algorithms for improved and efficient preoperative patient-specific guide design methods.

3 Patient-Specific Instrument Guides for Femoral Resection Depth Navigation

Although the use of patient-specific instrument guides for central-pin placement is well discussed in the literature, so far, the use of image-guided methods for navigation of proximal bone resection, and with this the position of the femoral component along the central-pin, is not investigated widely. In a randomized pilot clinical trial, we investigated whether adding simple navigation features to our femoral central-pin patient-specific guide could improve the accuracy of proximal femur head resection.

We performed a randomized trial with 10 patients scheduled for a patient-specific instrument guided HRA. The same surgeon operated on all patients and the prosthesis used in all procedures was the Birmingham Hip Resurfacing Implant (Smith and Nephew, Memphis, USA). In 6 of these 10 patients, the patient-specific guide used to navigate the femoral central-pin placement also had the resection depth navigation marks integrated as described below; while in the remaining 4 patients, these marks were missing. In these patients, the surgeon used the conventional methods to identify bone resection levels. Selection was randomized and the surgeon was not aware at the time of the planning whether the patient was in the conventional or navigated depth group.

During the preoperative planning, the surgeon identified the final position of the femoral component in addition to the location and orientation of the femoral central-pin and the femoral component size. To aid the surgeon in this planning step, a virtual 3D model of the femoral component was superimposed onto the femur model (Fig. 3). Changes in positioning along the central-pin axis were supported by the user interface. If required, horizontal and vertical offset could be measured in a frontal view.

During the virtual creation of the patient-specific instrument guide, notches were incorporated into the anterior head-neck part of the guide, which were aligned with the lower edge of the planned femoral component (Fig. 7). Intraoperatively, after the guide was registered to the proximal femur, an electrosurgical knife and/or surgical marking pen was used to transfer the position of the integrated notches onto the femoral head/neck junction (Fig. 8a, b).

During the use of the sleeve cutter, used to ream the femoral head, these marks were used to identify the depth of the reaming (Fig. 8). Once the teeth of the sleeve cutter were aligned with the marks on the femoral head, reaming was stopped. In the Birmingham Hip Resurfacing system, the sleeve cutters, which are unique for each femoral component size, have lines that mark the resection height for the proximal femur cut. With the sleeve cutter advanced to the navigated reamer stop, a surgical marking pen was used to mark the resection line on the bone surface through the 'window' in the sleeve cutter (Fig. 8d). For resection of the proximal bone, the plane cutter is advanced over the guide rod until it is aligned with the resection line on the bone surface. Final steps of preparing the proximal femur were performed in the conventional manner.

In all 10 cases, an optoelectronic navigation system was utilized for 3D evaluation of proximal femoral resection height. A Certus Optotrak (Northern Digital

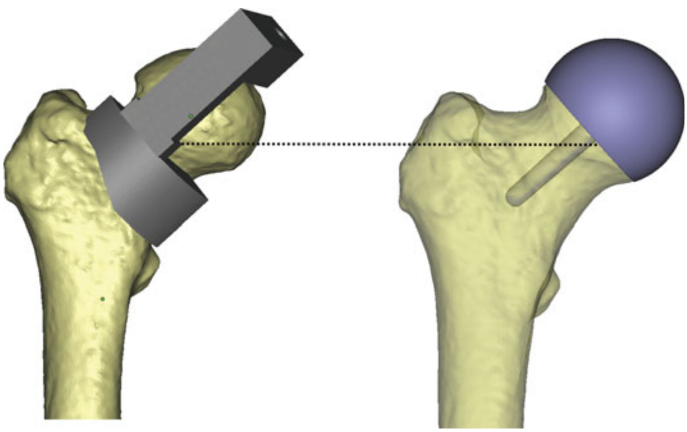

Fig. 7 Navigation of proximal femoral resection depth. Notches in the patient-specific instrument guide were aligned with the lower edge of the planned femoral component, to mark the stop of the required reaming of proximal bone

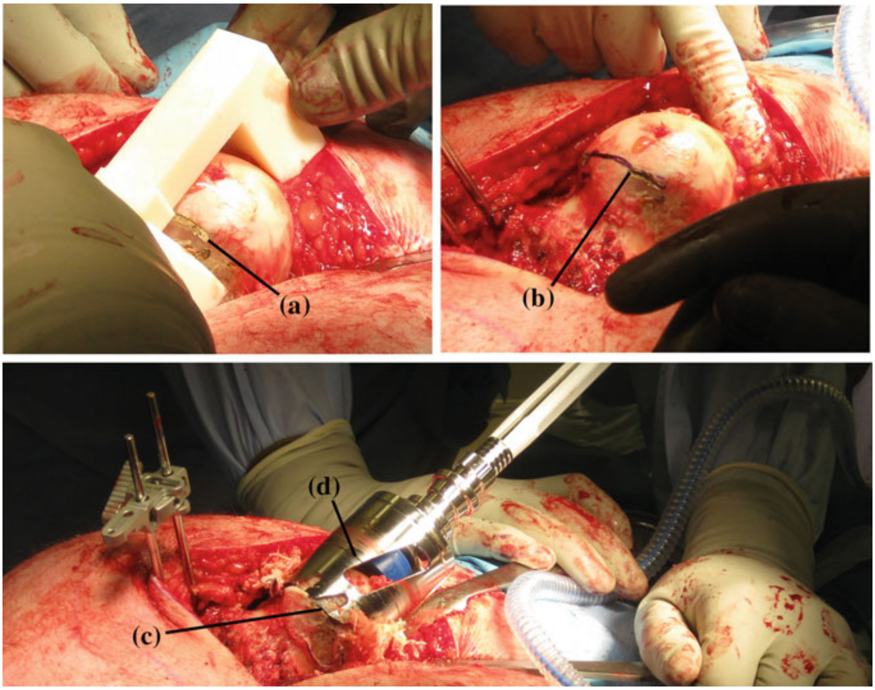

Fig. 8 Navigated reaming. *Top left* With the patient-specific instrument guide in place, the level of the integrated marks were transferred onto the femoral head using a electrosurgical knife (**a**). *Top right* A surgical pen was used to make the marks more apparent on the head (**b**). *Bottom* The sleeve cutter was advanced until the teeth aligned with the femoral head marks (**c**). In this position, the *marks* in the sleeve cutter (**d**) were used to mark the resection line for the plane cutter on the proximal head

Inc., Waterloo, Canada) was installed in the operating theater for this purpose and an optoelectronic marker was attached to the proximal femur. For registration, a combined pair-point and surface matching was performed. After successful registration, a tracked pointing device was used to collect 4–7 points on the femoral proximal resection plane. Care was taken to distribute these points as widely as possible.

Postoperatively, the collected points were transferred into the CT coordinate system and a 3D plane (surgical resection plane) was mathematically fitted. The distance between the surgical resection plane and the planned resection was determined and evaluated. Distance between both planes was calculated along the central-pin axis.

We found that the surgical resection height in the six cases in which the resection height marks were integrated into the patient-specific guide was on average 0.4 mm larger (range, 3.2 mm smaller to 1.9 mm larger) versus the planned resection height. In comparison, in the group in which resection height was navigated using conventional methods, the resection height was on average 3.6 mm larger (range, 0.7 mm larger to 6.5 mm larger) compared to the planned resection height. The difference in resection height errors in these two groups was significant ($p < 0.02$[3]).

3.1 Discussion

Proximal femoral resection height influences the postoperative femoral offset and leg length changes, and further, this has a direct link to the biomechanical reconstruction of the joint [17, 18, 20]. Like previous studies [21–24], we observed a tendency to over-resect proximal femoral bone during conventional resection of the femoral head, consequently decreasing the femoral offset. A postoperatively decreased femoral offset is linked to various functional problems of the hip, such as soft-tissue tension, impingement, and loss of abductor muscle strength. However, we found that simple features integrated into the patient-specific instrument guides which link the preoperatively planned component position to the intraoperative procedure of preparing the proximal femoral head can significantly decrease the error in proximal resection height. Our hypothesis is that such increased accuracy in femoral head resection can ensure a better postoperative biomechanical outcome for the hip resurfacing procedure.

4 Patient-Specific Instrument Guides for Acetabulum Cup Orientation

The importance of the acetabulum component orientation for the long-term success of hip resurfacing has been discussed more often recently and has triggered interest in easy-to-use and accurate intraoperative navigation possibilities for acetabulum cup orientation. However, to date most published research for patient-specific acetabulum component alignment guides is focused on total hip arthroplasty applications [57, 61–65]. Although the procedure for preparation and impacting of the acetabular component during a THR is similar to the procedure performed during a HRA, a different surgical exposure of the acetabulum during HRA might not allow an easy translation of patient-specific acetabulum component alignment guides from THR to HRA. For example, we believe that it might not be possible to register a guide at the acetabulum rim during a hip resurfacing procedure, due to the limited access to this feature. To our knowledge, so far only one group has published an acetabulum guide solution designed for HRA procedure. In 2011 Zhang et al. [54] introduced a concept for a patient-specific acetabulum component alignment guide for hip resurfacing procedures. As a registration area for the guide,

[3]Unpaired, one-tailed Student's t-Test.

the authors proposed the articular surface of the acetabulum cup. With the guide in place, the insertion of a 3.2 mm Kirschner wire in the center of the acetabulum cup was navigated using an integrated guidance cylinder. After removing the guide, the wire was used to guide a custom-designed cannulated reamer. The accuracy of the proposed method was compared to the conventional method for cup alignment in a study with 20 HRA patients, using postoperative CT scans of the hip. The measured average error in the abduction angle of 1.2° and the average error of anteversion angle of 2.1° were both significantly smaller compared to the errors in the conventional group.

5 Osteophytes: Limitations for Patient-Specific Instrument Guides Procedures?

As discussed in previous sections, a majority of authors report a significant overall improvement of intraoperative accuracy using patient-specific instrument guides. However, there are repeated reports of outliers, in which the intraoperatively achieved instrument trajectory was notably deviated from its planned position and/or orientation [66–68]. The most likely reason for such problems is poor registration of the instrument guide intraoperatively. An exact registration between the guide and the anatomy requires that the registration surface of the guide be chosen with sufficient registration features. Furthermore, the registration surface of the guide has to be a mirror image of the anatomy. To achieve such geometrical fit, the preoperative image modality (such as CT or MRI) from which the guide is designed needs to depict the real anatomy accurately. Particularly in patients with osteoarthritis (which is the main reason for joint replacement surgeries such as hip resurfacing), this consideration might be vital, as the disease is characterized by the breakdown of articular cartilage accompanied by the changing of local bone anatomy [69]. One example of such bone alterations is the development of osteophytes—abnormal osteo-cartilagenous tissue that grows along joints [70], which are considered a major limiting factor for accuracy in image-guided surgeries. Research into osteophyte development has shown that osteophytes grow in four distinct stages [70, 71]. The osteophyte tissue in stages I and II has cartilage and fibrocartilage characteristics; in stage III an ossification process (impregnation with calcium) starts in the deepest cell layers of the osteophyte (closest to the bone). Stage IV is characterized by extended ossification within the central core. The resulting high variability in density and composition can interfere with an accurate depiction in medical image modalities, such as CT scans. The following clinical case will demonstrate the significance of this issue.

The patient was a 46-year-old man, scheduled for a resurfacing procedure of the right hip. Six weeks prior to the surgery, a CT scan of the hip was obtained. The scan was taken with a LightSpeed VCT scanner (GE Healthcare, Waukesha, USA) in helical mode, with a slice thickness of 2.5 mm, a peak kilovoltage of 120 kVp, and a pitch factor of 0.984375. During the scan, the patient was positioned Feet First-Supine and a bone imaging convolution kernel was used. The pixel size for the scan was 0.7 × 0.7 mm.

A 3D virtual surface model of the femur (Fig. 9) was created using the commercially available software package Mimics (Materialize, Leuven, Belgium, version 15). The CT images were loaded and a semi-automatic segmentation was performed, using thresholding algorithms as well as manual editing functions. An experienced user with the goal of representing the anatomical surface with the highest possible accuracy, including osteophyte depiction, performed manual editing, consisting of adding and/or deleting voxels to the threshold segmentation.

At this stage the position and orientation of the central-pin was determined and the femoral component size chosen. A patient-specific instrument guide for navigation of femoral central-pin placement was designed and a physical model of the guide was produced using a Rapid Prototyping machine (dimension SST, Stratasys, Inc., USA). Using the same thermo-plastic production process, a plastic model of the patient's proximal femur was created (Fig. 10). Both the plastic femur model, as well as the patient-specific instrument guide, were sterilized and sent to the operating theater.

During the surgery, an antero-lateral approach was performed and the proximal femur was exposed. The surgeon inspected the exposed anterior aspect of the femoral neck and compared it to the corresponding surfaces on the plastic femur model (Fig. 10). In this patient, the surgeon detected a visible difference in osteophyte depiction between the real anatomical surface and the segmented femur

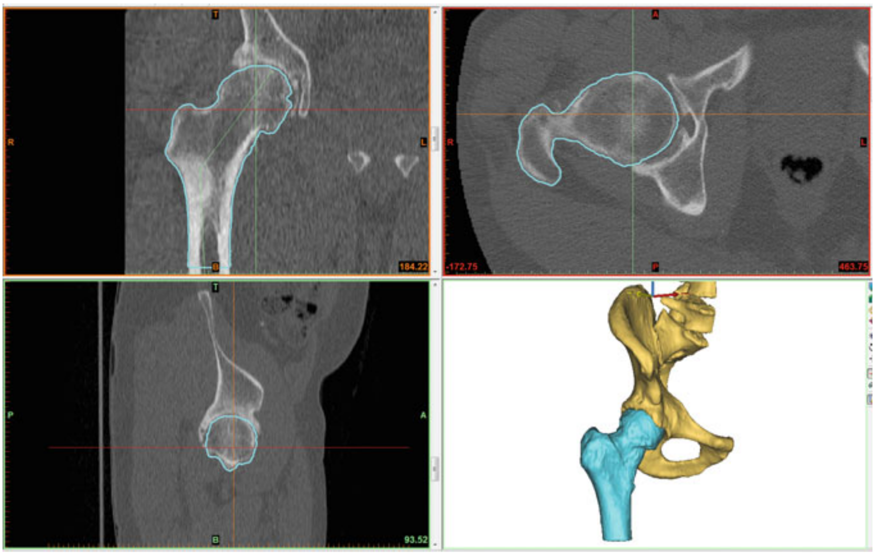

Fig. 9 Segmentation of preoperative CT dataset. The *blue outlines* show the final segmentation of the femur. In the *bottom right* window the final virtual models for proximal femur and acetabulum are displayed to the user for verification (Color figure online)

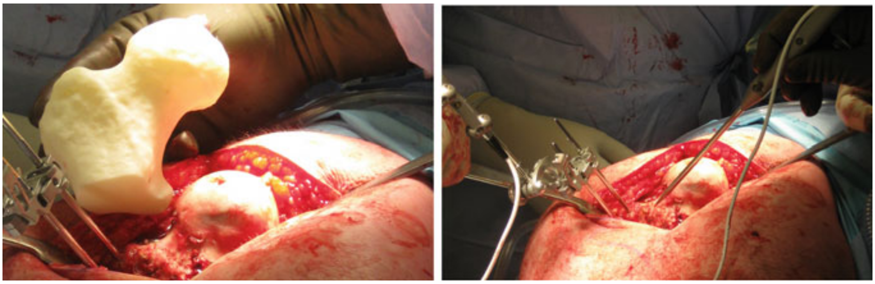

Fig. 10 Intraoperative collection of osteophytes. *Left side* A plastic model of the proximal femur was used to compare the segmentation to the real anatomy and identify undetected osteophytes. *Right side* A tracked pointing device was used to collect osteophyte border points intraoperatively

Table 1 Segmentation errors and Hounsfield units for osteophyte points collected intraoperatively

	1	2	3	4	5
Distance in (mm)	2.0	3.7	3.2	5.1	0.7
Hounsfield unit	290	65	125	125	160

model. To quantitatively measure this difference, an optoelectronical tracking system was used (Optotrak Certus Motion Capture System, Northern Digital Inc., Waterloo, Canada).

Following a registration step [60], a tracked pointing device was used to collect 5 points on the surface of undetected osteophytes (Fig. 10).

By using the registration information from the optoelectronical tracking system, we were able to transfer the collected positions into the CT coordinate system of the patient and evaluate the distance between the segmented femur surface and the points (which represent the real outlines of the osteophytes). Table 1 contains the error value for each collected point in mm. For a better understanding of the problem, we also identified the Hounsfield units (also known as CT numbers or CT attenuation numbers) of the collected positions in the preoperative CT scan, which are given in Table 1. In Fig. 11 the position of the five collected points are superimposed (red circle) onto corresponding axial slices of the CT dataset.

Although the distance errors for osteophyte 1 (2 mm) and 5 (0.7 mm) are within the resolution of the CT scan and as such might be the result of a partial volume effect [72], distance errors for the osteophytes 2–4 indicate depiction and/or segmentation errors.

It is interesting to note that only the identified Hounsfield unit of one of the five collected points was inside the well-known predefined bone threshold of 226–3070 Hounsfield units. The Hounsfield units of the remaining four points would have been identified as soft-tissue in automatic thresholding operations.

If these segmentation errors for the osteophytes had gone unnoticed, the deviation between the real anatomical registration surface and the integrated registration

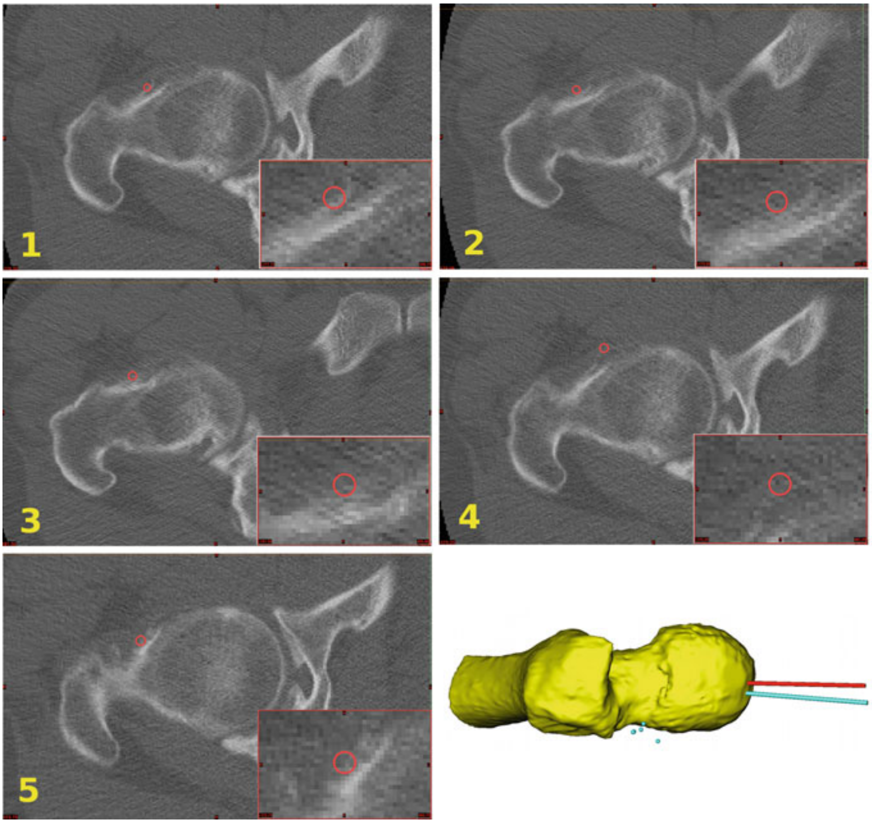

Fig. 11 Positions of the digitized osteophytes superimposed onto the CT dataset. The *numbers* in the *left lower corner* correspond to the number of osteophytes in Table 1. The *inlays* in the *right lower corner* are zoomed regions in the osteophyte area. The *lower right corner* of the figure illustrates the simulation of error to the central-pin placement. The *red axis* demonstrates the planned central-pin alignment, the *green line* the simulated central-pin alignment. The *green spheres* represent the digitized osteophyte points (Color figure online)

surface of the patient-specific guide could potentially result in errors in registration of the guide—which consequently would result in an error for the guided central-pin position and alignment.

We simulated this error for the patient[4] by virtually modifying the registration surface of the femur model based on the intraoperatively collected osteophyte information. To determine the deviation between the two registration surfaces (segmented and surgical), a point cloud for each surface was created. Initially, the collected osteophyte positions were added to the surgical surface point cloud and

[4]To guarantee the best possible surgical treatment for the patient, the surgeon removed the osteophyte completely or partially to correct the fit of the guide during the surgery.

the corresponding closest points from the segmented femur model to the segmented surface point cloud. In addition, about 20 points were collected on the lateral aspect of the femoral neck registration surface, which were added to both the surgical and the segmented surface point clouds. The reason for adding these points to both surface clouds was that the lateral aspect was unaffected by osteophytes and so was considered to be a stable registration area. Therefore, segmented and surgical registration surfaces in this area are represented identically. Taking these two sorted point clouds, a pair-point registration using Horn's method [73] was performed to estimate the registration error of placing the guide on the surgical surface containing the osteophytes compared to the planned registration on the segmented surface. The resulting transformation between the segmented and surgical surfaces was then applied to the position and orientation of the planned central-pin alignment and the deviation of the resulting pin position and orientation were evaluated in the transverse and frontal anatomical planes of the femur.

As Fig. 11 (bottom right) demonstrates, the registration of the patient-specific guide without the removal of the undetected osteophyte could have resulted in a substantial alignment error for the central-pin placement, especially in the transverse plane. In the figure, the red axis represents the planned central-pin position, and the blue axis, the simulated erroneous central-pin axis. In this case, the error in the entrance point for the central-pin axis on the femoral head was simulated with 1.2 mm deviation in the proximal direction and 4.9 mm in the anterior direction. For the orientation of the central-pin, we simulated the resulting error with 0.3° valgus and 4.9° anteversion.

The combination of a more anterior entrance point, as well as a more anteversion orientation of the pin, could have resulted in a notching of the femoral head during the reaming, which is discussed in the literature as a risk factor for postoperative femoral neck fractures [10, 11].

5.1 Discussion

The presented case demonstrated that undetected osteophytes in registration surfaces could present a substantial source of error for the postoperative outcome in patient-specific instrument guided procedures. On the other hand, the Hounsfield units of the undetected osteophytes ranged between 65 and 290, which suggests that the osteophyte borders were imaged with a wide range, indicating changing tissue properties along the osteophyte surface. This noteworthy high standard deviation of Hounsfield units on osteophyte borders was confirmed in a study we performed on 35 patients, collecting osteophyte data intraoperatively [74]. Here we found that the osteophyte points were depicted in a clinical CT dataset with an average of 156 Hounsfield units and a standard deviation of 112. In this study, about 80 % of the collected osteophyte border points had a Hounsfield unit outside of the defined threshold for bone and would have presented as soft-tissue in the scan. Considering the development of osteophytes from an abnormal cartilaginous mass [70] in stage I to hypertrophy and endochondral bone formation in stage IV, soft-tissue characteristics in HU representation is not unexpected. However, it does demonstrate the difficulties in segmenting osteophytes in preoperative CT datasets and supports the careful selection of registration surfaces for patient-specific instrument guides for femur and acetabulum excluding known osteophyte regions, such as femoral head-neck junctions or acetabulum rim.

6 Conclusions

Hip resurfacing procedures have many advantages. However, they are surgically challenging techniques with a small margin of error. This, plus the need for careful patient selection, leaves room for surgical errors that can result in minor as well as major postoperative complications. In this chapter we have discussed how patient-specific instrument guides can be utilized to create easy-to-use navigation systems for hip resurfacing arthroplasty. Although to date most applications are in the guidance of the femoral central-pin drilling, recent research in applying patient-specific guides to navigate acetabulum component alignment and proximal femoral resection depth are discussed as well. Many of the studies discussed in this contribution found that the application of patient-specific instrument guides significantly increased the accuracy of the intraoperative procedure compared to conventional surgical methods. Such improvement of intraoperative accuracy might lead to fewer postoperative complications and improved stability and functionality of HRA. However, further studies are needed to investigate the relationship between the use of image-guided technologies, such as patient-specific instrument guides, and the mid- or long-term outcome for HRA.

In addition to improved accuracy during the intraoperative procedure, the guides also have the potential to reduce surgical time for hip resurfacing procedures. For example, Zhang et al. [54] found that the average surgical time was significantly shortened, by 22 min, due to the use of patient-specific guides for femoral and acetabular component alignment. Olsen et al. [55] also found in an in vitro study that the time required for insertion of the femoral central-pin was significantly reduced using a patient-specific guide (1.3 min), compared to both the conventional placement technique (5.4 min) and the imageless optoelectronic guidance method (7.3 min). The elongation of surgery time using conventional image-guided methods (such as optoelectronic) is often discussed as a drawback for using this technology in the surgical room [75]. Patient-specific instrument guides in HRA not only avoid increased surgical time, but reduce it–advantages likely to make these guides more acceptable for routine clinical use.

A requirement for the application of patient-specific instrument guides is the preoperative detailed reconstruction of the patient anatomy, which allows generation of the contact surfaces of the guides. In all of the studies and applications for patient-specific instrument guides discussed in this chapter, a CT scan of the patient hip was the preoperative image modality. CT scans are relatively fast and easy to obtain and depict cortical and dense bone with a high resolution, which makes them an optimal image modality for preoperative planning prosthesis component positioning and the creation of patient-specific instrument guides. On the other hand, the use of CT also raises concerns, such as uncertainties in depiction of osteophytes and soft tissues (cartilage, etc.), as well as radiation exposure for the patient. For application of patient-specific instrument guides in other areas of orthopaedic surgery, such as Total Knee Arthroplasty, the use of Magnetic Resonance Imaging (MRI) as the preoperative image modality for surgical planning and guide creation is employed. Further investigations have to show whether MRI might also be a valuable alternative as an image modality for patient-specific instrument guides in hip resurfacing.

Metal-on-Metal Hip Resurfacing is a relatively young treatment option and research is still ongoing with respect to optimal component alignment. An accurate and widely available image-guided technology (such as patient-specific guides) to reliable implant components in predefined positions and orientations could be used in support of clinical studies as a valuable research tool.

Research into the application of patient-specific instrument guides for HRA combines expertise from many different fields, involving orthopaedic surgeons, computer scientists, radiologists, mechanical engineers and materials engineers, and demonstrates how interdisciplinary research can accelerate new developments in the medical fields.

Acknowledgments The authors are grateful to Paul St. John and Joan Willison for their always-enthusiastically technical support, and would like to thank the surgical and perioperative teams of Kingston General Hospital, as well as the Human Mobility Research Centre at Queen's University and Kingston General Hospital for their support.

References

1. Amstutz HC, Clarke IC, Christie J, Graff-Radford A (1977) Total hip articular replacement by internal eccentric shells: the Tharies approach to total surface replacement arthroplasty. Clin Orthop 128:261–284
2. Amstutz HC, Le Duff MJ (2012) Hip resurfacing; a 40-year perspective. HSS J 8(3):275–282
3. Amstutz HC, Takamura K, Le Duff M (2011) The effect of patient selection and surgical technique on the results of conserve plus hip resurfacing—3.5 to 14 year follow-up. Orthop Clin North Am 142(2):133–142
4. Bradley GW, Freeman MA (1983) Revision of failed hip resurfacing. Clin Orthop Relat Res 178:236–240
5. Klotz MCM, Breusch SJ, Hassenpflug M, Bitsch RG (2012) Results of 5 to 10-year follow-up after hip resurfacing. A systematic analysis of the literature on long-term results. Orthopade 41 (6):442–451
6. Vail TP, Mina CA, Yergler JD, Pietrobon R (2006) Metal-on-metal hip resurfacing compares favorably with THA at 2 years followup. Clin Orthop Relat Res 453:123–131
7. Sandiford NA, Ahmed S, Doctor C, East DJ, Miles K, Apthrop HD (2014) Patient satisfaction and clinical results at a mean eight years following BHR arthroplasty: results from a district general hospital. Hip Int 24(3):249–255

8. Bow JK, Rudan JF, Grant HJ, Mann SM, Kunz M (2012) Are hip resurfacing arthroplasties meeting the needs of our patients? A 2-year follow-up study. J Arthroplasty 27(6):684–689
9. Mont MA, Ragland PS, Etienne G, Seyler TM, Schmalzried TP (2006) Hip resurfacing arthroplasty. J Am Acad Orthop Surg 14(8):454–463
10. Amstutz HC, Campbell PA, Le Duff MJ (2004) Fracture of the neck of the femur after surface arthroplasty of the hip. J Bone Joint Surg 86-A(9):1874–1877
11. Siebel T, Maubach S, Morlock MM (2006) Lessons learned from early clinical experience and results of 300 ASR hip resurfacing implantations. Proc Inst Mech Eng [H] 220(2):345–353
12. Mellon SJ, Grammatopoulos G, Andersen MS, Pandit HG, Gill HS, Murray DW (2015) Optimal acetabular component orientation estimated using edge-loading and impingement risk in patients with metal-on-metal hip resurfacing arthroplasty. Biomechanics 48(2):318–323
13. Davies ET, Olsen M, Zdero R, Papini M, Waddell JP, Schemitsch EH (2009) A biomechanical and finite element analysis of femoral neck notching during hip resurfacing. J Biomech Eng 131(4):041002-1–041002-8
14. Beaule PE, Lee JLL, Le Duff MJ, Amstutz HC, Ebramzadeh E (2004) Orientation of the femoral component in surface arthroplasty of the hip. J Bone Joint Surg 86-A(9):2015–2021
15. Long JP, Barel DL (2006) Surgical variables affect the mechanics of a hip resurfacing system. Clin Orthop Relat Res 453:115–122
16. Konyves A, Bannister GC (2005) The importance of leg length discrepancy after total hip arthroplasty. J Bone and Joint Surgery 87-B(2):155–157
17. Lai KA, Lin CJ, Jou IM, Su FC (2001) Gait analysis after total hip arthroplasty with leg length equalization in women with unilateral congenital complete dislocation of the hip: comparison with untreated patients. J Orthop Res 19:1147–1152
18. McGrory BJ, Morrey BF, Cahalan TD, An K-N, Cabanela ME (1995) Effect of femoral offset on range of motion and abductor muscle strength after total hip arthroplasty. J Bone Joint Surg 77-B(6):865–869
19. Fackler CD, Poss R (1980) Dislocation in total hip arthroplasties. Clin Orthop Relat Res 151:169–178
20. Asayama I, Chamnongkich S, Simpson KJ, Kinsey TL, Mahoney OM (2005) Reconstructed hip joint position and abductor muscle strength after total hip arthroplasty. J Arthroplasty 20 (4):414–420
21. Silva M, Lee KH, Heisel C, Dela Rosa MA, Schmalzried TP (2004) The biomechanical results of total hip resurfacing arthroplasty. J Bone and Joint Surg 86-A(1):40–46
22. Loughead JM, Chesney D, Holland JP, McCaskie AW (2005) Comparison of offset in Birmingham hip resurfacing and hybrid total hip arthroplasty. J Bone and Joint Surg 87-B (2):163–166
23. Girard J, Lavigne M, Vendittoli P-A, Roy AG (2006) Biomechanical reconstruction of the hip. J Bone Joint Surg 88-B(6):721–726
24. Ahmad R, Gillespie G, Annamalai S, Barakat MJ, Ahmed SMY, Smith LK, Spencer RF (2009) Leg length and offset following hip resurfacing and hip replacement. Hip Int 19 (2):136–140
25. Kwon Y-M, Ostlere SJ, McLardy-Smith P, Athanasou NA, Gill HS, Murray DW (2011) "Asymptomatic" pseudotumors after metal-on-metal hip resurfacing arthroplasty. Prevalence and metal ion study. J Arthroplasty 26(4):511–518
26. Kwon YM, Xia Z, Glyn-Jones S, Beard D, Gill HS, Murray DW (2009) Dose-dependent cytotoxicity of clinically relevant cobalt nanoparticles and ions on macrophages in vitro. Biomed Mater 4(2):025018
27. Langton DJ, Sprowson AP, Joyce TJ, Reed M, Carluke I, Partington P, Nargol AV (2009) Blood metal ion concentrations after hip resurfacing arthroplasty: a comparative study of articular surface replacement and Birmingham hip resurfacing arthroplasties. J Bone Joint Surg 91-B(10):1287–1295
28. Kwon YM, Glyn-Jones S, Simpson DJ, Kamali A, McLardy-Smith P, Gill HS, Murray DW (2010) Analysis of wear retrieved metal-on-metal hip resurfacing implants revised due to pseudotumours. J Bone Joint Surg 92-B(3):356–361

29. Langton DJ, Joyce TJ, Mangat N, Lord J, Van Orsouw M, De Smet K, Nargol AV (2011) Reducing metal ion release following hip resurfacing arthroplasty. Orthop Clin North Am 42 (2):169–180
30. Kwon YM, Mellon SJ, Monk P, Murray DW, Gill HS (2012) In vivo evaluation of edge-loading in metal-on-metal hip resurfacing patients with pseudotumours. Bone Joint Res 1 (4):42–49
31. Mellon SJ, Kwon YM, Glyn-Jones S, Murray DW, Gill HS (2011) The effect of motion patterns on edge-loading of metal-on-metal hip resurfacing. Med Eng Phys 33(10):1212–1220
32. De Haan R, Pattyn C, Gill HS, Murray DW, Campbell PA, De Smet K (2008) Correlation between inclination of the acetabular component and metal ion levels in metal-on-metal hip resurfacing replacement. J Bone Joint Surg 90-B(10):1291–1297
33. De Haan R, Campbell PA, Su EP, De Smet KA (2008) Revision of metal-on-metal resurfacing arthroplasty of the hip: the influence of malpositioning of the components. J Bone Joint Surg 90-B(9):1158–1163
34. Hart AJ, Satchithananda K, Liddle AD, Sabah SA, McRobbie D, Henckel J, Cobb JP, Skinner JA, Mitchell AW (2012) Pseudotumors in association with well-functioning metal-on-metal hip prostheses: a case-control study using three-dimensional computed tomography and magnetic resonance imaging. J Bone Joint Surg 94-A(4):317–325
35. Liu F, Gross TP (2012) A safe zone for acetabular component position in metal-on-metal hip resurfacing arthroplasty: winner of the 2012 HAP PAUL award. J Arthroplasty 28:1224–1230
36. Arndt JM, Wera GD, Goldberg VM (2013) A initial experience with hip resurfacing versus cementless total hip arthroplasty. HSSJ 9:145–149
37. Hess T, Gampe T, Koettgen C, Szawloeski B (2004) Intraoperative navigation for hip resurfacing. Methods and first results. Orthopade 33(10):1183–1193
38. El Hachim M, Penasse M (2014) Our midterm results of the Birmingham hip resurfacing with and without navigation. J Arthroplasty 29:808–812
39. Bailey C, Gul R, Falworth M, Zadow S, Oakeshott R (2009) Component alignment in hip resurfacing using computer navigation. Clin Orthop Relat Res 467:917–922
40. Hodgson A, Helmy N, Masri BA, Greidanus NV, Inkpen KB, Duncan CP, Garbuz DS, Anglin C (2007) Comparative repeatability of guide-pin axis positioning in computer-assisted and manual femoral head resurfacing arthroplasty. Proc Inst Mech Eng H 221(7):713–724
41. Cobb JP, Kannan V, Brust K, Thevendran G (2007) Navigation reduces the learning curve in resurfacing total hip arthroplasty. Clin Orthop Relat Res 463:90–97
42. Romanowski JR, Swank ML (2008) Imageless navigation in hip resurfacing: avoiding component malposition during the surgeon learning curve. J Bone Joint Surg 90-A(Suppl 3):65–70
43. Seyler TM, Lai LP, Sprinkle DI, Ward WG, Jinnah RH (2008) Does computer-assisted surgery improve accuracy and decrease the learning curve in hip resurfacing? A radiographic analysis. J Bone Joint Surg 90-A(Suppl 3):71–80
44. Radermacher K, Portheine F, Anton M, Zimolong A, Kaspers G, Rau G, Staudte HW (1998) Computer assisted orthopaedic surgery with image based individual templates. Clin Orthop Relat Res 354:28–38
45. Birnbaum K, Schkommodau E, Decker N, Prescher A, Klapper U, Radermacher K (2001) Computer-assisted orthopedic surgery with individual templates and comparison to conventional operation method. Spine 26(4):365–370
46. Brown GA, Firoozbakhsh K, DeCoster TA, Reyna JR Jr, Moneim M (2003) Rapid prototyping: the future of trauma surgery? J Bone Joint Surg 85-A(Suppl 4):49–55
47. Owen BD, Christensen GE, Reinhardt JM, Ryken TC (2007) Rapid prototype patient-specific drill template for cervical pedicle screw placement. Comput Aided Surg 12(5):303–308
48. Boonen B, Schotanus MG, Kort NP (2012) Preliminary experience with the patient-specific templating total knee arthroplasty. Acta Orthop 83(4):387–393
49. Ng VY, DeClaire JH, Berend KR, Gulick BC, Lombardi AV Jr (2012) Improved accuracy of alignment with patient-specific positioning guides compared with manual instrumentation in TKA. Clin Orthop Relat Res 470(1):99–107

50. Moopanar TR, Amaranath JE, Sorial RM (2014) Component position alignment with patient-specific jigs in total knee arthroplasty. ANZ J Surg 84(9):628–632
51. Levy JC, Everding NG, Frankle MA, Keppler LJ (2014) Accuracy of patient-specific guided glenoid baseplate positioning for reverse shoulder arthroplasty. J Shoulder Elbow Surg 23 (10):1563–1567
52. Walch G, Vezeridis PS, Boileau P, Deransart P, Chaoui J (2014) Three-dimensional planning and use of patient-specific guides improve glenoid component position: an in vitro study. J Shoulder Elbow Surg 24(20):302–309
53. Du H, Tian XX, Li TS, Yang JS, Li KH, Pei GX, Xie L (2013) Use of patient-specific templates in hip resurfacing arthroplasty: experience from sixteen cases. Int Orthop 37(5): 777–782
54. Zhang YZ, Lu S, Yang Y, Xu YQ, Li YB, Pei GX (2011) Design and primary application of computer-assisted, patient-specific navigational templates in metal-on-metal hip resurfacing arthroplasty. J Arthroplasty 26(7):1083–1087
55. Olsen M, Naudie DD, Edwards RW, Schemitsch EH (2014) Evaluation of a patient specific femoral alignment guide for hip resurfacing. J Arthroplasty 29:590–595
56. Kitada M, Sakai T, Murase T, Hanada T, Nakamura N, Sugano N (2013) Validation of the femoral component placement during hip resurfacing: a comparison between conventional jig, patient-specific template, and CT-based navigation. Int J Med Robotics Comput Assist Surg 9:223–229
57. Sakai T, Hanada T, Murase T, Kitada M, Hamada H, Yoshikawa H, Sugano N (2014) Validation of patient specific guides in total hip arthoplasty. Int J Med Robotocs Comput Assist Surg 10:113–120
58. Kunz M, Rudan JF, Xenoyannis GL, Ellis RE (2010) Computer-assisted hip resurfacing using individualized drill templates. J Arthroplasty 25(4):600–606
59. Kunz M, Rudan JF, Wood GCA, Ellis RE (2011) Registration stability of physical templates in hip surgery. Stud Health Technol Inform 162:283–289
60. Ma B, Ellis RE (2003) Robust registration for computer-integrated orthopedic surgery: laboratory validation and clinical experience. Med Imag Anal 7(3):237–250
61. Hananouchi T, Saito M, Koyama T, Hagio K, Murase T, Sugano N, Yoshikawa H (2008) Tailor-made surgical guide based on rapid prototyping technique for cup insertion in total hip arthroplasty. Int J Med Robotics Comput Assist Surgery 5:164–169
62. Hananouchi T, Saito M, Koyama T, Sugano N, Yoshikawa H (2010) Tailor-based surgical guide reduces incidence of outliers of cup placement. Clin Orthop Relat Res 468:1088–1095
63. Zhang YZ, Chen B, Lu S, Yang Y, Zhao JM, Liu R, Li YB, Pai GX (2011) Preliminary application of computer-assisted patient-specific acetabulum navigational template for total hip arthroplasty in adult single development dysplasia of the hip. Int J Med Robotics Comput Assist Surg 7:469–474
64. Buller L, Smith T, Bryan J, Klika A, Barsoum W, Innotti JP (2013) The use of patient-specific instrumentation improves the accuracy of acetabular component placement. J Arthroplasty 28:631–636
65. Small T, Krebs V, Molloy R, Bryan J, Klika AK, Barsoum WK (2014) Comparison of acetabular shell position using patient specific instrument vs. standard surgical instruments: A randomized clinical trial. J Arthroplasty 29:1030–1037
66. Leeuwen JA, Grøgaard B, Nordsletten L, Röhrl SM (2014) Comparison of planned and achieved implant position in total knee arthroplasty with patient-specific positioning guides. Acta Orthop 11:1–6
67. Cavaignac E, Pailhé R, Laumond G, Murgier J, Reina N, Laffosse JM, Bérard E, Chiron P (2014) Evaluation of the accuracy of patient-specific cutting blocks for total knee arthroplasty: a meta-analysis. Int Orthop (Epub ahead of print)
68. Voleti PB, Hamula MJ, Baldwin KD, Lee GC (2014) Current data do not support routine use of patient-specific instrumentation in total knee arthroplasty. J Arthroplasty 29(9):1709–1712
69. Turmezei TD, Poole KE (2011) Computed tomography of subchrondral bone and osteophytes in hip osteoarthritis: the shape of things to come? Front Endocrinol (Lausanne) 13(2):97

70. Gelse K, Soeder S, Eger W, Dietmar T, Aigner T (2003) Osteohyte development—molecular characterization of different stages. Osteoarthritis cartilage 11(2):141–148
71. Aigner T, Sachsse A, Gebhard PM, Roach HI (2006) Osteoarthritis: pathobiology—targets and ways for therapeutic intervention. Adv Drug Deliv Rev 58(2):128–149
72. Baxter BS, Sorenson JA (1981) Factors affecting the measurement of size and CT number in computed tomography. Invest Radiol 16:337–341
73. Horn BKP (1987) Closed form solution of absolute orientation using unit quaternions. J Opt Soc Amer A 4(44):629–642
74. Kunz M, Balaketheeswaran S, Ellis RE, Rudan JF (2015) The influence of osteophyte depiction in CT for patient-specific guided hip resurfacing procedures. Int J Comput Assist Radiol Surg (Accepted for publication with minor revisions)
75. Cerha O, Kirschner S, Guenther K-P, Luetzner J (2009) Cost analysis for navigation in knee endoprothetics. Orthopaede 38(12):1235–1240 (Article in German)