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Patient-specific Component Alignment in Total Hip Arthroplasty

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Abstract

Appropriate component alignment is critical for improving stability, maximising bearing performance and restoring native anatomy after Total Hip Arthroplasty (THA). Due to the large variation in patient kinematics between functional activities, current technologies lack definition of what constitutes correct target alignment. Analysis of a large series of symptomatic THA patients confirms that apparently well-orientated components on standard radiographs can still fail due to functional component malalignment. Evidently, previously defined "safe zones" are not appropriate for all patients as they do not consider the dynamic behaviour of the hip joint.

The Optimized Positioning System™ (OPS™) comprises preoperative planning based on a patient-specific dynamic analysis, and patient-specific instrumentation for delivery of the target component alignment. This paper presents the application of OPS™ in three case studies.

Keywords: *total hip, arthroplasty, implant positioning*
Level of Evidence: *AAOS Therapeutic Level IV*

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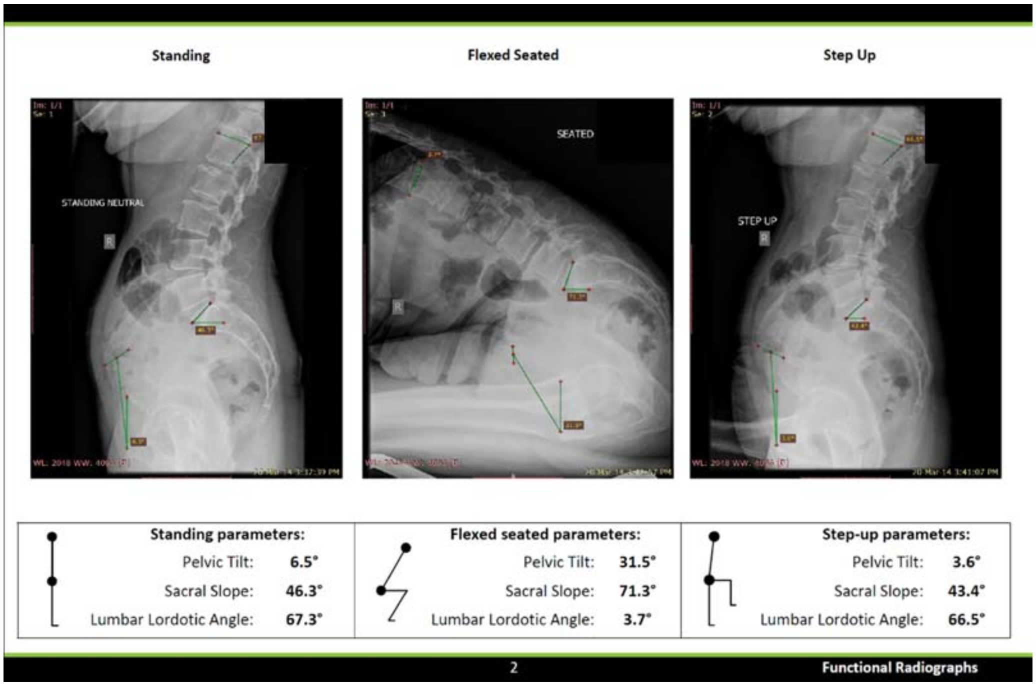
Introduction

Appropriate component alignment is critical for improving stability, maximising the performance of the bearing and restoring native anatomy after Total Hip Arthroplasty (THA). Femoral and acetabular component malalignment are key contributors to the leading causes of THA revision [1]. If appropriate component alignment can be achieved in all patients, the THA revision burden would be significantly reduced.

The limited precision with which a defined target alignment can be achieved intraoperatively, without assistive technologies, has been widely published [2-4]. Computer assisted surgery, and more recently robotics, were introduced to improve precision, but with slow uptake from the orthopaedic community. The limited acceptance of assistive technologies is likely due to the poor definition of what constitutes the correct target alignment for an individual. Contemporary literature has questioned the appropriateness of the most commonly accepted guidelines for implant alignment, with more failures observed when adhering to historical recommendations, than when not [5].

Edge-loading, accelerated wear, impingement and dislocation are leading contributors to THA revision. All occur during functional activities when the position of the pelvis and femur are different from that seen on standard radiographs or on the operating table [6-11]. Hip kinematics are specific to each individual and change the functional alignment of the components [10]. Consequently, component alignment should be planned individually, using dynamic information, if we want to optimise to reduce failure.

The Optimized Positioning System™ (OPS™) is a commercially-available medical device for patient-specific preoperative planning, intraoperative delivery and postoperative analysis in Total Hip Arthroplasty (Optimized Ortho, Sydney, Australia) [12]. The system comprises a preoperative planning and analysis component, along with patient-specific instrumentation for intraoperative delivery. The planning uses standard medical imaging to assess each patient's alignment, bone morphology and kinematics, and analyses the bearing contact mechanics and impingement using a rigid body dynamic simulation of functional activities. To date, over 3,000 patients have received OPS™ preoperative planning in Australia and Europe. This paper presents the application of OPS™ in three case studies.



Standing parameters:
Pelvic Tilt: 6.5°
Sacral Slope: 46.3°
Lumbar Lordotic Angle: 67.3°

Flexed seated parameters:
Pelvic Tilt: 31.5°
Sacral Slope: 71.3°
Lumbar Lordotic Angle: 3.7°

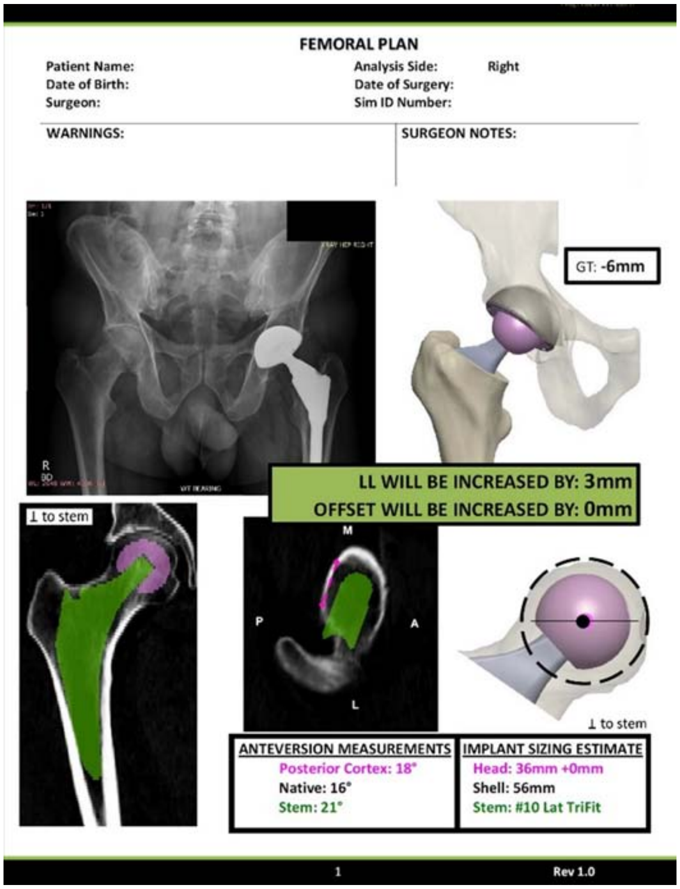
Step-up parameters:
Pelvic Tilt: 3.6°
Sacral Slope: 43.4°
Lumbar Lordotic Angle: 66.5°

Figure 1. The functional pelvic tilt, sacral slope and lumbar lordotic angles are measured from three lateral functional radiographs: standing, flexed seated and step-up.

Methods

Functional imaging: In the weeks preceding the operation each patient receives three lateral functional radiographs; standing, flexed seated and step-up (raising the contralateral leg), Fig 1. On each of the functional images, pelvic tilt, sacral slope and lumbar lordotic angles are measured. The measured angles are used to define the positions of the bones at the limits of hip flexion and extension. In addition, bony geometry for each patient is captured in a low-dose Computed Tomography (CT) scan and three-dimensional coordinates of soft tissue and bony landmarks are virtually identified.

Implant positioning: Using the manufacturer's 3D implant geometries, femoral stem and acetabular shell templating is performed by a qualified engineer, Fig 2. The implants are virtually positioned within the patient's femur and acetabulum to restore native anatomy and to achieve optimal metaphyseal loading. The surgeon can feed into the preoperative plan any patient-specific clinical observations or requirements, such as preoperative leg length discrepancies measured at clinical review.



FEMORAL PLAN

Patient Name:
Date of Birth:
Surgeon:

Analysis Side: Right
Date of Surgery:
Sim ID Number:

WARNINGS:

SURGEON NOTES:

LL WILL BE INCREASED BY: 3mm
OFFSET WILL BE INCREASED BY: 0mm

ANTEVERSION MEASUREMENTS
Posterior Cortex: 18°
Native: 16°
Stem: 21°

IMPLANT SIZING ESTIMATE
Head: 36mm +0mm
Shell: 56mm
Stem: #10 Lat TriFit

1 Rev 1.0

Figure 2. Femoral stem and acetabular shell templating.

Dynamic simulation: The segmented bone models and planned component alignment are inputs to a rigid body dynamics simulation of flexion and extension activities, driven by the kinematic inputs from the functional radiographs. The simulation calculates the magnitude and direction of the hip joint reaction force throughout the two activities and determines the path of the contact patch [13,14] as it traces across the articulating surface, Fig 3. These contact patch paths are presented in a polar plot that represents the bearing surface in two dimensions viewed perpendicular to the face of the cup. The polar plots are generated for nine different cup orientations, defined in angles of radiographic inclination and anteversion [15], Fig 4. The nine plots demonstrate the effect of cup orientation on contact mechanics across a patient-specific zone, to assist the surgeon in determining an optimal cup orientation for the patient.

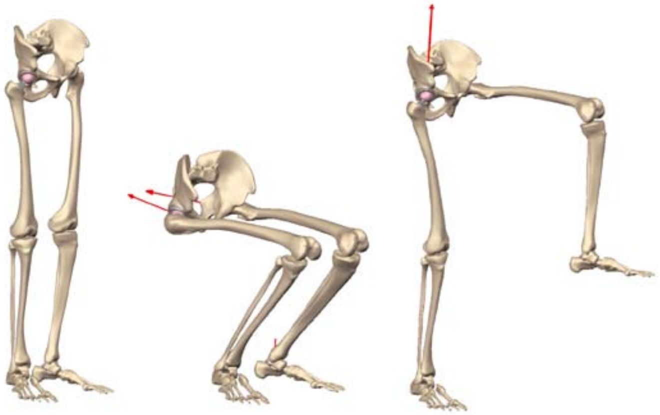


Figure 3. The hip joint reaction force is calculated during a simulation of hip flexion (middle) and hip extension (right) activities.

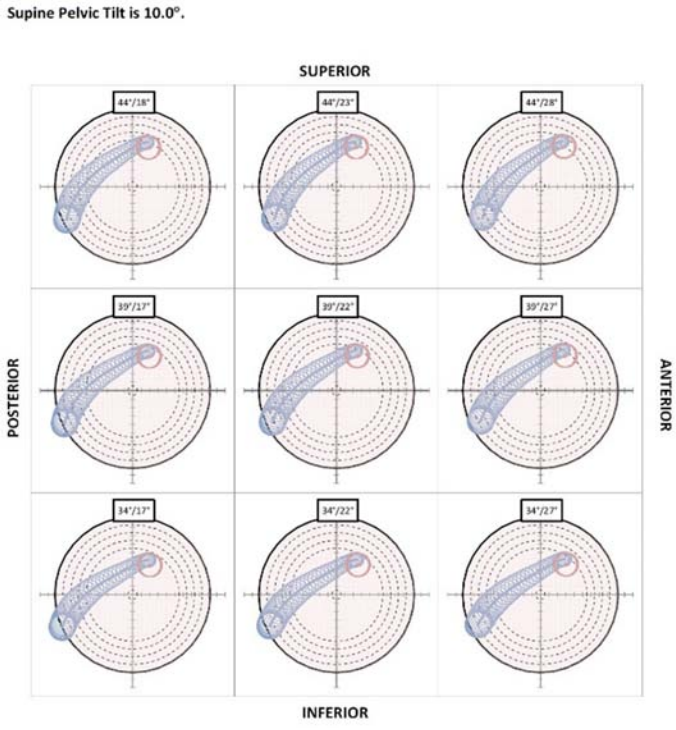


Figure 4. Polar plots illustrating the flexion (blue trace) and extension (red trace) contact patch path for nine different cup orientations.

Preoperative report: The preoperative plan, including results from the dynamic analysis and implant templating, is presented to the surgeon for approval in the weeks prior to surgery. The system determines a preliminary target orientation based on a series of preferences defined by the surgeon. These parameters take into consideration the surgeon's accepted ranges for acetabular inclination and anteversion, the surgical approach, acetabular shell coverage, acceptable boundaries from the anterior and posterior edges of the bearing, as well as any expected changes in pelvic kinematics postoperatively. The surgeon has the opportunity to change the templated implants and target orientation prior to finalising the plan.

Patient-specific guide design: Two patient-specific guides are designed to deliver the preoperative plan in surgery. The acetabular guide is designed to fit within the patient's acetabulum and guide the planned cup orientation, Fig 5a. The femoral guide is designed to fit on the available surface of the femoral head and neck and guide the planned femoral osteotomy, Fig 5b. Once the guide designs have

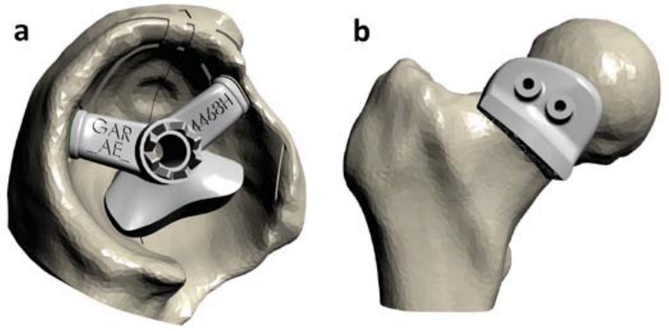


Figure 5. a) the acetabular guide delivers the target cup orientation; b) the femoral guide controls the femoral neck osteotomy.

been accepted by the surgeon, both guides and corresponding bone models are 3D printed from medical grade Nylon and sterilised for use in surgery.

Intra-operative delivery: The OPS™ guides can be used with any surgical approach. After the surgeon performs their routine exposure, the femoral guide is positioned on the femoral head-neck junction, and secured in place with a spring-loaded pin. The osteotomy is made along the open capture feature on the femoral guide. The acetabular guide is then seated within the acetabulum after the fat pad and any soft tissue remnants in the acetabular fossa are excised. The in vivo position can be checked against the markings on the sterile bone model. A laser handle connects to the axis of the guide and projects the target orientation onto the operating room ceiling or wall. A second laser mounted to the pelvis is orientated to converge with the projection on the ceiling or wall, and secured to mark the target orientation relative to the pelvis. Any intra-operative movement of the pelvis will therefore not affect the target orientation, which is not dependent on a particular position in the operative theatre. Reaming is completed per the surgeon's routine technique, to the preoperatively planned depth. Final cup orientation is guided by a laser on the end of the impactor handle. The handle is orientated so the laser aligns with the projection of the pelvic reference laser. Cup orientation is also confirmed by referencing anatomical features such as osteophytes around the acetabulum to the rim of the cup, using the markings on the sterile bone model. The placement of the patient-specific guide and planned cup in the acetabulum can also be visualised in three-dimensional models on a tablet during the operation.

All patients provided consent that they were happy to be involved in the case series review.

Results

Case Study 1

79 year old male requiring right side THA, Fig 6. Patient also had an arthritic left side. CT analysis showed equal pre-op leg length. The femoral neck osteotomy was planned 13mm above the lesser trochanter to provide 0mm of lengthening on the right side. 3D planning recommended a 125° Metafix stem (Corin Group, Cirencester, UK) with a +4mm head and the cup positioned 2mm off the true acetabular floor. Planned stem anteversion was 21° to preserve the AP position of the native femoral head.

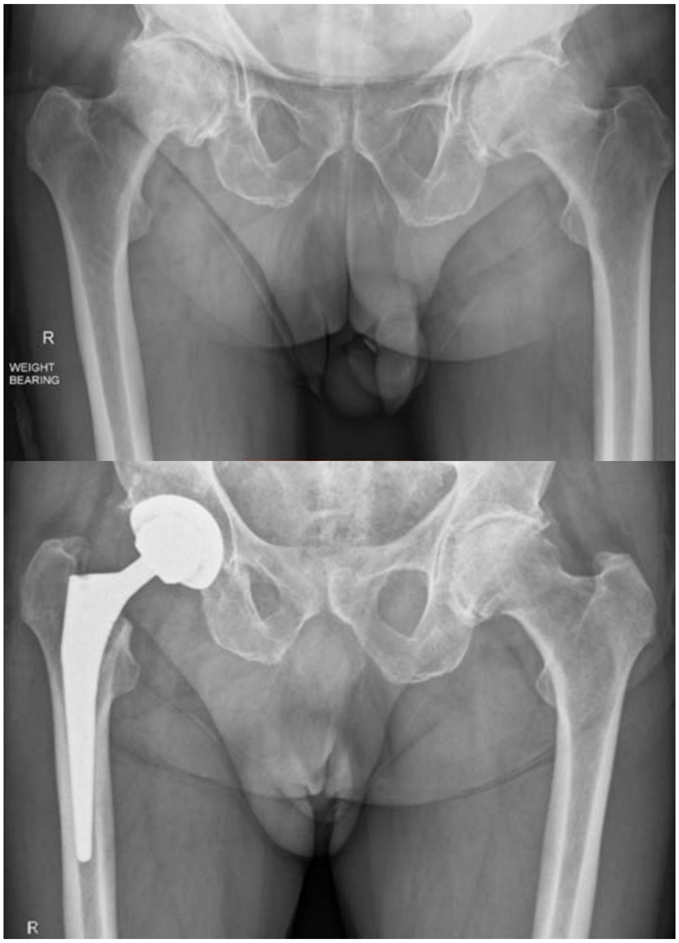


Figure 6. Preoperative and postoperative radiographs.

Dynamic analysis showed the patient had minimal pelvic movement between functional positions, with no risk of edge-loading. Consequently, due to the low risk profile of the patient's pelvic kinematics, the surgeon chose a standard cup orientation of 40°/20° (inclination/anteversion). Large osteophytes could be visualised in the OPS™ report which was used intraoperatively as a guide for what needed to be removed, Fig 7.

The procedure was performed through a posterolateral approach.

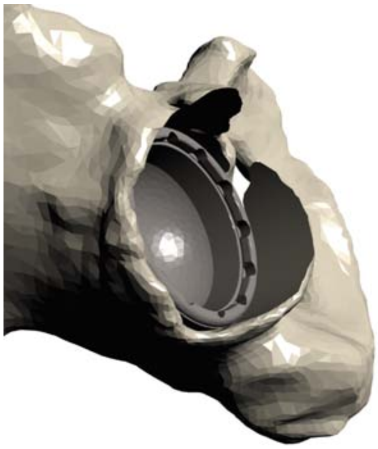


Figure 7. Three-dimensional model from the OPS™ report illustrating the templated acetabular cup and surrounding osteophytes.

Case Study 2

52 year old female requiring right side THA. CT analysis showed a 6mm leg length discrepancy (LLD), with the right side shorter. The femoral neck osteotomy was planned 15mm above the lesser trochanter to provide 6mm of lengthening on the right side, Fig 8. 3D planning recommended a lateralised TriFit stem (Corin Group, Cirencester, UK) with the cup positioned 2mm off the true acetabular floor. This alignment restored global hip offset. Planned stem anteversion was 18° to preserve the AP position of the native femoral head.

Dynamic analysis showed the patient had a significant anterior pelvic tilt (32°) in the flexed seated position, Fig 1. This represented a 25° anterior rotation from standing, and highlighted the risk of posterior edge-loading and instability in flexion. There was minimal sagittal pelvic rotation from supine to standing. There were no signs of degenerative disease of the lumbar spine. The surgeon would generally favour a ceramic-on-ceramic bearing in this younger patient. However, given recent literature showing an increased risk of squeaking in patients with large anterior pelvic tilts in flexion [11], the surgeon chose to discuss bearing choice with the patient in more detail. In consultation with the patient, the decision was made to use a ceramic-on-ceramic bearing, with a target orientation of 34°/27° (inclination/anteversion). The amount of uncovered posterosuperior shell could be visualised in the OPS™ report, Fig 9.

The procedure was performed through a posterolateral approach.

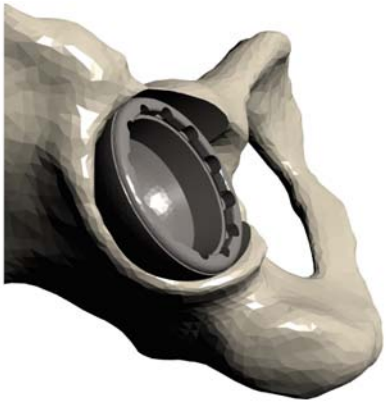


Figure 9. Three-dimensional model from the OPS™ report illustrating the templated acetabular cup position and orientation in relation to the surrounding anatomy.

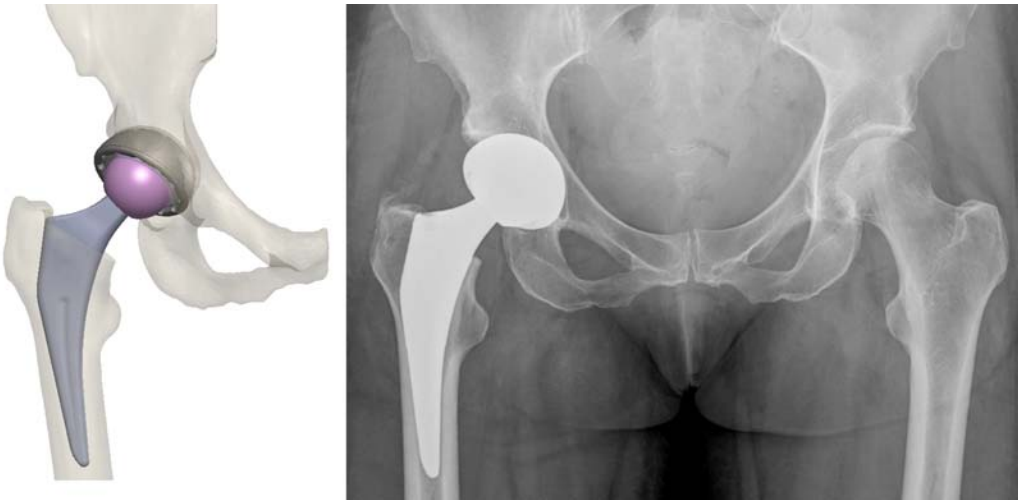


Figure 8. Left: Templated implants from OPS™ report; Right: postoperative radiograph.

Case Study 3

51 year old male with contralateral THA required right side replacement. CT analysis showed a 3mm LLD, with the right side shorter. The femoral neck osteotomy was planned 20mm above the lesser trochanter to provide 3mm of lengthening on the right side, Fig 2. 3D planning recommended a lateralised TriFit stem (Corin Group, Cirencester, UK) with the cup positioned 2mm off the true acetabular floor. This alignment restored global hip offset. Planned stem anteversion was 21° to preserve the AP position of the native femoral head.

Dynamic analysis showed significant changes in pelvic tilt during functional activities. The pelvis rotated 15° posteriorly from the supine to the standing position, leaving the patient with a 19° posterior pelvic tilt in extension. In the flexed seated position the pelvic tilt was 5°, a 24° anterior rotation from the standing position. There were no signs of degenerative disease of the lumbar spine. With the patient potentially at risk of functional cup malorientation in both flexion and extension, a dual mobility bearing was considered most appropriate by the operating surgeon, with a target orientation of 42°/13° (inclination/anteversion).

The procedure was performed through a direct anterior approach.

Discussion

Total hip arthroplasty is a successful operation, providing pain free function for patients with debilitating osteoarthritis. Fortunately, the procedure is relatively forgiving of component malalignment, and this has concealed the poor levels of precision achievable without assistive technologies [2-4,16-21]. Despite the generally high rates of patient satisfaction, failures still occur. It is important to address these failure mechanisms through responsible innovation, in both preoperative planning, as well as intraoperative delivery, to continue to improve outcomes and reduce revision rates in THA.

This paper provides an introduction to the OPS™ dynamic planning and delivery system for THA. Using standard medical imaging, OPS™ determines optimal component sizing and alignment for each patient. The defined targets are then achieved intraoperatively using 3D patient-specific guides. The OPS™ technology emphasises the importance of component alignment as well as functional analysis of patients.

The position of the pelvis in the sagittal plane changes significantly between functional activities [10]. The extent of change is specific to each patient. Often components will appear well oriented on standard views, but become malorientated during more functionally-relevant postures. Lembeck et al. showed that for every 10° of pelvic rotation in the sagittal plane, the anteversion of the acetabular component will change by around 7° [22]. Posterior pelvic rotation will increase the functional anteversion and inclination of the acetabular cup. This mechanism is protective in flexion, but problematic in extension. Conversely, an anterior pelvic rotation will decrease the functional orientation of the acetabular component. This is beneficial in extension, but can lead to posterior instability in flexion. It is not possible to predict these functional pelvic tilts from a standard AP radiograph.

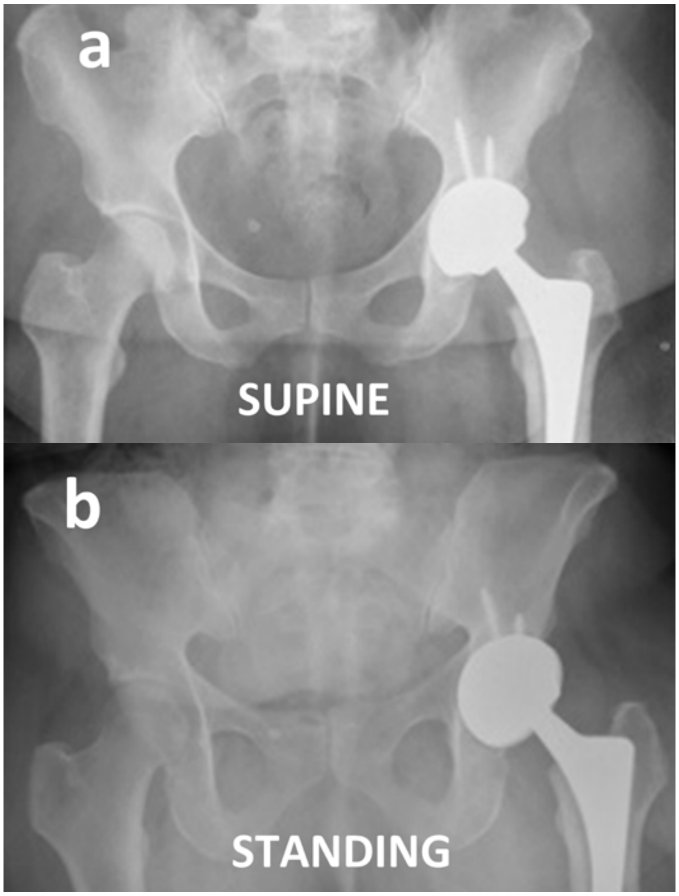


Figure 10. Supine and functional radiographs of a patient experiencing recurrent anterior dislocations.

Understanding the clinical relevance of functional component malalignment in the symptomatic THA was the catalyst for the development of the OPS™ preoperative planning system. Analyses of hundreds of symptomatic THA patients confirmed that apparently well-orientated components on standard pelvic radiographs can still fail due to impingement, dislocation, squeaking and runaway wear [23]. Fig 10 shows an example of a patient with recurrent anterior dislocation. Computer-assisted surgery was used to implant the acetabular component at an orientation of 42°/25° through a posterolateral approach. The supine radiograph looks unremarkable. However when standing, the patient's pelvis rotated posteriorly by 23°, leading to a functional cup orientation in extension of 54°/42° and anterior subluxation. Retrospective OPS™ analysis determined a more appropriate target orientation, given the patient's kinematics, would have been 34°/9°. This orientation would have reduced the risk of anterior subluxation in extension, whilst maintaining a safe boundary at the posterior edge in flexion.

The precision of the acetabular patient-specific guides has been confirmed in clinical practice. In a consecutive series of 100 OPS™ THAs, Spencer-Gardner et al. showed mean absolute deviations from the planned cup inclination and anteversion of 3.9° and 3.6° respectively. 91% of cups were within 10° of both the planned inclination and anteversion [24]. These results are comparable with published data on the precision of computer-assisted THA surgery [16-19], summarised in Table 1. Importantly, the OPS™ system defines a patient-specific target derived from functional, dynamic analysis, and does not require any registration to define the intraoperative reference frame.

Recreation of the femoral head centre in THA is important for maintaining leg length and offset, as well as improving muscle function and tissue tension. The femoral neck osteotomy can influence the size and alignment of the femoral component in THA, which in turn can affect the position of the prosthetic head centre. Dimitriou et al dem-

Table 1: Summary of published precision of the acetabular cup orientation for computer-assisted surgeries as compared with the OPS™ system.

Literature Reference	Mean Absolute Inclination Deviation ± SD (Range)	Mean Absolute Anteversion Deviation ± SD (Range)
Kalteis 2006	**3.6°** (1° to 12°)	**4.2°** (0° to 10°)
Lass 2014	**3.0°** ± 2.5° (0 to 10°)	**5.5°** ± 3.6° (0° to 14°)
Hohmann 2011	**3.4°** ± 2.2° (0.2° to 6.8°)	**5.5°** ± 4.0° (0.2° to 14.7°)
Gurgel 2014	**3.0°** ± 1.8° (0.3° to 6.2°)	**5.5°** ± 3.8° (0.5° to 12.3°)
Spencer-Gardner 2016	**3.9°** ± 2.9° (0.0° to 13.6°)	**3.6°** ± 3.2° (0.0° to 12.9°)

onstrated that the level and angle of the femoral neck osteotomy affects the varus/valgus alignment and anteversion of the stem, respectively [25].

Two-dimensional radiographs are conventionally used to template implant sizes and plan the femoral neck osteotomy. Often, the scale of the radiographs and the rotational alignment of the proximal femur misrepresent the patient's anatomy. The OPS™ preoperative planning determines the optimal position of the components to restore native anatomy and to achieve optimal metaphyseal loading based on three-dimensional reconstruction of the anatomy from CT. The target osteotomy is defined from the planned stem position, and delivered intraoperatively with a 3D printed guide.

In a series of 33 cases performed by two surgeons at a single institution, the OPS™ femoral guides reproduced the planned osteotomy level within 1mm in 85% of the cases [26]. Accurately achieving the optimal osteotomy will assist in attaining the desired post-operative leg length.

Hip kinematics are highly variable between individuals and between different functional activities. These dynamic changes have a significant effect on the functional alignment of the prosthetic components. Previously defined "safe zones" are not appropriate for all patients as they do not consider this dynamic behaviour of the hip joint. Further, templating from two-dimensional radiographs does not provide the surgeon with information about the three-dimensional position of the femoral head and proximal femoral anatomy. The OPS™ preoperative planning and delivery system is an innovative new technology that provides a dynamic simulation and personalised implant alignment, from standard medical imaging.

Disclosure

One or more of the authors have disclosed information that may present potential for conflict of interest with this work. For full disclosures refer to last page of this journal.

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