



## Cup positioning in total hip arthroplasty

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The “optimal” positioning of the cup in total hip arthroplasty can improve hip function and reduce wear, impingement and dislocation. The cup position is described as the spatial relation between the hip rotation centre and the pelvis and, as the cup orientation around the rotation centre. The first parameter affects hip balance and, if not managed properly, might result in poor function and leg length discrepancy. The second parameter is often “silent”, unless impingement or dislocation occurs. However, inappropriate cup orientation can accelerate wear and cause early failure. As such, it is mandatory to get both right, taking into account multiple parameters : the stem position, the approach, the bearing surface, the cup coverage and the pelvic orientation during loading. In most cases a “standard” cup position is adequate. However, specific anatomic features might require an individualized approach. This paper aims at reviewing the parameters that impact on the optimal cup position. This should allow for more judicious choices in those particular cases.

**Keywords :** hip arthroplasty ; cup orientation ; acetabular component ; biomechanics.

tends to improve (22). On the other hand, the proportion of liner exchanges and isolated cup revisions is increasing (22). As such, and because younger, more demanding and more active patients are getting operated on (16), the focus of hip arthroplasty might shift towards improving function, preventing dislocations and avoiding wear. In that respect, the correct implantation of the acetabular component is crucial as cup malposition can lead to poor hip biomechanics (11,33), dislocation (10,20,31,56), squeaking of ceramic-on-ceramic components (1,32) and increased wear (1,18,25,26,31,43,61).

Determining the optimal cup position is not trivial as it depends on multiple factors. This review addresses two cup position issues : the position of the hip rotation centre in relation to the pelvis and the spatial orientation of the cup around the hip rotation centre. In an effort to optimize cup positioning, we analysed the consequences of different choices in terms of hip biomechanics and function, probability of impingement and dislocation as well as wear.

### INTRODUCTION

Cup positioning remains one of the biggest challenges in total hip arthroplasty. Aseptic loosening and wear still represent a frequent cause for hip revision on the long term (16,22). However, with the development of better implant fixation techniques and bearing materials, the survival of hip implants

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## THE HIP ROTATION CENTRE IN RELATION TO THE PELVIS

The position of the rotation centre of the acetabular component in relation to the pelvis has an impact on hip biomechanics (11,33), squeaking of ceramic-on-ceramic components (32), hip stability (56) and acetabular load transmission (9,11). Because suboptimal restoration of hip biomechanics might influence hip function and leg length, patients will often notice when the hip rotation centre has not been managed properly.

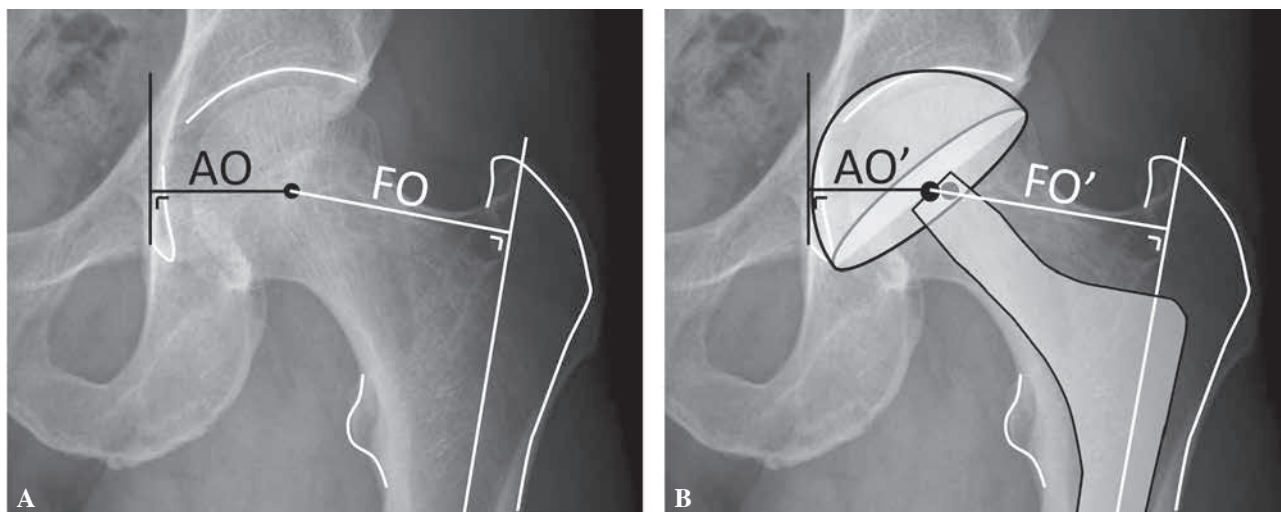
### Medializing or lateralizing the hip rotation centre

Medializing or lateralizing the hip rotation centre will mainly impact on hip stability and biomechanics. To maintain or restore both factors it is important to provide an adequate tension and level arm for the abductor muscles. An adequate tension within the gluteal muscles can be provided by restoring the native spatial relationship between the greater trochanter and the pelvis. This means restoring the combined offset or the sum of the femoral and acetabular offset (58) (Fig. 1A). If the combined offset decreases, abductor muscle tension drops and hip

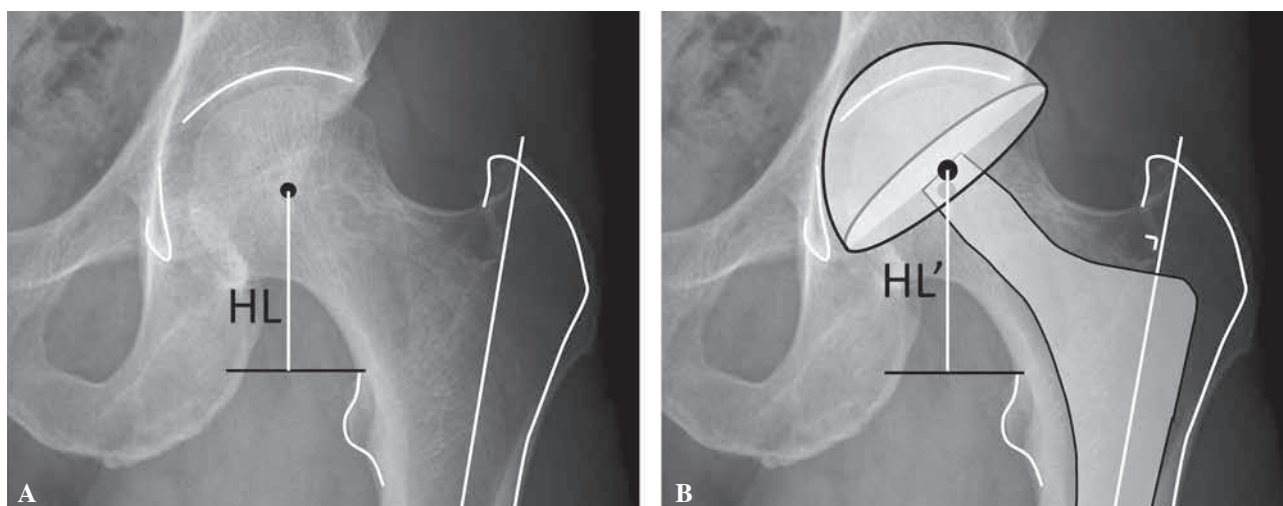
instability can occur (56). Opposite, an increased combined offset can produce excessive tension within the gluteal muscles and the iliotibial band and cause trochanteric pain.

When the hip rotation centre is lateralized compared to the original rotation centre, femoral offset needs to decrease to maintain the native relationship between greater trochanter and pelvis. As such, the level arm of the abductor muscles will decrease and joint reaction forces on the acetabular component (9) as well as wear (6) will increase. Opposite, when the hip rotation centre is medialized, and the femoral offset is increased to compensate for the lack of acetabular offset, the abductor level arm becomes more favourable (Fig. 1B). As such, less abductor force is needed during monopodal stance and joint reaction forces on the acetabulum decrease (11,34). That strategy can optimise hip function in the presence of gluteal muscle insufficiency. Moreover, increasing the femoral offset will reduce acetabular load (9,34) and wear (34,57). On the other hand, increased femoral offset will generate more torque on the stem and could theoretically favour stem loosening and periprosthetic fractures.

Medializing the acetabular component has also been proposed to allow a horizontal cup placement while maintaining sufficient bone coverage (63,69).



**Fig. 1.** — A. The combined offset is the sum of the acetabular offset (AO) and the femoral offset (FO). B. When the cup is medialized, the acetabular offset (AO') decreases and this should be compensated by increasing the femoral offset (FO') in order to maintain the combined offset (AO' + FO').



**Fig. 2.** — A. The hip length (HL) can be defined as the vertical distance between a fixed reference on the femur and the hip rotation centre. B. When a high hip rotation centre is chosen, the hip length (HL') should be increased to maintain leg length and abductor muscle tension.

This approach is clinically successful (6,63,69) and could be useful to reconstruct the acetabulum in cases of severe hip deformity.

### Superior or inferior cup placement

Moving the hip rotation centre more proximally or distally will mainly impact leg length and abductor muscle tension. When the hip rotation centre is brought proximally, leg length and gluteal muscle tension decrease. This can lead to hip instability, abductor muscle weakness and increased load transfer to the acetabular component (9). However, when a prone stem insertion compensates for a high hip rotation centre, wear, abductor muscle tension and leg length can be controlled (14,34,63) (Fig. 2).

### SPATIAL ORIENTATION OF THE CUP AROUND THE HIP ROTATION CENTRE

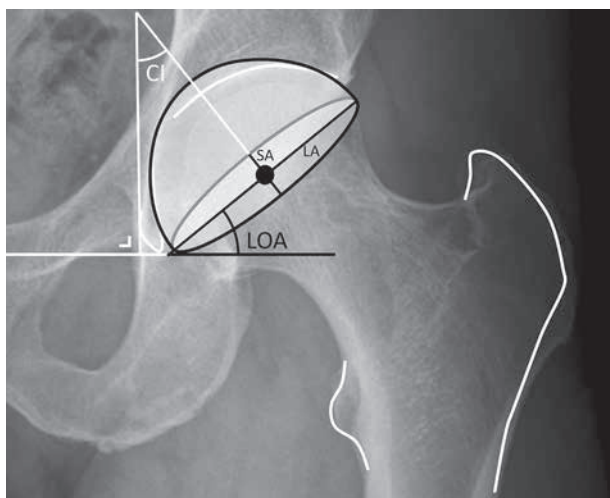
The special orientation of the acetabular component around the hip rotation centre will influence the risk of dislocation (10,31) and stem-cup impingement (15,27,46) as well as the load distribution and wear of the bearing surface (18,25,26,31,43,61). In contrast to changes in the position of the hip rota-

tion centre, patients will not perceive a suboptimal cup orientation, unless impingement or dislocation occurs.

### Definitions

Traditionally, the radiographic cup orientation is described on an anteroposterior pelvic radiograph taken with the radiographic plane parallel to the anterior pelvic plane, i.e. a plane defined by both anterior superior iliac spines and the symphysis pubis (42,44,51). Such radiographic measurements are reproducible and reliable compared to computer tomography based assessment (44). Cup orientation around the hip rotation centre is defined in terms of cup inclination or opening angle and cup anteversion (42,51). These terms describe the angles between radiographic landmarks and the projection of the acetabular axis, i.e. a line through the hip rotation centre and a perpendicular to the plane of the cup opening face (51).

The radiographic cup inclination is defined as the angle between the longitudinal axis of the patient and the radiographic projection of the acetabular axis, i.e. a perpendicular to the major axis of the cup projection (51) (Fig. 3). The lateral cup opening



**Fig. 3.** — The cup inclination (CI) is defined as the angle between the longitudinal axis of the patient and a perpendicular to the major axis of the cup projection. The lateral opening angle (LOA) is defined as the angle between the interteardrop line and the major axis of the cup projection. SA : Short axis of the acetabulum. LA : Long axis of the acetabulum.

angle or cup abduction angle is the angle between the interteardrop line (49) and the major axis of the cup projection (42,44) (Fig. 3). Without leg length discrepancy, the interteardrop line is perpendicular to the longitudinal axis of the patient, and the cup inclination angle equals the lateral opening angle.

The radiographic cup anteversion is defined as the angle between the acetabular axis and the coronal plane (51). That angle can be calculated based on the proportion between the major and minor axis of the cup projection (anteversion =  $\arcsin(\text{short axis}/\text{long axis})$ ) (44) (Fig. 3). Because the projection of the acetabulum depends on the pelvic tilt (i.e. the angle between the anterior pelvic plane and the coronal plane of the body), it is important to measure cup anteversion on standardized radiographs, i.e. with the radiographic film parallel to the anterior pelvic plane (62). When such radiographs cannot be obtained or when a more functional anteversion needs to be calculated (in sitting or standing position), the cup position in relation to the upper endplate of the first sacral vertebra can be assessed with a CT scan (37).

### Effect of cup orientation on impingement

After hip arthroplasty, impingement or involuntary contacts between bony structures or prosthetic components can occur in extreme hip positions. Beside increased range of motion caused by excessive joint laxity, soft tissue or prosthetic impingements can follow alterations of hip biomechanics or changes in the orientation of the acetabulum and the femoral neck.

Bony impingement is often due to incorrect restoration of leg length or combined offset or, to inadequate femoral orientation (7). It is not related to the orientation of the cup around the hip rotation centre. Bone-on-bone impingement occurs mostly during hip flexion and squatting (21) and can cause pain and dislocation (46). Yet, compared to implant-on-implant impingement, it is less likely to produce excessive acetabular peak stresses and dislocations (21).

Impingement of the prosthetic neck against the acetabulum rim has been described in 39% to 66% of acetabular revisions (24,59,60,68). It can cause excessive articular (13,60,68) and backside (60) wear, increase torque on the acetabular component and favour cup/stem loosening (12,28,50), dislocations (21,59) and hardware damage (13,21). Factors promoting cup-neck impingement include: poor cup and/or stem orientation (68), reduced neck-shaft angles (70) ( $120^\circ$  compared to  $135^\circ$ ), small femoral heads (68) or a reduced head-to-neck ratio (24,68) (skirted neck or head-to-neck ratio  $< 2$  (60)), acetabular wear (24,28) and an elevated rim (especially when positioned inadequately (60,68)). Several numerical models have been used to study the effect of cup/stem orientation, head size and neck shape on impingement-free prosthetic hip range of motion (13,15,70).

Cup inclination influences the degree of anterosuperior and posteroinferior coverage, and so the impingement-free range of motion (7,13,15,70). A horizontal cup position increases anterosuperior coverage, but uncovers the posteroinferior aspect of the acetabulum. Opposite, increasing the cup abduction angle will expose the anterosuperior aspect of the acetabulum but will increase the posteroinferior coverage.

Cup and stem anteversion have opposite effects on impingement. Increasing cup anteversion and decreasing stem anteversion will favour impingement of the posterior aspect of the neck against the posteroinferior rim of the acetabulum in extension and exorotation (13). Opposite, decreasing cup anteversion and increasing stem anteversion will favour anterosuperior impingement in flexion and adduction (13). As such, it is the sum of the cup and stem anteversion or the “combined anteversion” that affects cup-neck impingement (19). For a given neck-head ratio and a given neck-shaft angle, both the combined cup-stem anteversion and the cup inclination can be optimised to allow a maximal impingement-free range of motion (7,15,27,66,70). To avoid impingement, a cup inclination of 45° to 55° has been recommended, the optimal combined anteversion depending on the acetabular abduction angle (15). According to Yoshimine *et al* (70), a cup position avoiding impingement can be estimated with the following formula: (Cup inclination) + (Cup anteversion) + 0.77 × (Stem anteversion) = 84.4. As such, a cup inclination of 40° and a stem anteversion of 20° will require a cup anteversion of 29°. Widner *et al* (66) recommends 40° to 45° of cup inclination, 20° to 28° of cup anteversion and a stem anteversion between 12° and 24°, according to: (Stem anteversion) = (37° - Cup anteversion)/0.7. This is similar to the advice of Histome *et al* (27), suggesting a cup inclination of 45° and a combined anteversion of 42° calculated with the formula: (Cup anteversion) + 0.7 × (Stem anteversion).

In clinical practice, a combined cup-stem anteversion between 20° and 30° (20) or between 25° and 50° (37° ± 12°) (19) has been advocated. Because stem anteversion is more difficult to control than cup anteversion, especially with uncemented stems, some authors (19) suggest starting with the stem implantation and adapting the cup orientation to the stem anteversion.

### Effect of cup orientation on hip stability

Hip dislocation can occur without impingement but impingement is the largest contributing factor (13). Especially cup-neck impingement seems detrimental as compared to bone-on-bone impinge-

ment, even with the use of head diameters of 32 mm or more (21). As such, 94% of revisions performed for hip dislocation present signs of cup-neck impingement (59). The optimal cup position to avoid dislocation should take both into account, avoiding impingement and providing intrinsic stability within the envelope of impingement-free range of motion.

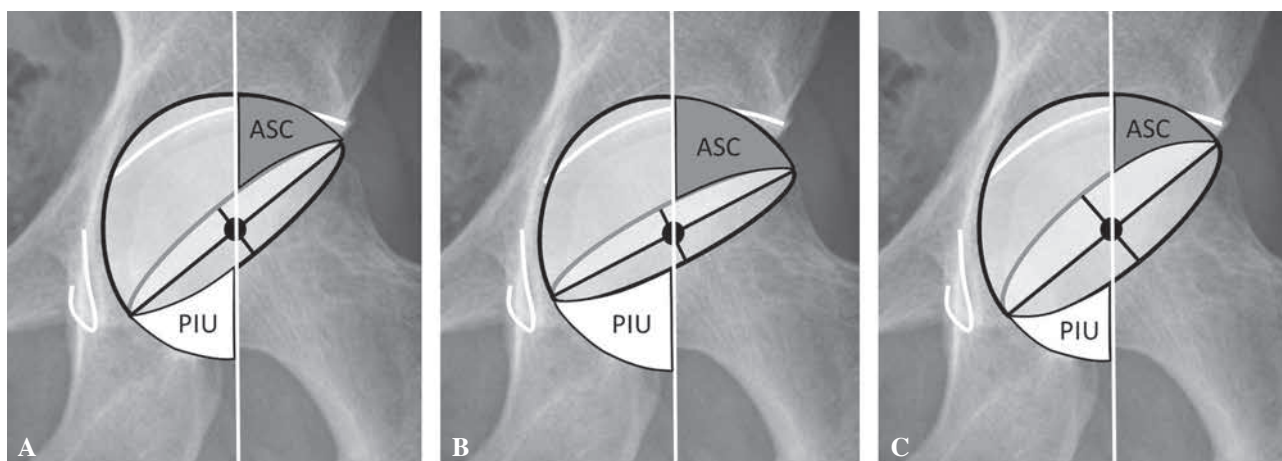
From a clinical point of view, a “safe zone to avoid hip dislocations” has been defined between 40° ± 10° of cup abduction (42,48) and 15° ± 10° (42) or 30° ± 10° (48) of anteversion. These clinical recommendations do not take into account the femoral anteversion, the neck/shaft angle, the restoration of hip biomechanics, the surgical approach and the interaction between cup abduction and anteversion in terms of coverage and risk of impingement. Only mathematical models can do this, but such models are theoretical and have not been validated in clinical practice.

### Effect of cup orientation on the cup-head contact area and wear

Wear of hip arthroplasty bearing surfaces has been related to the contact stresses at the cup-head interface, generated during activities of daily living (34). These contact stresses depend on loading parameters and the loading area of the cup and head. The cup-head loading area and the resulting wear are influenced by head size (29,36,41), cup inclination (4,18,25,26,34,36) and anteversion (25), femoral anteversion (25), pelvic orientation during activities of daily living (37), cup coverage (64) and the presence of an elevated rim.

To avoid excessive wear, the cup abduction angle should be 45° or less (63). Steep cups, with an abduction angle of 50°-55° or more, are prone to excessive wear and edge loading (4,17,18,25,31), especially with metal-on-metal articulations and when microlaterization (67) or microseparation (40) do occur. On the other hand, wear of ceramic-on-ceramic bearings seems less sensitive to a vertical cup position (2,30,54).

The effect of cup anteversion on wear is less straightforward and should be considered with regard to the femoral version (25). Some studies (45) report increased wear rates when the cup antever-



**Fig. 4.** — A. The anterosuperior coverage (ASC) and posteroinferior uncovered area (PIU) evolve in similar ways when the cup position is altered. A horizontal cup position (B), increases the anterosuperior coverage and exposes the posteroinferior area. A more anteverted cup position (C), decreases the anterosuperior coverage and increases the posteroinferior coverage.

sion is below  $15^\circ$ , whereas others (35,36) report increased wear with high degrees of cup anteversion. Overall, a cup anteversion between  $5^\circ$  and  $25^\circ$  has been advocated (42), outside that range the incidence of complications can increase dramatically (17).

Modifying the cup inclination and/or anteversion will influence both, the anterosuperior and the posteroinferior cup-head contact area in opposite ways (Fig. 4). A more horizontal cup, increases the anterosuperior cup-head contact area, but uncovers the posteroinferior aspect of the acetabulum. Increasing the cup abduction angle has the opposite effect. This might lead to higher contact stresses and even edge loading in a standing position (64). In a similar way, decreasing cup anteversion will increase the anterosuperior contact area, but will uncover the posteroinferior aspect of the head. Increasing cup anteversion will have the opposite effect.

From a wear point of view, a horizontal cup position combined to a minimal anteversion is preferable because it maximizes the anterosuperior cup-head contact area during walking. However, that cup position will uncover the posteroinferior region and will reduce the cup loading area in deep flexion, for example during rising from a chair. It might also increase the risk of dislocation in flexion-adduction-internal-rotation, especially when a posterior approach has weakened the soft tissues. As such, a compromise needs to be found between the optimal

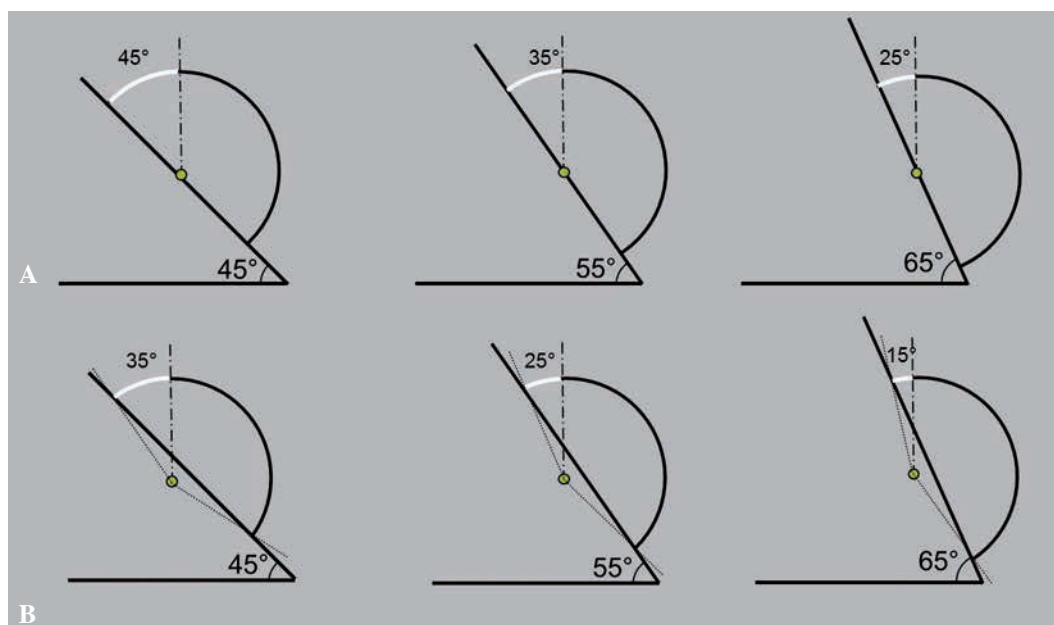
cup position in terms of wear and in terms of impingement and dislocation risk.

Because both, cup inclination and cup anteversion, influence the anterosuperior loading area and the posteroinferior shielding in opposite ways, optimising cup position should consider both parameters together. As a more vertical cup position tends to decrease the anterosuperior contact area of the cup, this should be compensated for by decreasing cup anteversion. Opposite, a horizontal cup should be implanted with more anteversion.

#### Effect of decreasing cup coverage

In order to avoid neck-cup impingement after hip resurfacing with an unfavourable head-neck ratio, the coverage of large head metal-on-metal cups has been reduced between  $152^\circ$  and  $166^\circ$  (23). As such, for the same cup orientation, implants with a reduced coverage have a smaller cup-head loading area and will be more prone to high contact stresses, edge loading and wear (18,64). Additionally, decreasing cup coverage reduces the shielding effect of the cup, making these implants more prone to dislocation. However, that effect might be less problematic because of the intrinsic stability of large prosthetic heads.

Considering cup inclination only, an acetabular component with  $160^\circ$  of coverage, positioned in an



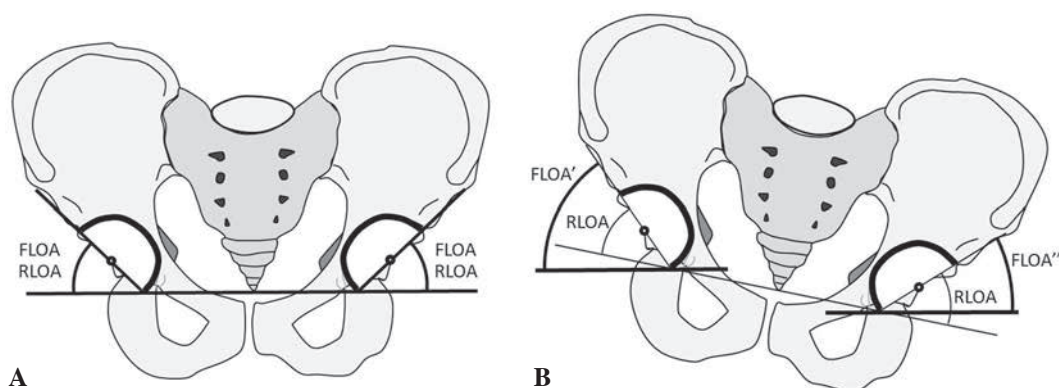
**Fig. 5.** — When positioned in the same degree of inclination, a cup with 180° of coverage (A) has a larger arc of cover than a cup with 160° of coverage (B).

“ideal” opening angle of 45°, will have the same arc of cover than a cup with the same diameter but with 180° of coverage inserted with a “suboptimal” abduction angle of 55° (Fig. 5). Similarly, a 180° cup positioned too vertically (65° of inclination) would still have the same arc of cover than a 160° cup positioned at the upper limit of inclination (55°). So, lowering the cup coverage to limit impingement decreases the boundaries of an acceptable cup position in terms of wear. Additionally, lowering cup coverage decreases the press fit of the cup in the acetabular bone and the implant/bone contact area, making these cups more vulnerable to early loosening (3,8,38,52). Accepting such compromises to allow a better ROM only makes sense for hip resurfacings because of the unfavourable head/neck ratio. However, the use of low coverage acetabular components in combination with large diameter heads and standard stems, was mainly inspired by economic/logistic issues and should be discouraged (3,8).

### Functional cup orientation

Strategies to optimize cup orientation around the hip rotation centre are based on an “average” pelvic position during hip loading. However, sometimes the pelvis will be tilted, either in the coronal plane (leg length discrepancy) or in the sagittal plane (hyper- or hypolordosis). Such modifications in pelvic tilt will influence the loading pattern of the hip during activities of daily living. In most cases, when the pelvic tilt is not severe, it is not necessary to take this into account. However, when pelvic tilt in one or both planes is severe, cup orientation should be adapted.

Pelvic tilt in the coronal plane is generally due to a residual leg length discrepancy after hip arthroplasty. At the shorter side, the “functional” cup abduction angle will decrease, while it will increase at the opposite side (Fig. 6). A more horizontal cup orientation in standing position at the shortest side, will have limited consequences as it increases the



**Fig. 6.** — Without leg length discrepancy (A), the functional lateral opening angle (FLOA) is equal to the radiological lateral opening angle (RLOA) based on the interteardrop line. When a leg length discrepancy exists (B), the cup appears more vertical at the longer side ( $FLOA' > RLOA$ ) and more horizontal at the shorter side ( $FLOA'' < RLOA$ ).

cup loading area. However, a functionally more vertical cup position at the longer side might result in edge loading, even if the cup is positioned correctly when evaluated on a balanced pelvis. As such, it is important to insert the cup in a more horizontal position when performing a hip replacement that will result in a longer leg.

Similarly, changes in anteroposterior tilt of the pelvis will influence the anterosuperior cup coverage during activities of daily living (5,37,39,47). As such, the anteroposterior pelvic tilt will influence the loading area of the cup, the probability of impingement and/or dislocation. In normal subjects, the sagittal sacral tilt (angle between a horizontal plan and a tangent to the upper part of the first sacral vertebra) varies  $30^\circ$  between the standing and sitting position (37). Limitations in that range of motion between the pelvis and the spine or changes in the sagittal balance of the spine should be taken into account when orienting the cup around the hip rotation centre.

Hyperlordosis will cause a forward pelvic tilt (pelvic flexion) and increase the functional anterosuperior coverage, but decrease the functional posteroinferior shielding of the cup. Increasing the anterosuperior cup coverage in standing position is beneficial from a wear point of view, but decreases the posteroinferior cup shielding and raises the risk of dislocation in deep flexion, especially when a posterior approach was used to insert the implants.

As such, in the case of hyperlordosis, it might be advised to antevert and verticalize the cup (39). Opposite, in case of hypolordosis or backward pelvic tilt (pelvic extension), the functional anterosuperior cup coverage will decrease (65) and the posteroinferior cup shielding will increase. As such, inserting the cup in a less anteverted and a more horizontal position should be considered (39).

## GLOBAL STRATEGY

The “optimal” cup position relies on the integration of multiple aspects of hip replacement such as : hip anatomy and possibilities to restore global offset with available implants, functional pelvic orientation, expected postoperative leg length discrepancy, the bearing surface and the surgical approach.

For example, when implanting a ceramic-on-ceramic hip arthroplasty through a posterior approach in a patient with a normal hip morphology, a normal sagittal pelvic tilt and without leg length discrepancy, the “optimal” cup position might be as follows : a slight medialization of the hip rotation centre, inserting the cup in close contact to the acetabular fossa, and the use of a stem with sufficient offset to restore the combined offset. This would reduce the load on the bearing surface and the cup-bone interface, and increase the level arm of the abductor muscles. The cup inclination could be targeted at  $40^\circ$  to ensure sufficient anterosuperior



coverage and avoid peak stresses even if the cup would be inserted 10° more vertical than the targeted position. To avoid posterior dislocation after a posterior approach, sufficient posteroinferior coverage should be provided. As a horizontal cup position has been selected (40° of inclination), and because a ceramic liner has no elevated rim, 25° of anteversion could be suggested. The stem could be inserted with 20° of anteversion to obtain a combined cup-stem anteversion of 45° and to maximize impingement-free range of motion. Finally a cup with 180° of coverage should be selected.

For a varus hip replaced with a metal-on-poly bearing surface through an anterolateral approach, the hip rotation centre should be placed as medial as possible taking into account the possibilities of an offset stem to restore the combined offset. In extreme cases, this could mean minimal acetabular reaming and the use of a large cup to lateralize the hip rotation centre. If needed, this could be combined with an offset stem, inserted as deep as possible, and the use of a long neck to maximize the femoral offset. A cup inclination targeted at 40° could be combined with a cup anteversion of 15°. This is less than after a posterior approach as the posterior dislocation risk is limited and allows improving anterosuperior coverage and wear. A stem anteversion of 20° would result in 35° of combined anteversion which would be acceptable. If needed, a liner with a 10° posterior elevated lip could increase the posteroinferior coverage and increase the combined anteversion to 45°. In all cases, a cup with 180° of coverage should be selected. If leg lengthening is expected, a more horizontal cup position should be chosen. If the patient presents insufficient lordosis, the cup could be inserted even more horizontally and with less anteversion.

## CONCLUSION

Defining the optimal cup position is challenging. A good understanding of anatomic, patient and implant related factors that affect the “optimal” cup position is mandatory. In most cases, restoring the original hip rotation centre and a “fixed standard target” of 40° of inclination and 20° of anteversion will result in a good clinical outcome. However,

some patients with anatomic variations or with a functional pelvic orientation outside the normal range, could benefit from a more in depth analysis of their case and a “personalised” cup position.

Defining the optimal cup position is one thing, but achieving the targeted position in a reproducible way is even more difficult (55). Computer assisted cup navigation systems can reduce the number of outliers (53). However, most systems use a fixed target position, not taking into account the multifactorial nature of optimal cup positioning. With a better understanding of the factors affecting optimal cup positioning, a customized approach should be pursued in order to avoid impingement, dislocations and to minimize wear in an individual patient (5).

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