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HIP

The accuracy of restoration of femoral head centre of rotation in the anteroposterior plane after uncemented total hip arthroplasty

A CT-BASED STUDY

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Aims

Hip arthroplasty aims to accurately recreate joint biomechanics. Considerable attention has been paid to vertical and horizontal offset, but femoral head centre in the anteroposterior (AP) plane has received little attention. This study investigates the accuracy of restoration of joint centre of rotation in the AP plane.

Methods

Postoperative CT scans of 40 patients who underwent unilateral uncemented total hip arthroplasty were analyzed. Anteroposterior offset (APO) and femoral anteversion were measured on both the operated and non-operated sides. Sagittal tilt of the femoral stem was also measured. APO measured on axial slices was defined as the perpendicular distance between a line drawn from the anterior most point of the proximal femur (anterior reference line) to the centre of the femoral head. The anterior reference line was made parallel to the posterior condylar axis of the knee to correct for rotation.

Results

Overall, 26/40 hips had a centre of rotation displaced posteriorly compared to the contralateral hip, increasing to 33/40 once corrected for sagittal tilt, with a mean posterior displacement of 7 mm. Linear regression analysis indicated that stem anteversion needed to be increased by 10.8° to recreate the head centre in the AP plane. Merely matching the native version would result in a 12 mm posterior displacement.

Conclusion

This study demonstrates the significant incidence of posterior displacement of the head centre in uncemented hip arthroplasty. Effects of such displacement include a reduction in impingement free range of motion, potential alterations in muscle force vectors and lever arms, and impaired proprioception due to muscle fibre reorientation.

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Article focus

- This study investigated the accuracy of restoration of the centre of rotation of the prosthetic femoral head in the anteroposterior (AP) plane.
- Studies so far have focused mainly on horizontal and vertical offset, but have largely ignored the AP plane.

Key messages

- A significant incidence of posterior displacement of the femoral head was found.
- Analysis suggested that the stem anteversion would have to be increased by 10.8° in order to recreate the head position in the AP plane.

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- Failure to do so can reduce the impingement free range of motion, and can reorientate and reduce muscle fibre length, which may account for some of the functional deficits seen after hip arthroplasty.

Strengths and limitations

- This was a real-world evaluation of a single-surgeon series of hip arthroplasties, with high intra- and interobserver reliability noted for the measurement method used.
- The clinical impact of the observed posterior displacement is however yet to be determined.
- However, the contralateral native hip was used as the comparator for the operated hip; ideally pre- and postoperative CT scans of the same hip would be used.

Introduction

Total hip arthroplasty (THA) is an increasingly popular and successful procedure. Despite reported satisfaction rates of greater than 90%, THA patients frequently demonstrate abnormal gait patterns when compared to the contralateral normal native hip or matched controls. Deficits include reduction in sagittal range of motion, power generation, particularly hip flexor strength, gait speed, and stride length.[1]

Accurate biomechanical reconstruction is thought to be key to optimizing the functional outcome of a THA. This can be broken down into acetabular and femoral factors. Once acetabular position and orientation have been determined, accurate femoral reconstruction is critical in optimizing both kinetic and kinematic outcomes.

Considerable attention has been paid to vertical and horizontal femoral offset. Vertical offset determines leg length, and the horizontal offset determines the abductor musculature lever arm. Alterations in both have been shown to have adverse effects on hip biomechanics, including reduced gait velocity, stride length, swing speed, and range of motion.[2-4] Deficits in offset from as little as 5 mm can have an adverse effect. The head centre position in the third dimension (y axis or anteroposterior (AP) plane) and its effect on hip kinetics and kinematics has not been subject to the same level of research; indeed, it has been largely ignored.

The aim of this study was therefore to determine the accuracy in restoration of the head centre position in the y-axis, i.e. the AP position. Our hypothesis was that despite recreating the native femoral anteversion, the head centre will be posteriorly displaced, due to the posterolateral entry point used to obtain neutral sagittal alignment of the stem.

Methods

Patient selection. This study included 40 patients who had undergone unilateral primary total hip arthroplasty (THA). This was a consecutive series of patients originally recruited for a study investigating the accuracy of restoration of femoral version following uncemented hip arthroplasty. Indications included primary hip osteoarthritis and avascular necrosis. Patients with ipsilateral or contralateral knee arthroplasty, or contralateral hip dysplasia, were excluded. Ethical approval was granted by the Lyon University Croix Rousse hospital ethics committee.

All patients were operated on by a single surgeon (TASS) through a posterolateral approach using an uncemented construct comprising a Pinnacle acetabular shell and Corail stem (Depuy, UK). Standard femoral broaching technique was used. A posterolateral entry point was defined on the osteotomized neck surface in order to achieve neutral sagittal alignment, and the initial broach inserted parallel to the posterior neck cortex in order to recreate the native femoral anteversion. Subsequent broaches were then inserted within the same bony envelope until longitudinal and rotational stability was achieved. The rotation of the broaches was determined by the proximal femoral helitorsion and neck anteversion.

Evaluation of anteroposterior offset displacement of the centre of rotation. Each patient underwent a postoperative CT scan which included both hips and distal femora. Femoral anteversion and anteroposterior offset (APO) was measured on the operated and unoperated side. In addition, stem sagittal tilt was measured on the operated side.

Femoral anteversion was evaluated using the method of Reikerås et al.[5] This was the angle subtended between the posterior condylar axis and the femoral neck axis on axial slices through the knee and hip, respectively.

APO was measured by creating a composite image constructed of three CT axial slices comprising an image of the knee posterior condylar axis, centre of the femoral head, and an axial slice of the proximal femur that demonstrated the anterior-most point on the proximal femur. This was done using Adobe Photoshop (Adobe Inc, USA). The composite DICOM image was then imported into RadiAnt DICOM viewer (Medixant, Poland) in order to make the measurements. The anterior-most point was invariably the innominate tubercle on the anterior intertrochanteric line.[6] The anterior reference line was then created from innominate tubercle, parallel to the posterior condylar plane, in order to correct for rotation of the limb. The perpendicular distance from this line to the centre of the femoral head was the APO. This was measured on both the operated and unoperated sides. A positive value indicated that the head centre was posterior to the anterior reference line (Figures 1 and 2).

Sagittal tilt of the femoral stem was measured on sagittal reconstructions of the operated side. This was defined as the angle subtended between the proximal femoral axis and femoral stem. The anterior displacement of the femoral head as a result of sagittal tilt was then calculated using this angle and the distance between the centre of the femoral head and the intersection point of the proximal femoral axis and stem axis (Figure 3).

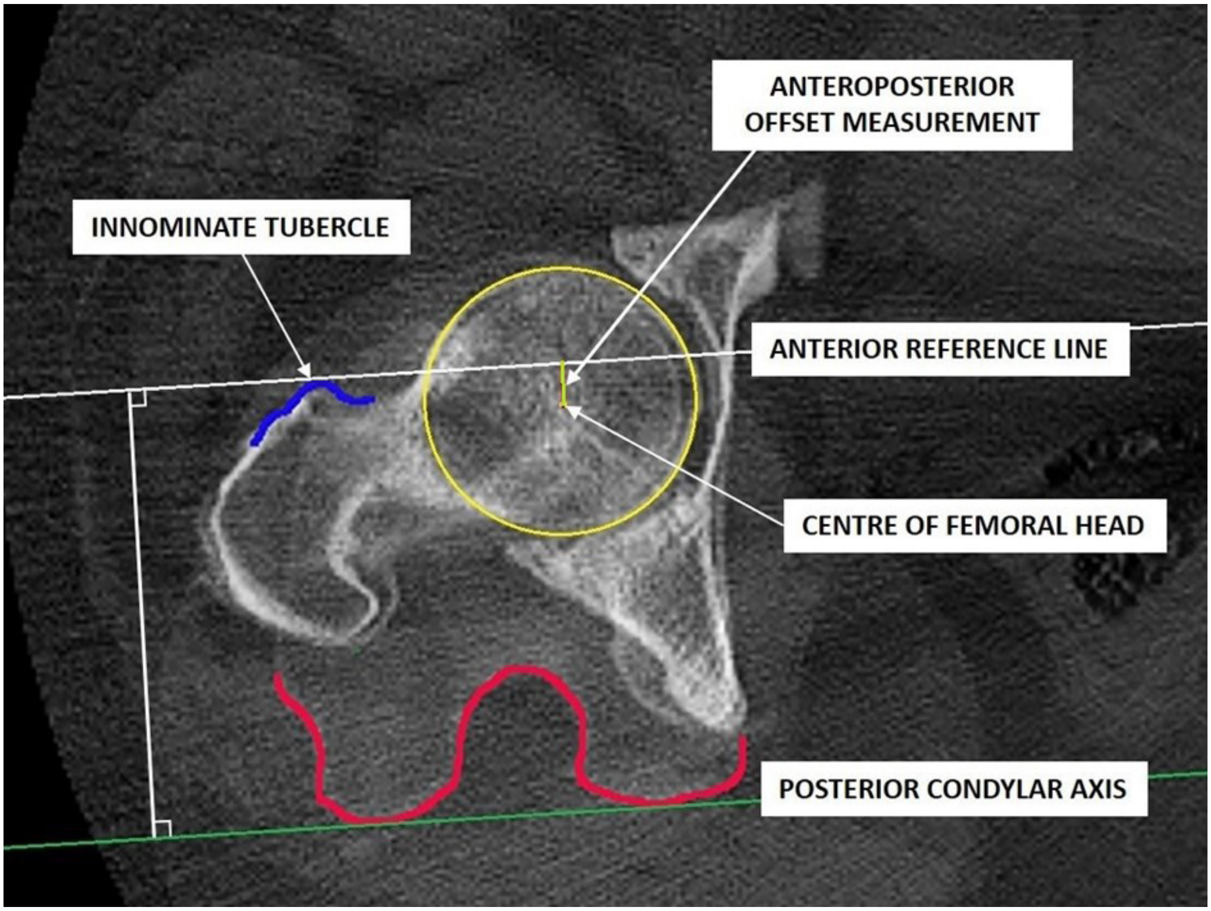

Fig. 1

Diagram highlighting the composite image constructed in order to measure the anteroposterior offset.

Statistical analysis. Statistical analysis for inter- and intraobserver agreement on APO measurement was performed using the intraclass correlation coefficient test for absolute agreement using the two-way mixed effects model. Measured variables were found to be normally distributed, and all data are expressed as mean and standard deviation (SD). Linear regression analysis, comparing difference in anteversion versus difference in APO between the operated and non-operated side, was carried out. A paired *t*-test was used to compare the differences in APO and femoral anteversion between the operated and non-operated sides. All statistical analysis was performed using SPSS software version 25 (IBM, USA). A p-value < 0.05 was considered statistically significant.

Results

The mean APO on the operated side was higher at 13.1 mm (SD 7.6) compared to 10.3 mm (SD 6.1) on the contralateral native side, with a mean difference of 2.8 mm (SD 6.5) (Table I). The difference was statistically significant (p < 0.001, paired *t*-test). Overall, 26 of the 40 patients demonstrated an increase in APO on the operated side compared to the native side. This was despite a higher mean anteversion on the operated side of 12.9° (SD 9.8°) compared with 8.5° (SD 8.1°) on the contralateral native hip. This indicates an overall trend towards posterior displacement of the head centre during THA. The mean sagittal tilt of the femoral prosthesis was 2.3° (SD 1.8°) tilted anteriorly. Once corrected for the sagittal tilt, in order to model the effect of having all the stems with neutral sagittal tilt as would be surgically intended, the mean APO of the operated hip was 17.4 mm (SD 7.3). The mean difference now in APO between the THA and native side was 7.1 mm (SD 6.3). The difference was statistically significant (p < 0.001, paired *t*-test), and further highlights the potential for posteriorly displacing the reconstructed head centre following THA.

For the APO measurements, correlation coefficient was 0.998 (95% confidence interval (CI) 0.992 to 1.000) for intraobserver agreement and 0.997 (95% CI 0.983 to 0.999) for interobserver agreement. This indicates a very good agreement between the two independent observers (AR, SGA).

There was a strong negative correlation between difference in APO and the difference in femoral anteversion when comparing the operated and native sides ($r = -0.73$). Overall, 26 of the 40 hips demonstrated a posteriorly displaced head centred on the operated side

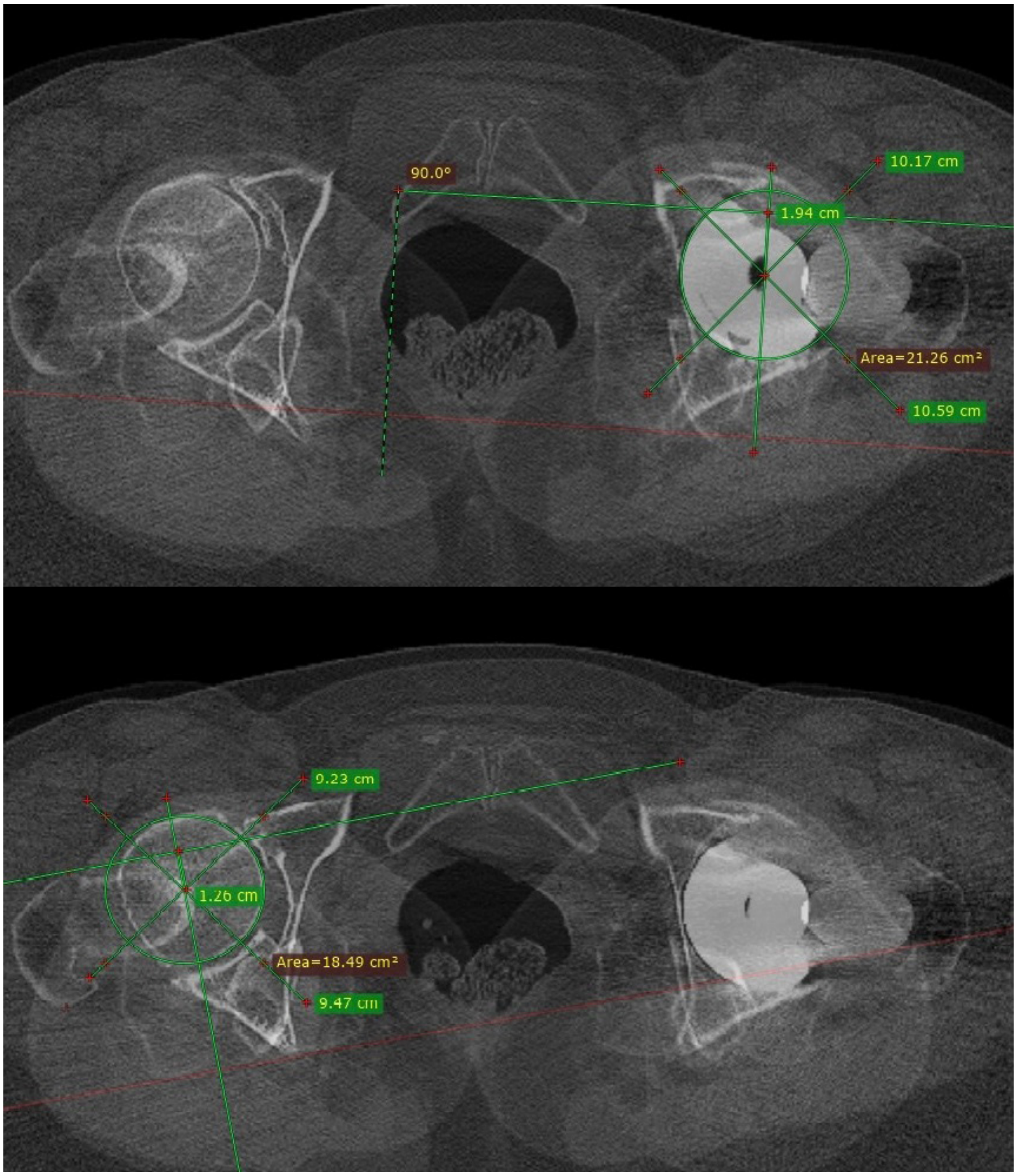

Fig. 2

Composite image imported into RadiAnt software demonstrating anteroposterior measurement on both the operated (1.94 cm) and non-operated (1.26 cm) sides.

compared with the contralateral native hip (increase in APO). The regression line did not pass through the origin of the scatterplot and its equation (y = –0.8x + 6.7) suggests that an increase in stem version of 6.7° is required to match the APO of the contralateral native hip (Figure 4). The intersect of the regression line on the x-axis suggests that merely recreating the native version would posteriorly displace the head by 8.4 mm.

This effect was further magnified once the APO was corrected for sagittal tilt. A strong negative correlation was once again seen (r = –0.8) when the difference in the corrected APO and femoral anteversion between the operated and native sides was compared; 33 of the 40 hips now demonstrated posterior displacement of the head centre on the operated side compared with the contralateral native hip. The regression line was now further away from the origin, and its equation (y = –0.9x + 10.85) suggests that an increase in stem version of 10.8° is required to match the APO of the contralateral hip if the stem was implanted with neutral sagittal alignment (Figure 5). The x-axis intersect point is now at 12 mm.

Discussion

The majority of THAs currently carried out are performed with 2D planning on AP pelvic radiographs. This allows appropriate stem sizing to account for the native vertical

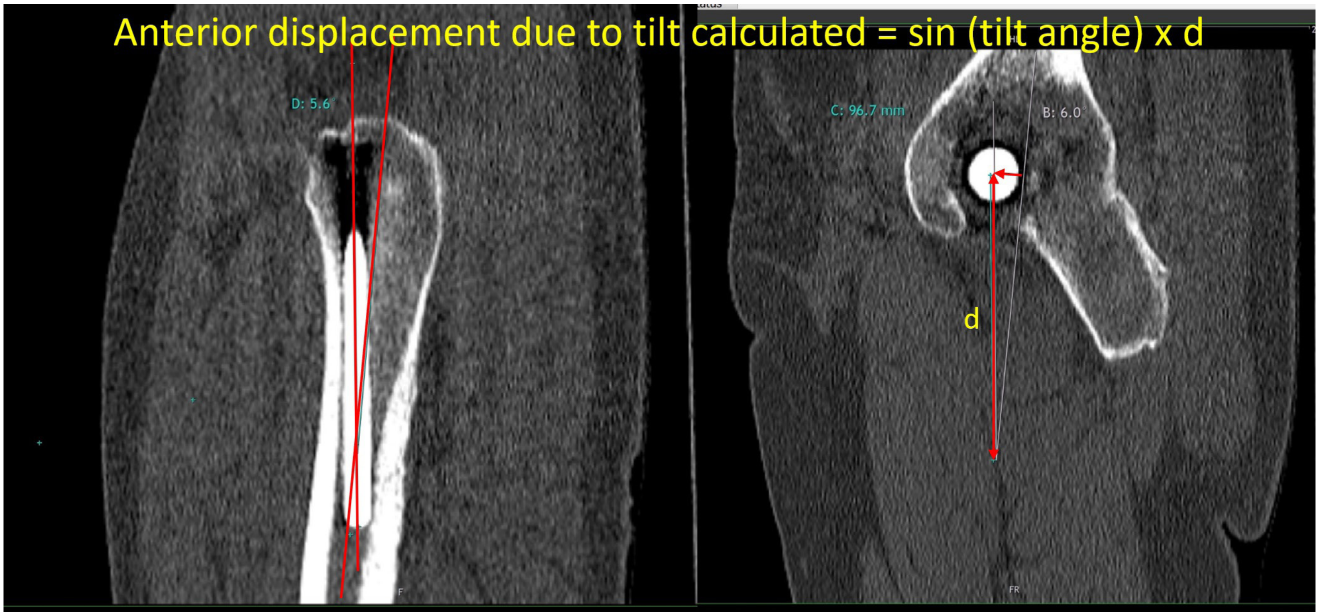

Fig. 3

Diagram of sagittal CT slices used to measure sagittal tilt of femoral stem and the resulting anterior displacement of the femoral head; "d" is the distance from the centre of the femoral head to the intersection of the stem axis and proximal femoral axis.

Table I. Descriptive statistics of anteroposterior offset, femoral anteversion, and stem sagittal tilt on the operated and non-operated sides. All data were normally distributed.

Variable	Mean	SD	Range
Native anteversion, °	8.5	8.1	-14.6 to 26.4
THA anteversion, °	12.9	9.8	-11.6 to 31
Native APO, mm	10.3	6.1	-3.5 to 22.8
THA APO, mm	13.1	7.6	-2 to 39.1
Difference in APO between THA and native side, mm	2.8	6.5	-7.4 to 25
THA APO corrected for tilt, mm	17.4	7.3	0.94 to 33.3
Difference in APO between THA and native side once THA side corrected for sagittal tilt, mm	7.1	6.3	-4.4 to 19.2
Sagittal tilt, °	2.3	1.8	-4 to 6

APO, anteroposterior offset; SD, standard deviation; THA, total hip arthroplasty.

and horizontal offset, but neglects the AP position of the femoral head. Intraoperative measurement of horizontal offset and leg length is standard practice by many surgeons, however there are no standardized techniques to measure preoperative and postoperative APO during surgery.

This study demonstrates that the traditional method of recreating the native anteversion may not be enough to accurately recreate the AP head centre position. Overall, 65% of the THAs studied had an increased APO compared to the contralateral hip, indicating posterior displacement of the femoral head. In order to recreate the APO, the anteversion may need to be increased by up to 10.8° in order to compensate. As the neck axis and proximal femoral axis do not intersect, using a straight stem inserted through a posterolateral entry point in order to achieve neutral sagittal alignment will cause the reconstructed head centre to move posteriorly.[7] The strengths of this study are that it is a real-world evaluation of operated hips, by a single experienced surgeon. A standardized measurement method was also used with very good intra- and interobserver correlation.

The clinical relevance of posteriorly displacing the femoral head is yet to be determined, but based upon prior biomechanical studies, we feel that they may be threefold. Firstly, this may cause a reduction in the impingement free range of motion. A relative posterior shift of the head centre, compared to the rest of the proximal femur in the AP plane, will result in earlier contact of the anterior aspect of the proximal femur with the anteroinferior iliac spine in flexion with internal rotation. Hirata et al[8] conducted a computer simulation study to examine the effect of APO on range of motion before bony impingement. Simulated THAs were carried out on 3D models created from CT scans of healthy individuals. APO was altered by changing stem version and sagittal tilt. A 10 mm change in APO, by posteriorly displacing the head centre, resulted in a 14° reduction in flexion and a 21° reduction in internal rotation at 90° of flexion. Inadequately recreating the AP centre may therefore increase the risk of bony impingement and subsequent posterior instability.

Another effect of change in APO could be an alteration of muscle force vectors. Significant deficits in force

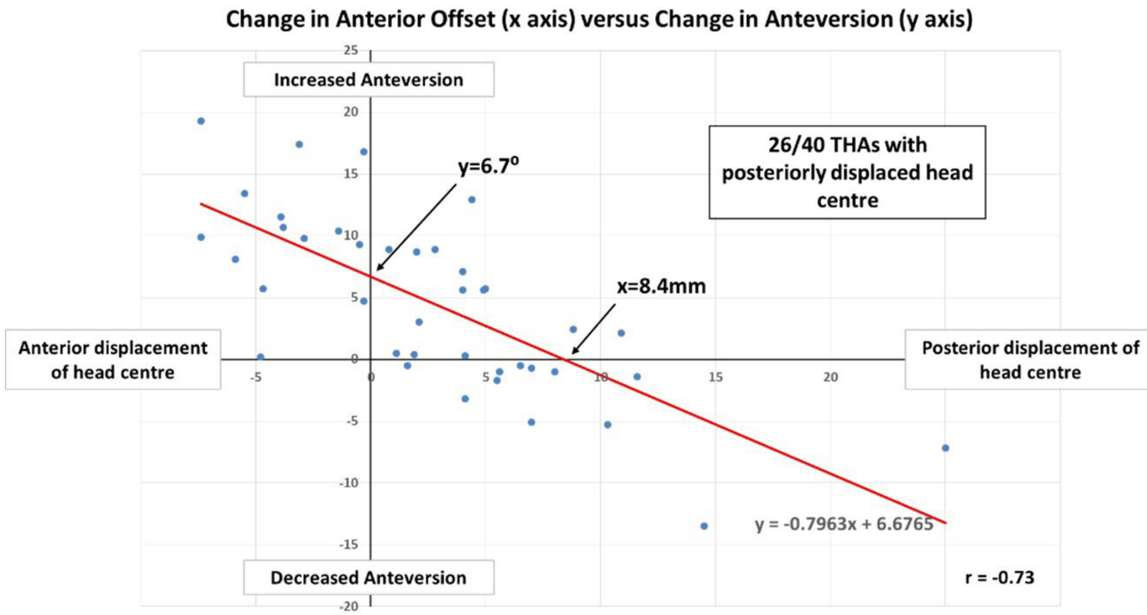

Fig. 4

Scatterplot of difference in anteversion between the operated and non-operated sides (y-axis) and difference in anteroposterior offset between the operated and non-operated sides (x-axis). THA, total hip arthroplasty.

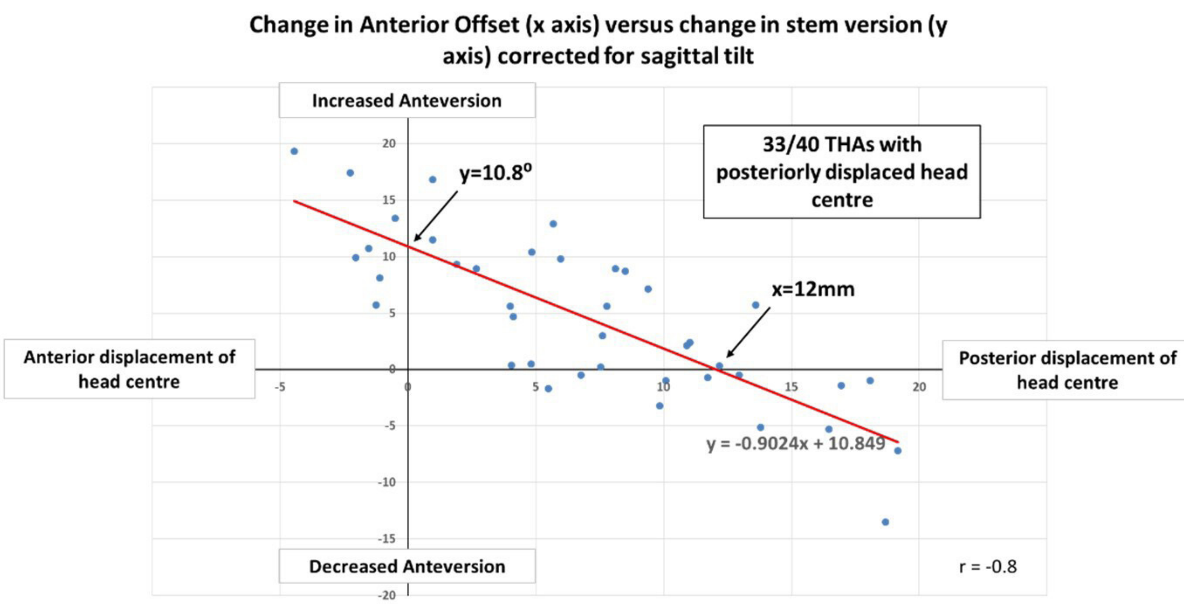

Fig. 5

Scatterplot of difference in anteversion between the operated and non-operated sides (y-axis) and difference in anteroposterior offset between the operated (once corrected for stem sagittal tilt) and non-operated sides (x-axis). THA, total hip arthroplasty.

generation in the parasagittal plane post-THA have been noted, particularly hip flexor strength,[1,9] clinically manifesting as a reduction in stride length and peak swing velocity. Reductions in horizontal offset adversely affect the abductor lever, leading to suboptimal gait patterns.[4,10] Alterations in the AFO may also have a similar effect to muscular function in the sagittal plane, particularly the hip flexors, such as the iliopsoas.

As the iliopsoas passes anteriorly across the hip joint towards the lesser trochanter, it curves around the femoral head, which acts as a fulcrum, increasing the angle of insertion relative to the femoral head. This increases the muscle's leverage for hip flexion.[11,12] Posterior displacement of the head centre following THA would effectively anteriorize the lesser trochanter, reducing the fulcrum effect of the femoral head and making the force vector

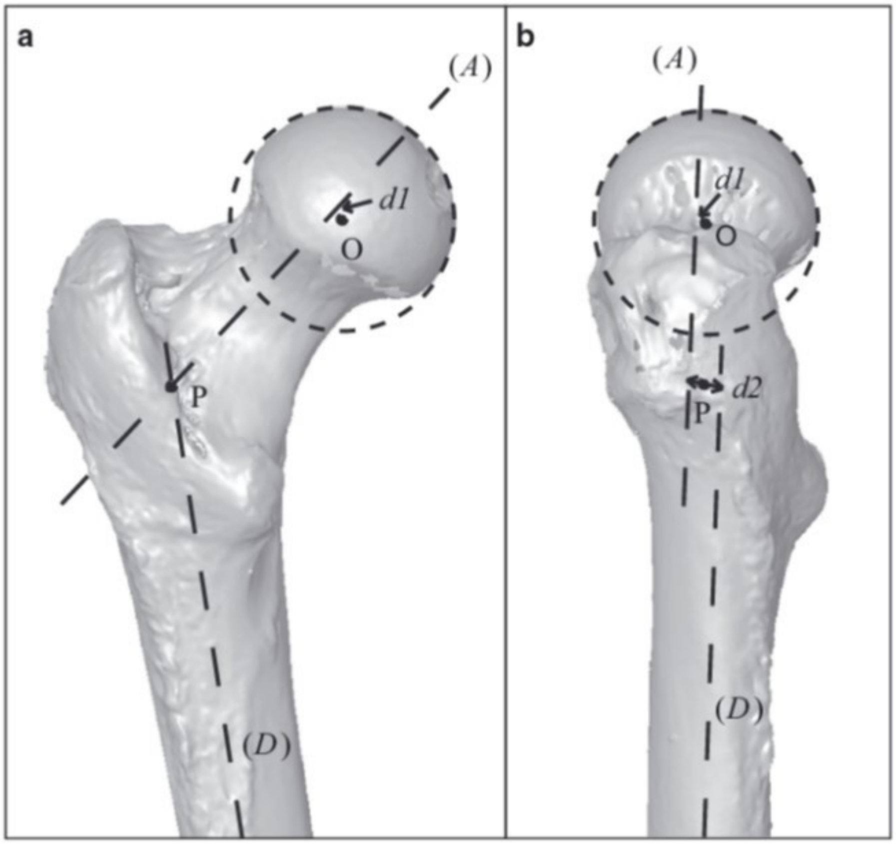

Fig. 6

Diagram demonstrating a) the position of the 3D axis of the femoral neck and the femoral shaft in a frontal view and b) a sagittal view. Distance (d2) demonstrates the offset between the two. Copyrighted image reproduced under permission from John Wiley & Sons, Inc.

more vertical, thereby reducing the horizontal, anteriorly directed component responsible for hip flexion. It would also reduce the resting muscle length, reducing the force generation capability of the muscle.[13] As the iliopsoas is the primary hip flexor, changes in APO may be responsible for some of the abnormal kinetics seen post THA.

The third effect may be on proprioception following THA. Other muscles, such as the gluteus medius and minimus, contribute less to parasagittal force generation. Their multipennate architecture does allow the anterior and posterior fibres to act as weak flexors and extensors, respectively.[11] Using finite element modelling, Rüdiger et al[14] have demonstrated how non-anatomical reconstructions of the head centre in the AP plane can result in fibre reorientation, altering their moment arms, causing fibres that would normally contribute to flexion to become extensors and vice versa. Their overall contribution to flexion and extension of the hip is relatively small, but this could have a significant effect on proprioception if fibres that are normally used to contracting during hip flexion are now elongating, and vice versa. Conventional stemmed THA patients have demonstrated impaired balance and stability compared to matched controls.[15] Resurfacing patients, however, had equal balance and stability performance compared to controls. Resurfacing arthroplasty may be more likely to accurately reproduce APO, as most of the native head is retained and used to position the new implant. This could account for the improved proprioceptive performance relative to conventional stemmed THA.

The cumulative effect of the three postulated effects of alteration of APO could overall clinically manifest in abnormalities in gait. Gait analysis has shown superiority of terms of gait normalization for resurfacing patients versus conventional stemmed THA, especially at higher speed and on inclines.[16-18] We postulate that a more accurate restoration of APO in resurfacing arthroplasty may be partly responsible for this superior performance.

Limitations of this study include the use of the contralateral native hip as the reference. Preoperative CT scans of the operated side were not available. The contralateral hip is commonly used to template for the diseased side, and Bonneau et al[7] studied 43 pairs of femora, finding no significant side to side differences in the 3D anatomy of the proximal femur. We therefore feel that using the contralateral hip is a reasonable reference to use. Despite this, we appreciate that, ideally, pre- and postoperative CT scans would be used. Additionally, only one uncemented stem design was used in all cases, and all were implanted using a posterior approach. This design has a rectangular cross-section and relies on a compacted cancellous bed of bone. Blade-type stems, or stems that are more fit-and-fill, may restore version differently, and this warrants further study. The posterior approach used is thought to allow better sagittal plane alignment of the stem compared with anterior approaches. As a negative side effect of a neutrally aligned stem, the centre of rotation may be displaced posteriorly compared with an anteriorly tilted stem, which may be more common with other approaches, and therefore the influence of approach also warrants further investigation. The method of measurement of APO was also a manual method, which may introduce some error. Intra- and interobserver agreement, however, was very high. Moving forwards, we propose using a 3D coordinate-based system to define the proximal femoral axis, innominate tubercle, and centre of the femoral head. This would allow distances to be calculated using trigonometry and vector equations and this may be more accurate. Our definition of APO is similar to that of Shoji et al,[19,20] i.e. using the anterior aspect of the proximal femur as the reference point to measure the APO. Hirata et al[8] have used the proximal femoral axis as the reference point. Further work to evaluate the pros and cons of each approach is warranted.

Besides using resurfacing arthroplasty, which has downsides related to metal ion release, 3D CT-based templating may help to improve the accuracy of APO restoration. Intraoperative execution of the proposed plan could be aided using robotic execution or 3D printed jigs to accurately guide neck resection and the required broach angle for APO restoration. Robotic arm-assisted arthroplasty has demonstrated the ability to accurately execute 3D planned acetabular placement, with accurate restoration of the native centre of rotation.[21-23] Such technology may also assist restoration of the femoral head centre in all three planes. This would allow restoration of functional anteversion and APO rather than merely prosthetic anteversion, which fails to account for the entry point and sagittal tilt of the stem. The concept of functional anteversion was first described by Müller et al.[24] This is defined as the angle subtended between a line connecting the centre of the femoral head and the proximal femoral axis, and the posterior condylar axis. As the neck axis is, on average, 4.9 mm anterior to the proximal femoral axis, merely using the native neck axis version, and aligning the prosthesis with the proximal femoral axis in the sagittal plane, will not recreate the functional anteversion of the hip (Figure 6).[7] Patients with broad femoral necks in the AP plane may therefore have an increased risk of non-anatomical APO restoration, as they will have an increased offset between the neck and proximal femoral axis.

This study included only one design of uncemented stem, a quadrangular cross-section design. Anteversion of uncemented stems is generally guided by the host anatomy, principally the native neck version and proximal femoral helitorsion. Sided anatomical stems with anteverted necks may provide an option to increase the functional anteversion and restore APO. Cemented stems also provide greater flexibility in adjusting version intraoperatively. Using 3D planning, custom implants may also provide better recreation of the host anatomy, as they are not limited to a straight design when viewed in cross-section as per conventional implants.

In conclusion, this is one of the first studies to look at restoration of the head centre in the AP plane post-THA. So far this has been a relatively neglected parameter when planning and executing THA. We have identified a significant incidence of non-anatomical reconstructions of APO, and feel this may have significant kinetic and kinematics implications. Practically, this could effect THA planning, intraoperative technique, and stem design. Further research is planned using both computer modelling and gait analysis to study its effect.

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- T. Ait Si Selmi: Conceptualization, Investigation.
- T. Board: Conceptualization, Writing – review & editing.

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