

Accuracy of reconstruction of the hip using computerised three-dimensional pre-operative planning and a cementless modular neck

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Pre-operative computerised three-dimensional planning was carried out in 223 patients undergoing total hip replacement with a cementless acetabular component and a cementless modular-neck femoral stem. Components were chosen which best restored leg length and femoral offset. The post-operative restoration of the anatomy was assessed by CT and compared with the pre-operative plan.

The component implanted was the same as that planned in 86% of the hips for the acetabular implant, 94% for the stem, and 93% for the neck-shaft angle. The rotational centre of the hip was restored with a mean accuracy of 0.73 mm (SD 3.5) craniocaudally and 1.2 mm (SD 2) laterally. Limb length was restored with a mean accuracy of 0.3 mm (SD 3.3) and femoral offset with a mean accuracy of 0.8 mm (SD 3.1).

This method appears to offer high accuracy in hip reconstruction as the difficulties likely to be encountered when restoring the anatomy can be anticipated and solved pre-operatively by optimising the selection of implants. Modularity of the femoral neck helped to restore the femoral offset and limb length.

In hip replacement the implantation of cementless femoral stems has been shown to be more difficult to plan than with cemented stems, and to yield poorer agreement between the pre-operative plan and the post-operative result when using radiographs and two-dimensional templates,¹⁻⁵ especially for determining the final position of the stem and hence the limb length. Angles of anteversion and torsional abnormalities are not accurately analysed using plain radiographs, and the femoral offset may be underestimated from the radiographs in patients with marked restriction of external rotation.⁶ Three-dimensional assessment based on CT scanning may improve pre-operative planning and the accuracy of hip reconstruction by optimising the choice of implants before operation. To our knowledge there is no study in the literature about the accuracy of hip reconstruction using three-dimensional planning and a cementless modular-neck stem.

We present a new technique of pre-operative three-dimensional planning. The goals of this study were to determine the accuracy of three-dimensional planning of total hip replacement (THR) using our method with HIP-PLAN software (Symbois, Yverdan Les Bains, Switzerland) to compare the pre- and post-operative anatomy of the hip using an

anatomical cementless modular-neck stem (SPS-Modular Symbios). We have analysed the clinical relevance of this method.

Patients and Methods

Between February 2004 and June 2006 a prospective non-comparative, non-randomised study was undertaken. Two senior surgeons (AM, GP) performed 223 consecutive THRs (223 patients) using the cementless SPS-Modular femoral stem. This stem has an anatomical shape with a design derived from experience creating custom-made prostheses.⁷ The acetabular component is hemispherical and contains two peripheral ridges, thereby increasing the external diameter by 1.4 mm. An anterolateral approach was used in 183 patients (183 hips) by the first surgeon (AM) and a posterior approach in 40 hips by the second (GP). There were 136 women and 87 men, with a mean age of 70 years (41 to 88) and a mean body mass index of 28 kg/m² (19 to 40). The operated side was the right in 129 patients and the left in 94. All patients underwent surgery for primary osteoarthritis, which was grade 2 in 207 cases and grade 3 in 16, according to the Tönnis classification.⁸

Prior to surgery, patients underwent three-dimensional planning and a surgical simulation in order to determine the prosthesis

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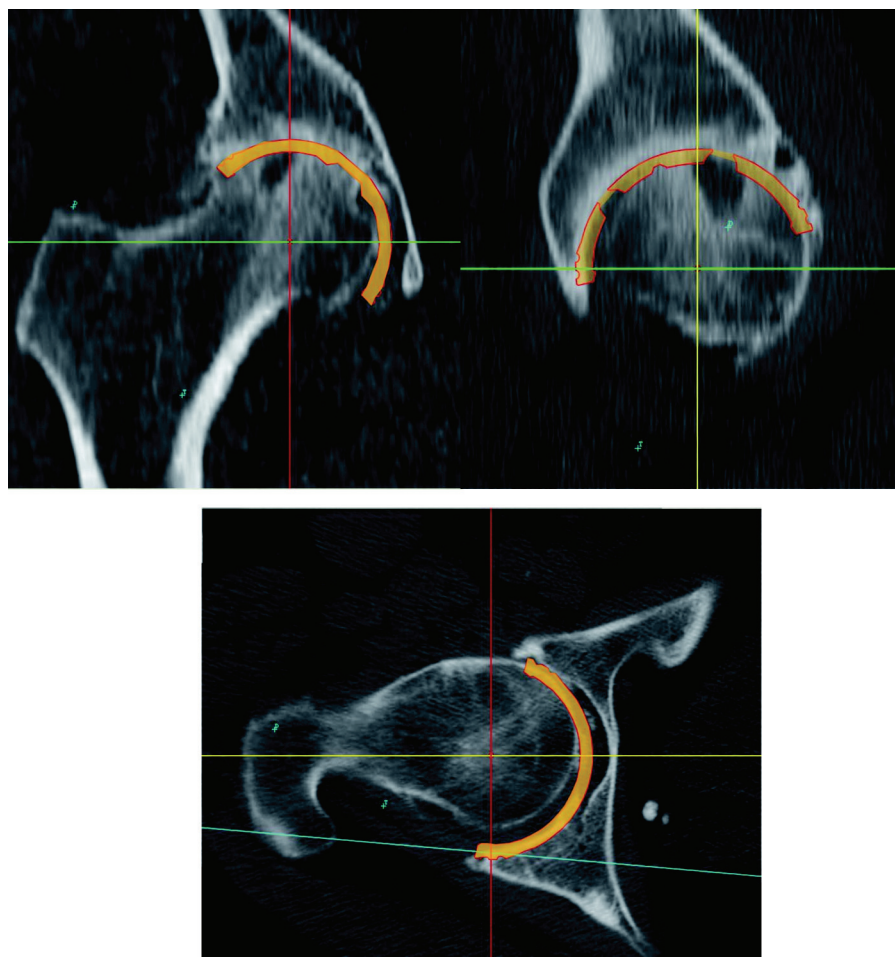


Fig. 1

Implantation of the acetabular component. A 3D template is used to simulate the implantation.

which would restore their hip anatomy to that existing before the onset of osteoarthritis most accurately. Planning and the simulation of surgery were performed using the HIP-PLAN software, which is based on CT scans. All patients had pre- and post-operative scans in order to compare the post-operative anatomy of the hip with the situation before operation.

Spiral CT protocol. The patients were positioned supine, with their legs in neutral rotation. Spiral CT (GE Medical systems, Light speed 16, Danbury, Connecticut) included the pelvis from the iliac crest proximally to the femoral isthmus distally. Additionally, six CT slices of the knee were taken in order to establish the bicondylar reference plane for the measurement of femoral anteversion. The CT comprised contiguous sections of 2.5 mm thickness. The radiation exposure was evaluated on ten randomly selected patients by calculating the effective dose in milliSieverts (mSv). The same calculation was done for the plain radiographs, including the anteroposterior pelvic view, and anterior and lateral radiographs of the hip. The mean effective dose for CT scanning was found to be about 11.2 mSv (9.7 to 13.9), which is

equivalent to five plain radiographs each with an effective dose of 2.1 mSv.

Description of HIP-PLAN software. This program allows the operator to modify the perspective on the hip, performing translations in the three directions and rotations around the three axes. The bicondylar axis of the knee was determined on an axial view, and was used as a reference line in order to calculate the angles of anteversion of the femoral neck.

Acetabular analysis was undertaken in the anterior pelvic plane, as defined by the anterior superior iliac spines and the pubic tubercles as references. The acetabular position was determined using the superimposition of a hemisphere, on the coronal, sagittal and axial views. The software calculates the values of acetabular anteversion and abduction angles in the anterior pelvic plane. Simulation of the implantation of the acetabular component was by using three-dimensional templates with increasing diameters (Fig. 1). The 3D-acetabular template was placed relative to the anterior and posterior acetabular columns as well as to the superolateral acetabular margin, so that removal of the supporting subchondral bone was

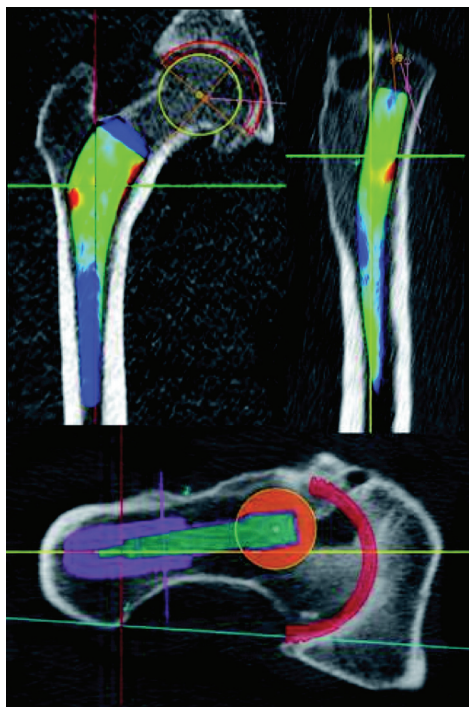


Fig. 2

Pre-operative 3D planning with HIP-PLAN software. The density of the stem is used to predict the blockage level.

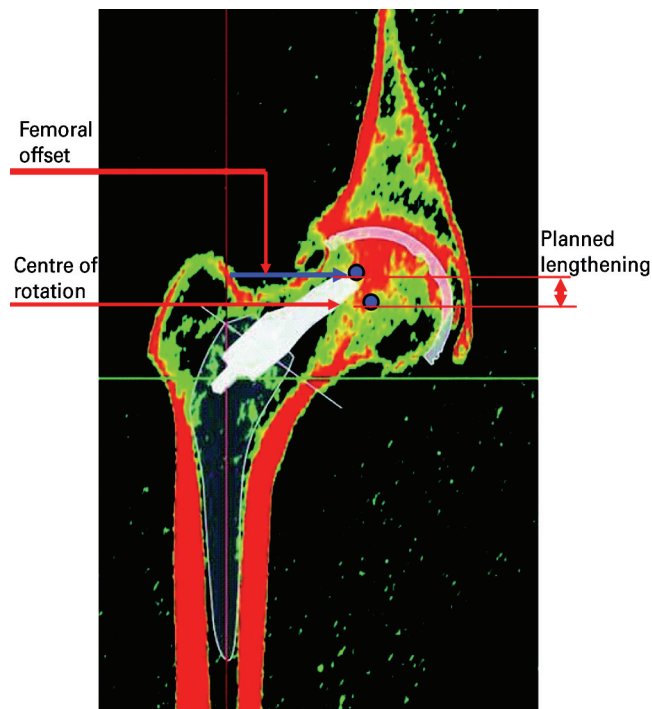


Fig. 3

Once the acetabular component and stem were implanted, a modular neck was selected to restore the femoral offset and limb length. The centre of hip rotation was planned to match the centre of the acetabular component.

minimised and the centre of rotation of the hip was closely restored.

The femoral analysis was performed in a femoral frame, which was determined so as to maximise the view of the femoral metaphyseal canal on both the frontal and the sagittal views. The origin of the frame was the centre of a cross-section through the base of the femoral neck as used by Billing⁹ and Murphy et al.¹⁰ The mediolateral axis was chosen parallel to the femoral metaphyseal axis on a cross-section through the base of the neck, and the craniocaudal axis was parallel to the diaphyseal axis of the femur (Fig. 2). A sphere was superimposed on the femoral head in order to determine the coordinates of its centre. Afterwards, the femoral offset was calculated as the distance between the centre of the femoral head and the femoral axis (Fig. 3). Femoral anteversion was calculated according to the technique described by Murphy et al.¹⁰ Implantation of the stem was simulated with 3D templates of increasing size (Fig. 2). The SPS-Modular stem obtains metaphyseal fixation and therefore the stem size was chosen to maximise both fit and fill in the metaphyseal region. The final craniocaudal position of the stem would be reached when this femoral implant was blocked from more distal implantation, reflecting a good fit within the femoral canal. In order to determine the craniocaudal blocked position of the stem matching a safely reamed femur, a colour image mode was cited which reflected the density of the bone in contact with

the stem (Fig. 2). This colour grading was calculated using the Hounsfield density.¹¹ In order to achieve good primary mechanical stability the authors assumed that the stem should be in contact with dense bone, at least on the lateral flare of the stem and at the calcar. Finally, the distance from the top of the lesser trochanter to the top of the stem was measured in order to control the depth to which the stem was inserted during surgery. A view in the plane of the osteotomy of the femoral neck was given to the surgeon in order to control visually the position of the stem during the operation and to assess the femoral anteversion. Once the acetabular component and the stem were implanted, modular necks and heads were used in order to restore the extramedullary anatomy, especially limb length and offset (Fig. 3). Modularity of the neck allowed three different neck-shaft angles (8° varus, straight, 8° valgus), three anteversion angles (10° retroversion, 0°, 10° anteversion) and two different lengths for each neck (short, long). The straight neck corresponded to a 132° neck-shaft angle. For the femoral head, four lengths could be used: -3 mm, 0 mm, 3 mm, and 6 mm.

Anatomical parameters studied. The planned sizes of implant were compared with the actual sizes used at operation. In order to determine the accuracy of the anatomical restoration, the following parameters were studied:

1. Distances (Fig. 3): a) The co-ordinates of the centre of rotation of the hip in the pelvic plane and those of the

centre of the femoral head in the femoral frame. Change in the length of the leg was calculated by the software, using the difference between the pre- and the post-operative positions of these two centres. b) The femoral offset.

2. Angles: a) The angle of anteversion of the acetabular component and the angle of acetabular abduction. b) The anteversion of the femoral component.

Surgical technique. Both surgeons ream the acetabulum with removal of minimal bone in order to avoid medialising the centre of rotation of the hip. The osteophytes detected pre-operatively on the CT scan are removed, and the acetabular component is orientated to match to the skeleton. The surgeons try to visually reproduce the 3D planned position of this implant relative to the acetabular circumference by checking the distances from the margin of the component to the bone roof, and the anterior and posterior columns. The femoral stem has a lateral flare which is designed to ensure primary mechanical stabilisation. The femoral canal is always prepared with a curette before the reaming procedure. First, the cancellous bone in contact with the lateral cortical bone under the great trochanter is removed in order to prepare the site where the lateral flare of the stem would be received; and second, if a large internal calcar septum^{12,13} is detected on the pre-operative CT scan, it is removed. The operators check the stem position with two parameters. First, the distance from the top of the lesser trochanter to the shoulder of the stem. This measure is calculated pre-operatively on the 3D plan (3D CT measurement). Second, in order to control the anteversion of the femoral component, the surgeons perform a visual check of the position of the stem in relation to the femoral cross-section in the plane of the osteotomy of the femoral neck, which has been planned and provided to the surgeon pre-operatively. Once the acetabular component and the stem are implanted, the planned neck is used, and then hip stability, leg length, craniocaudal laxity and mediolateral laxity are assessed. The operators adapt the type and the length of the neck, and the length of the modular head, in order to improve the correction of limb length and the stability of the reconstruction.

CT scan comparison method: matching software. One independent observer (ES) analysed the post-operative images. In order to compare the planned anatomical parameters and the clinical outcome, the same cartesian reference landmarks were used. The pre- and post-operative CT scans were matched with the HIP-PLAN software by separately aligning the pelvis and then the femoral bony landmarks (Fig. 4). This allowed the post-operative anatomy of the hip to be compared with the pre-operative situation in order to check whether the anatomy had been restored. The accuracy was calculated as the mean difference with the SD between the planned values and the final clinical post-operative outcome.

Even if the intention is to restore the anatomy, the planned values for the defined parameters may be different from the pre-operative situation. Therefore, three potentially different values were analysed: the pre-operative

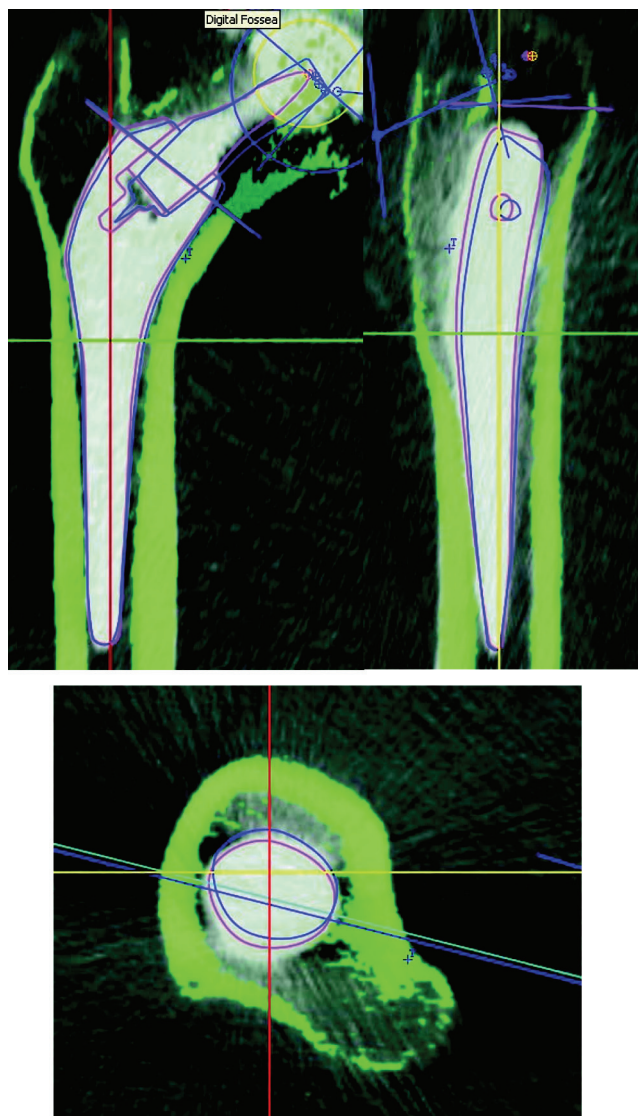


Fig. 4

Comparison between pre- and post-operative CT scans. The two CT scans were matched by aligning the pelvis and the femoral bony landmarks. The pre-operative CT scan is grey and the planned stem is in blue. The post-operative CT scan is green and the real stem is in red.

anatomical values corresponding to the native anatomy; the planned values corresponding to the 3D planning; and the post-operative values corresponding to the anatomy of the new hip.

Statistical analysis. Pearson's correlation coefficient was used to study the correlation between two variables. This was evaluated using the grouping recommended by Landis and Koch.¹⁴ Scores between 0.61 and 0.8 represented substantial agreements, and those greater than 0.81 were considered to have perfect agreement. Accuracy of all the parameters was assessed as the mean difference between the planned values and the post-operative values which had been calculated as means with their SDs.

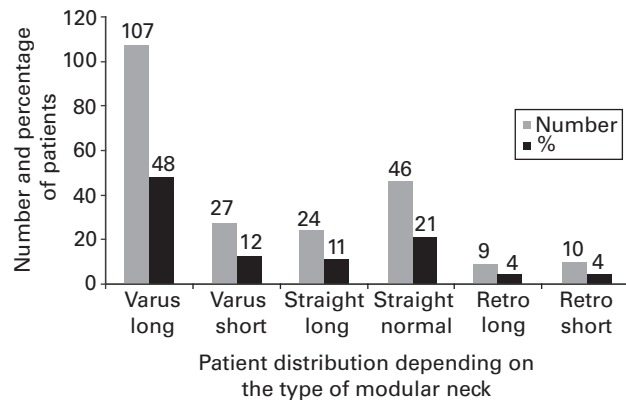


Fig. 5

Distribution of the modular femoral neck sizes used. The most frequent neck used was long varus, suggesting that a reference 132° neck-shaft angle is too high.

The distribution of variables was tested for normality using the Ryan-Joiner and Shapiro-Wilk tests. For normally distributed variables, when two groups had the same variances, the differences between them were analysed using Student's *t*-test. For variables lacking a normal distribution or normally distributed variables with unequal variances, the Mann-Whitney U-test was applied. A *p*-value < 0.05 was considered to be statistically significant.

For the analysis of the change in the femoral offset, (medial or lateralisation) two thresholds of significance were used. First, a threshold with a change of 12% above which functional manifestation of abductor weakness begins to appear, and secondly, a threshold of 28% change above which clinical functional decompensation always exists, as noted by Asayama et al.¹⁵

Results

In 192 (86%) of hips the implanted acetabular component and in 209 (94%) the implanted stem was identical to the one planned. If precision was expanded to include all implants within one size of the templated size, the precision was 100%. **Distribution of neck type.** The neck-shaft angle and the length of the implanted neck were the same as the planned sizes in 174 (78%) hips. Considering the final neck-shaft angle alone, the same size as the one planned was used in 207 hips (93%). The neck type was modified in nine hips in order to improve stability; in six anterior instability was solved by using a retroverted neck, and in three a more anteverted neck was implanted because of posterior instability. In all these cases the instability was due to a malpositioning of the implants, with a global over- or under-anteversion. The most frequently implanted neck was a long varus in 107 hips (48%) (Fig. 5).

Planned and real femoral anteversion. Perfect agreement was obtained between the planned femoral anteversion and that found post-operatively with no significant difference between the mean planned anteversion value of

26.1° (SD 11.8) and the post-operative value of 26.9° (SD 14.1; 0.18); there was a high correlation between these two values (0.84, *p* < 0.001) (Fig. 6).

Planned and real acetabular anteversion. There was no substantial agreement between the planned acetabular anteversion and that measured post-operatively (correlation coefficient 0.17). The mean post-operative acetabular anteversion was 31.3° (SD 8.9) representing a mean increase of 6.3° (SD 8.5) compared with the mean planned value of 25° (SD 5.7; *p* = 0.001, paired Student test). The mean increase of acetabular anteversion of 7.9° (SD 8.5) was significantly higher in the patients operated on using an anterior approach compared with those operated on using a posterior approach, where the mean increase was 2.7° (SD 9.3; *p* < 0.001, Student test).

Planned and real acetabular abduction. There was no substantial agreement between the planned acetabular abduction and that found post-operatively (correlation coefficient 0.5). The mean post-operative acetabular abduction of 47.5° (SD 6.4) was increased by a mean of 2° (SD 4.7) compared with the mean planned value of 45.5° (SD 4.1; *p* = 0.001, Student test).

Hip rotation centre. Lower limb length. Femoral offset. The centre of rotation was restored with a mean accuracy of 0.73 mm (SD 3.5) craniocaudally (*t*-test, *p* = 0.002), 1.2 mm (SD 2) laterally (*t*-test, *p* < 0.001) and 0.05 mm (SD 1.8) sagittally (*t*-test, *p* = 0.62). Limb length was restored with a mean accuracy of 0.3 mm (SD 3.3) and the femoral offset with a mean accuracy of 0.8 mm (SD 3.1).

Comparison of the pre-operative anatomy and the post-operative restoration

Native and post-operative femoral offset. No significant modification of femoral offset was found (*p* = 0.4, Student test). When using 12% as a threshold, femoral offset was restored in 82% (183 of 223) of hips, increased by a mean of 6 mm (SD 1.7) in 25 (11%) and reduced by a mean of 7.5 mm (SD 2.7) in 15 (7%); thus femoral offset was unchanged or slightly increased in 208 (93%) of hips. Considering the threshold reported by Asayama et al,¹⁵ below which clinical functional decompensation always exists, the offset was restored in 219 (98%) of hips. The mean global lengthening was 5.8 mm.

Native and post-operative anteversion angles. Anteversion of the acetabular component was found to be increased by a mean of 5.2° (SD 9.2) over the anatomical anteversion (*p* < 0.001, Student test), whereas abduction of the acetabular component was a mean of 3° (SD 6.9) less than the anatomical abduction angle. Anteversion of the femoral component was increased by a mean of 5.8° compared to the anatomical femoral anteversion (*p* = 0.001, Student test). The mean total acetabular component and femoral anteversion was 49.5° (SD 15).

Clinical relevance: anticipation of intra-operative difficulties Almost all the technical surgical difficulties were anticipated, especially for the femoral reaming and the simultaneous restoration of offset and limb length. In the event of

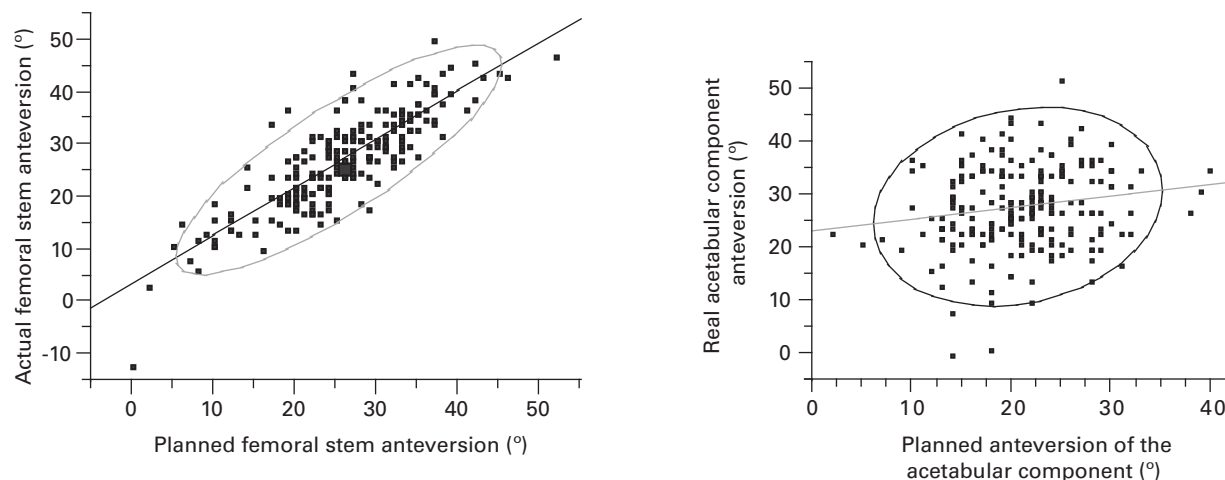


Fig. 6

Correlation between the planned values and those achieved for the angle of anteversion of the acetabular component and the angle of femoral anteversion.

high bone density, powered reaming was planned allowing a safe and easy procedure. As previously reported,^{12,13} we have confirmed that a constant cortical spur was localised at the lower part of the femoral metaphysis adjacent to the medial endosteal line. Sometimes this spur is enlarged and impedes reaming and positioning of the stem. In this situation the spur has to be removed entirely. A pre-operative fixed external rotation deformity led to an underestimation of the femoral offset on the radiographs. We experienced many cases of disproportion between the size of the stem and the femoral offset where either a small femoral metaphysis was associated with a high offset (Fig. 7) or the reverse was found. In these cases the extramedullary anatomy was adapted separately.

Discussion

Computer-assisted planning was found to be accurate and helpful in restoring the femoral offset, limb length and centre of hip rotation. It has been stated^{15,16} that these parameters must be restored in order to improve the functional outcome after THR. However, the results reported in the literature show that when using current non-modular stems, these parameters may not be restored, especially the femoral offset and limb length, in up to 32% of cases,¹⁶ and might contribute to limping or dislocation.¹⁵

Recently, Sarialli et al¹⁷ reported that the femoral offset may be underestimated by up to 13.7 mm when measured on two-dimensional radiographs rather than with a 3D CT scan, leading to functional impairment.¹⁵ The method presented appears to be accurate for hip reconstruction, as the difficulties associated with restoration of the anatomy can be detected and solved pre-operatively by optimising the implants, such as by using a varus neck to increase the femoral offset without increasing the length of the limb. The clinical relevance of 3D planning has already been reported in a case report of revision THR for instability.¹⁸

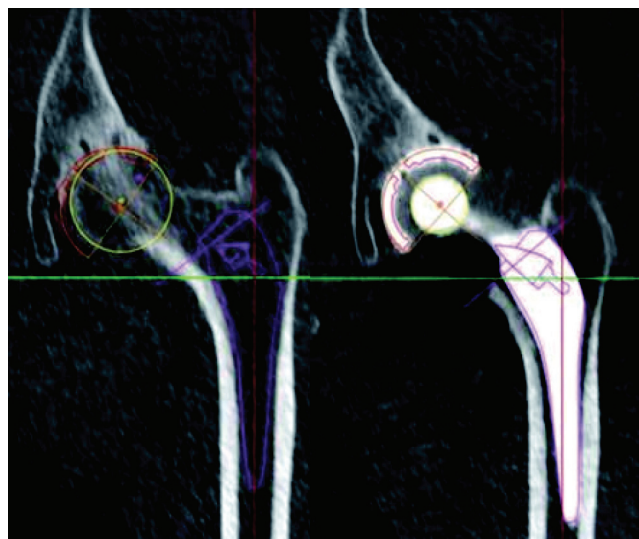


Fig. 7

Disproportion between the femoral metaphysis dimension and the femoral offset. This patient had a narrow femoral metaphysis and a high offset. A long-varus neck allowed restoration of limb length and femoral offset. This may not be feasible with current non-modular stems.

There is a limited amount of literature assessing the accuracy of pre-operative templating using conventional techniques.¹⁻⁵ For cementless stems, Carter et al¹ found that in only approximately 50% of their cases did the 2D templated size correspond directly to the final femoral implant, whereas using our 3D method this occurred in 94% of cases. Gonzalez et al³ found a predictability of 51% for the acetabular cementless component. Knight and Atwater⁴ noted a predictability of 42% for the stem and showed that the error was related to the magnification of the radiographs. Only Eggl et al² observed good predictability for two-dimensional templating, at 92% for the stem and 90% for the acetabular

component. However, a cemented stem was used in more than 90% of cases; cemented devices have been shown to be easier to plan and to yield better agreement between the pre-operative plan and the post-operative result.^{2,5}

The poor predictability of two-dimensional templating for cementless stems is probably related to inadequate estimation of bone morphology. The stability of a cementless stem is ensured by an optimised fit between the stem and the prepared femoral cavity, but the reaming procedure will stop when a maximum resistance due to bone density is reached. Thus, the final size is a compromise between intrafemoral anatomy and bone density. Analysis of the intramedullary femoral canal using radiographs does not seem to be accurate enough, as it does not explore these two parameters. A colour mode was used in this study in order to visualise accurately the density of cancellous bone and to determine whether the reaming procedure was safely achievable.

Higher predictability of 3D planning has already been reported by Sugano et al,⁶ who found that, when the combined femoral neck anteversion and fixed external rotation of the hip exceeds 15°, plain radiographs and the template method are not sufficient for planning THR. In this case, CT-based pre-operative planning is recommended. The 2D templating predictability for the proximal fit of the femoral component to the medial endosteal line was poor, with a sensitivity of 41% and a specificity of 23%, whereas the CT-based method had 93% sensitivity and 86% specificity.

There was no statistically significant difference between the mean planned value of femoral anteversion of 26.1° (SD 11.8) and the post-operative value of 26.9° (SD 14.1; $p = 0.18$), and a strong correlation between the two values was found ($p = 0.84$). We believe that this excellent agreement is due to the anatomical shape of the stem, which was derived from the experience of custom-made devices.⁷ In contrast, the mean acetabular component anteversion was increased by 6.9° compared with the planned anteversion. Surprisingly, the mean increase in acetabular component anteversion was found to be significantly greater in the patients operated on via an anterior approach, which might be a function of the surgeon being drawn by the exposure to position the components in this manner. The findings suggest that a guidance system may be useful for orientation of the acetabular component. Navigation systems have been shown to increase the reproducibility of positioning of the acetabular component.¹⁹⁻²¹ However, it may be difficult to determine the precise values for anteversion of the acetabular component, as pelvic tilt is often a confounding factor in pre-operative templating when using plain radiographs.²² It has been shown that pelvic orientation changes according to the position of the patient^{23,24} and induces variations in anteversion of the acetabular component.²⁵ Pelvic orientation has recently been reported to change after THR, generating errors of up to 20° for measurement of anteversion.²⁶ This variable is eliminated by 3D planning, as the unwanted pelvic rotations are removed and the planning performed in the ante-

rior pelvic plane. The ideal solution would probably be to combine pre-operative 3D planning in order to determine the ideal intended position and the best implants for hip reconstruction, with the navigation system to execute the planning with a higher reproducibility.

The centre of rotation of the hip was restored with a mean accuracy of 0.73 mm (SD 3.5) between the planned and actual positions of the centre vertically and 1.2 mm (SD 2) laterally. Though these differences were statistically significant they were very small and much less than the thresholds that may lead to clinical consequences.²⁷

The restoration of the femoral offset was achieved in 98% of cases, which exceeds values reported in the literature, which range from 40% to 90%, depending on the design of the stem.^{3,16} It should be noted, however, that these authors did not report any threshold of significance for the analysis of the femoral offset, so that any comparison with our results should be interpreted with caution. Sariali et al¹⁷ showed that there was a significant underestimation of the pre-operative femoral offset when using radiographs because of the femoral anteversion and the external rotational contracture that is generally corrected post-operatively. The use of CT overcomes this problem and increases the accuracy of the analysis of femoral offset. There was a high correlation between the predicted neck-shaft angles and the one implanted, indicating that the femoral offset was corrected by restoring the neck-shaft angle.

In nine (5%) cases, misplacement of the femoral implant induced instability, which was detected during the surgical procedure and resolved by adapting the modular neck.

In some hips a disproportion exists between the stem size and the femoral offset, which can make reconstruction more difficult when using non-modular stems. Many currently available non-modular designs of femoral stems have an offset which increases as the size of the component increases. In hips with a narrow femoral canal with thick cortices and a large offset, it may be difficult to restore the offset and limb length simultaneously with a non-modular stem. If a small stem is used which can be accommodated by the femur, mediolateral laxity may be produced, for which the surgeon might lengthen the limb in order to tighten the soft tissues to avoid instability. It has been noted by Krishnan et al²⁸ that there is no mathematical correlation between femoral offset and canal size, suggesting that the extramedullary anatomy is probably independent of the intramedullary anatomy. A modular system of necks addresses this concern, and may account for the precision which we achieved in restoring limb length.

As predicted from pre-operative planning, the most frequently used type of neck was the long varus component, which suggests that a 132° stem-neck angle is probably too high. This is supported by mean values in two reports of 124° and 129°.^{29,30}

We acknowledge certain weaknesses in our study, namely that it was non-randomised, non-comparative, and no intra-observer variability tests were performed.

Some concerns exist about the irradiation exposure, as Jurik, Jensen and Hansen³¹ have shown that a spiral CT scan is equivalent to four plain pelvic radiographs. Our results are comparable in that the effective dose was five times higher than the exposure of conventional radiographs. However, the delivered dose was about 11 mSv, which is very low, far beneath the reported dose which has been related to a higher cancer risk (200 mSv to 5000 mSv).³² In clinical use, CT should be performed only pre-operatively for the 3D planning. Improvements in the CT scanning techniques and the processing software may solve the radiation dose problem. Henckel et al³³ reported that specific protocols combining filters and image post-processing on multiple detector helical CT scan may reduce the radiation dose to a level comparable with standard radiographs.

The accuracy of the 3D planning using the HIP-PLAN software is good, and greatly superior to that of the two dimensional templating.

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