Templating of Total Hip Replacement: Technique and Biomechanical Basic Knowledge

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Content

Manual for Templating of Total Hip Replacement

Introduction

Preoperative planning of total hip arthroplasty (THA) is important to achieve accurate reconstruction and anticipate intraoperative difficulties and obstacles [1, 2]. Eggli demonstrated that exact planning on plain pelvic radiographs has significant value on the success of hip prosthesis implantation [1]; 80% of all intraoperative obstacles could be detected preoperatively with adequate planning by anticipating difficulties associated with large osteophytes, a thin medial wall or acetabular retroversion. Various templating techniques have been described and include two- [1] and three-dimensional approaches [2, 3]. This manual provides a step-by-step guide for THA templating on plain pelvic radiographs. The stem, which we used for templating in this manual was a Corail®-Stem (DePuy, Warsaw/IN). Some aspects (e.g. neck options) of templating may therefore differ when other implants are used. In addition, we address the key biomechanical aspects in the form of a narrative review, which can be considered essential for optimal hip reconstruction. The method we describe here is one of many techniques for planning a THA. Most often, the planning procedure is dependent on specific software.

Our approach allows the surgeon to plan a THA independent of the available software tools, which integrates leg length, femoral offset as well as other biomechanical or anatomical parameters with the aim that the analysis with early recognition of possible intraoperative difficulties can be anticipated.

Part 1: Planning technique

THA templating – Important steps prior to hip prosthesis implantation

Standard radiographs for templating include a preoperative anteroposterior (AP) view of the pelvis. For THA templating, a low-centered AP view of the pelvis is preferred as the proximal femurs need to be visible down to the tip of the prosthetic stem. Therefore, the central beam is placed just above the symphysis. Defined criteria characterize an adequate pelvic AP view for preoperative planning: rotation and tilt must be taken into account with respect to the pelvic projection. Neutral rotation is apparent when the coccyx is in line with the pubic symphysis; in this case, the obturator foramina are symmetrical. Pelvic tilt is considered adequate if the distance of the tip of coccyx is within 2 to 4 cm above the pubic symphysis. Patients with lumbar spine rigidity (e.g. after lumbar fusion surgery or patients suffering from ankylosing spondylitis) often have a fixed (i.e. rigid) reclination of the pelvis.

In order to achieve accurate femoral reconstruction, templating of the femoral offset is mandatory. Femoral offset is correctly projected when it is approximately parallel to the film. In most cases, the offset is correctly projected with 15° – 20° internal rotation of the hips, which represents the amount of normal femoral antetorsion. In most cases, the lesser trochanter is symmetrical to the contralateral side and partially superimposed by the calcar (Figure 1).

Scaling is usually performed with a calibration ball (e.g. 25 mm), but other techniques can also be used (e.g. contralateral THA with known diameter of the prosthetic femoral head, calibration belt, fixed factor (e.g. 115 %) or true femoral head size as measured using Computed tomography (CT) or Magnetic resonance imaging (MRI) (Figure 2).

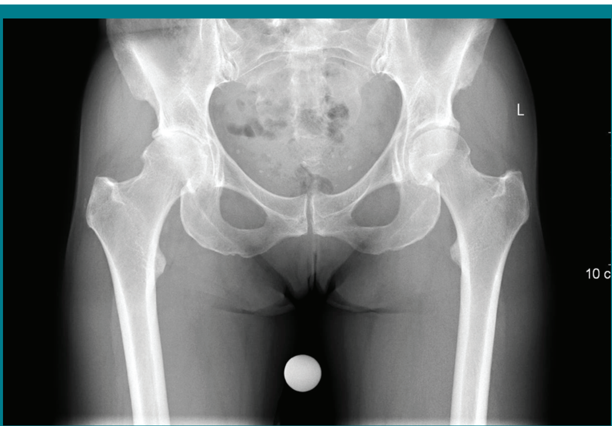

Figure 1
Standard AP pelvic radiograph showing a patient with significant arthrosis of the right hip joint. A calibration ball, positioned in the lower middle section of the image, is used for scaling purposes

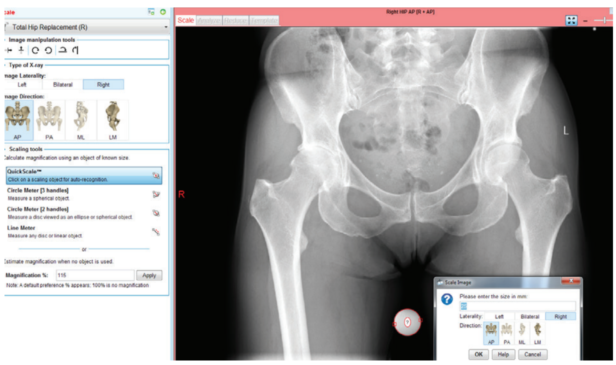

Figure 2
Standard AP pelvic radiograph used for THA planning (OrthoView Version 7.0.6, Meridian Technique Limited. 2 Venture Road, Southampton Science Park, Southampton, Hampshire, SO16 7NP, United Kingdom). Various scaling tools are available such as the QuickScale™ or Circle Meter (with 3 handles) tools for calibration

Define leg length discrepancy at the hip level –

Horizontal line

To define the leg length discrepancy (LLD) at the hip level, a horizontal line is drawn through the pelvis (Figure 3). Due to the fact that pelvic asymmetries are common, we recommend using several landmarks on each hemipelvis. Possible landmarks include the distal end of the sacroiliac joint, the acetabular roof (note any erosion in the case of advanced joint degeneration), the pelvic teardrop, the rotational center of the femoral head, the bottom of the obturator foramen or ischial tuberosity (note any ossification of tendon insertions). We favour the horizontal line passing through the bottom of the pelvic teardrop or U-figure on both sides. At right angles to the horizontal line, the distance to the proximal end of the lesser trochanter is compared to determine leg length discrepancy (LLD). When the two femora are not equally rotated or the shape of the lesser trochanters are not symmetrical, the apex of the lesser trochanter may be used. The latter is more robust against differences in femoral rotation. The measured leg length discrepancy must be proven plausible by estimating the level of degeneration-related articular shortening. Leg length discrepancy following THA is a significant source of patient dissatisfaction.

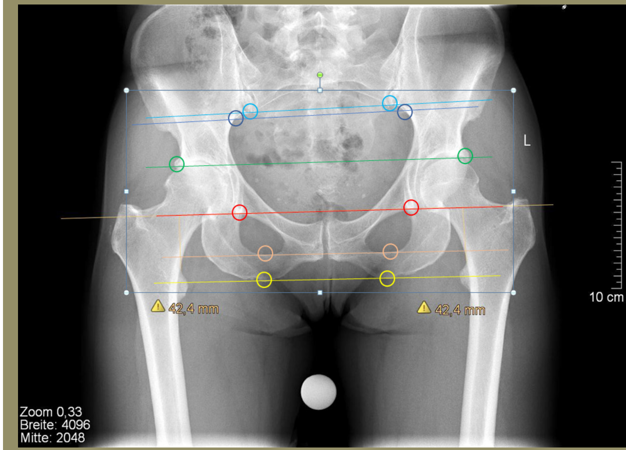

Figure 3
Standard AP pelvic radiograph with various horizontal reference lines, which can be applied to define the leg length discrepancy and are indicated as follows: light blue shows the level of the distal aspect of the sacroiliac joint; dark blue, greater sciatic notch; green, lateral edge of acetabulum; red, pelvic teardrop or U-figure; brown, obturator foramen; and yellow, ischial tuberosity. Leg length may be evaluated by comparing the distance of these lines to a femoral landmark (e.g. lesser trochanter)

The next step is to precisely evaluate the pelvic radiograph in preparation for accurate templating. Automated Orthoview software tools such as the SmartHip Wizard, Hip Joint Wizard AP/PA, Acetabular Angle Wizard, and Transischial Line Wizard (OrthoView Version 7.0.6, Southampton, UK) can be used to measure the femoral head diameter and therefore estimate the required prosthesis cup size, calculate femoral dimensions, ensure for the correct positioning of the cup, and check for LLD, respectively. If the clinical LLD differs from the length difference measured on the AP pelvic view, we would perform a full leg view (e.g. EOS).

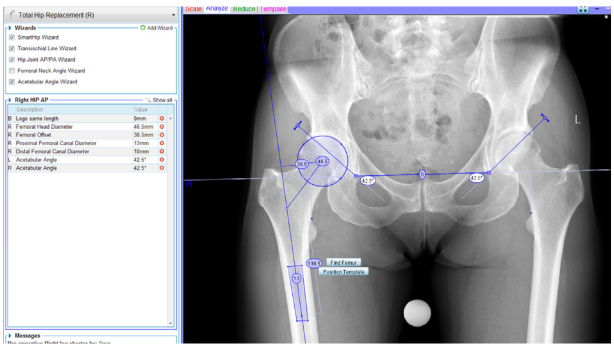

Figure 4
Screenshot of preoperative analyzing of a plain pelvic x-ray using the automated Orthoview software tool

Cut out the femur

To simulate correction of leg length and offset, some software packages offer the possibility to cut out the femur and virtually reduce the hip once the cup and stems are implanted. This function often includes an automatic calculation of the LLD.

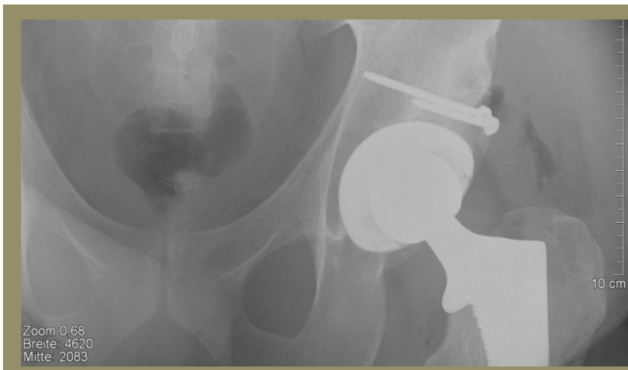

Figure 5
Radiograph showing acetabular roof reconstruction using a femoral head autograft, which is applied to avoid proximalization of the acetabular center of rotation

Cup positioning

Malpositioning of the acetabular component is a risk factor for postoperative dislocation or excessive wear rates after hip replacement. Correct cup placement (i.e. center of rotation and cup orientation) is therefore very important. The acetabular center of rotation should be placed anatomically on the cranio-caudal axis. Minimal proximalization of the cup may be accepted, if a more complex acetabular reconstruction using for example a graft can thereby be avoided. As most surgeons, on the medio-lateral axis we do however recommend a slight medialization of the cup (and hence the center of rotation) to the floor of the acetabular fossa. In the case of acetabular dysplasia, proximalization of the center of rotation should be avoided. In most cases, the medial aspect of the cup opening is in close proximity to the pelvic teardrop. The cup should not be placed medial of the ilioischial (Köhler) line. In the case of a coxa profunda or medial femoral head protrusion, central bone grafting should be considered. The cup size is selected a few millimeters larger than the diameter of the native femoral head as all the remaining acetabular cartilage is removed, and the subchondral sclerotic bone is exposed throughout the entire acetabular cavity. In general, the cup is chosen as small as possible. Oversizing of the cup should be avoided in order to conserve bone stock (e.g. thinning and shortening of the anterior and posterior acetabular wall), which in turn allows for sufficient bone coverage of the edge of the cup and reduces the risk of psoas tendon irritation. When there is insufficient lateral bone covering of the cup, application of an autograft derived from the femoral head may be considered (Figure 5). There is no consensus regarding optimal cup inclination. We generally aim for an angle of 42,5º (36° – 45°) (Figure 6). For posterolateral approaches, some surgeons prefer a more inclined and anteverted cup position.

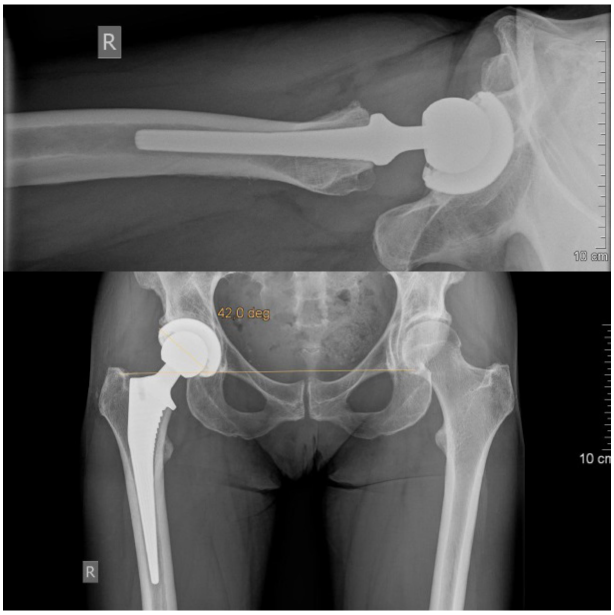

Figure 6
Six-week postoperative AP and lateral view radiographs (above and below respectively) highlighting the ideal positioning of the THA cup

Femoral positioning

For optimal preoperative planning of the femoral stem, the anatomy of the femur also needs to be considered. Femoral intramedullary anatomy is classified into three distinct types according to Dorr [7]. Type A describes a narrow canal with thick cortical walls (champagne flute canal); for this type A femur, the stem must be inserted deeper to prevent proximal oscillation of this component. Type B is indicative of moderate cortical walls and type C describes a wide canal with thin cortical walls (stovepipe canal) (Figure 7). Type B and C proximal femurs are at greater risk of sustaining an intraoperative fracture.

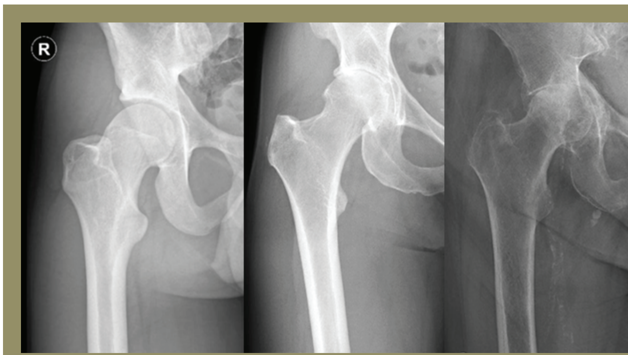

Figure 7
Standard AP view radiographs showing the three different femoral stem types according to Dorr [7]
a) Dorr type A femoral bone with a narrow canal and thick cortical walls
b) Dorr type B indicating moderate cortical walls
c) Dorr type C femoral bone with a wide canal and thin cortical wall

Stem templating

For stem templating, the following four parameters are taken into account (Figure 8):

1. Axis
2. Leg length
3. Femoral offset
4. Stem size
5. Position of the femoral head center in correlation to the greater trochanter tip
   - if femoral head center is higher than the trochanter tip, a stem with a CCD of 135° should be used
   - if femoral head center is lower than the trochanter tip, a stem with a CCD of 125° should be used

The stem is inserted in line with the anatomical femoral axis. Varus positioning should be avoided to reduce excessive loading of the calcar area. Valgus positioning of the stem may be dictated by a valgus morphotype of the proximal femur with a steep calcar. In this case, the stem sits in a 3-point fixation, which is mechanically suboptimal. Varus or valgus positioning of the stem influences femoral offset and leg length, which is difficult to control during surgery. The height of the stem is then chosen so that the femoral prosthetic center of rotation, the desired correction of the leg length is obtained once the hip is reduced. Another landmark that can also be used intraoperatively for correct stem positioning is the obturator externus footprint (Figure 9) [8].

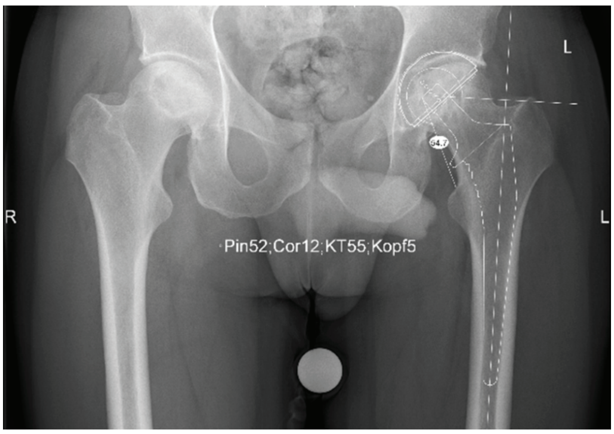

Figure 8
Correct templating of the prospective THA prosthesis on a standard AP pelvic radiograph

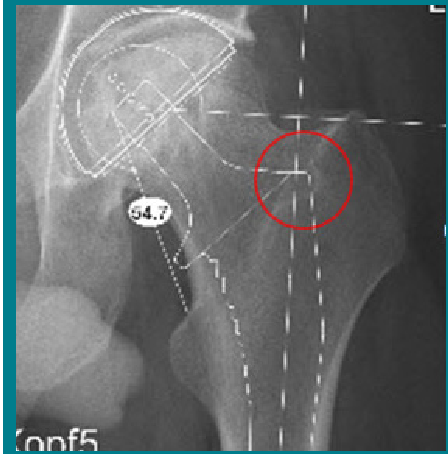

Figure 9
Obturator externus footprint as indicated by the red circle on the radiograph template for preoperative THA planning is another landmark that can also be used during surgery [8]

The stem size is chosen to ensure that bicortical contact is achieved (NB: stem manufacturer recommendations may differ). The stem size is chosen as large as possible. Ideally, the cortex-implant contact should span the longest possible distance to establish a progressive press-fit during implantation. Three-point fixation should be avoided as well as the extreme distal fixation of the stem on a very short segment. Finally, the offset is templated. Most implant systems support various offset options; the offset option is chosen so that the anatomical global offset (i.e. the sum of acetabular and femoral offset) is reconstructed (Figure 10). As the acetabular center of rotation is medialized in most cases (i.e. the acetabular offset is reduced), the femoral offset has to be increased to achieve the correct (i.e. anatomical) global offset. We do not recommend increasing the global offset in cases of lateral subluxation of the femoral head; alternately, we reconstruct the offset based on how the anatomy was before the onset of joint degeneration. Templating of the contralateral side might help in choosing the correct offset option within a stem system.

Leg length mostly relies on the position and size of the stem. If the apparent press-fit is obtained intraoperatively using a stem of two or more sizes smaller than that prescribed by the template, incorrect positioning of the stem needs to be excluded with the use of an image intensifier. In most of these cases, the stem acquires a varus or flexed position.

Neck options

The main goal of THA is to restore anatomical leg length and global offset. A 15% decrease (from 6 mm) in femoral offset has been reported to generate a weakness of the abductor muscle [9], which leads to alterations in gait. A loss of femoral offset may lead to abductor weakness and hence, joint instability, whereas an increase may lead to trochanteric pain due to excessive tension of the abductor tendon. Restoration of this aspect reduces the wear on THA prosthesis [10]. For this reason, most modern implant systems include

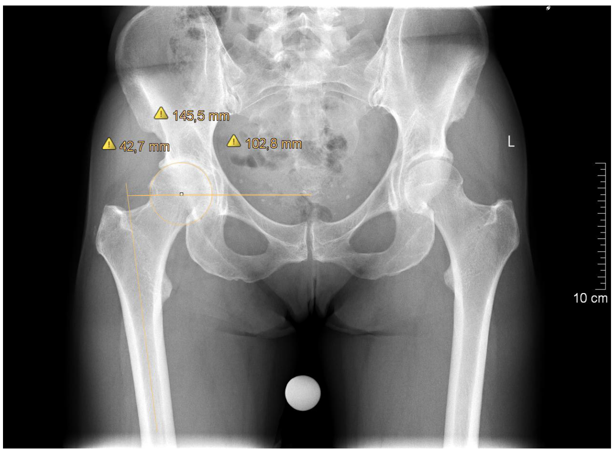

Figure 10
Standard AP pelvic radiograph with the plotted femoral offset (42.7 mm), acetabular offset (102.8 mm) and anatomical global offset (145.5 mm). Leg length, offset and stem size have to be adjusted

various neck options including Standard, High offset, Coxa vara (or valga) or Short necks. These options allow for the accurate reconstruction in a vast majority of patients (Figure 11 – 13). For most implant systems, the femoral neck options are independent of the intramedullary stem size.

Head length

Modular heads are available to correct for soft tissue tension and leg length. Since lengthening always occurs in the direction of the neck, changes of head length consistently impact on both the leg length and offset (Figure 13 – 15). The impact of head length on leg length and femoral offset may be calculated according to the Pythagorean theorem.

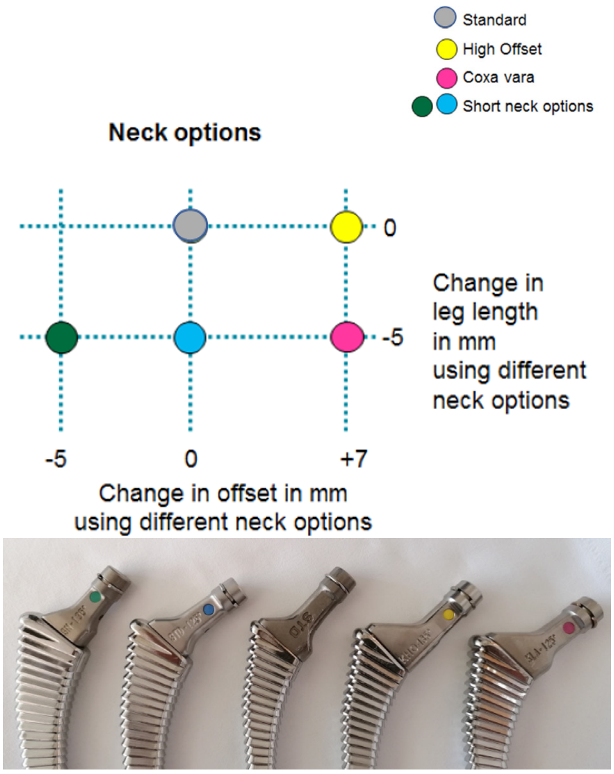

Figure 11
Influence of neck options of Corail® stems on the offset and leg length compared to the Standard neck (135°- in the middle, without collared dot). The Short neck 135° (far left), Standard neck 125° (second to the left) and Lateralized neck 125°(far right) offer -5 mm leg length compared to the Standard neck and the High offset (HO) neck 135°(second to the right).
Regarding the change in offset both Standard necks offer the same offset while the Lateralized and the HO neck increase the offset for 7 mm and the Short neck 125° decreases it for 5 mm. Of note, neck options including offset, CCD angle and length may differ significantly with other implants

Figure 12
Direct comparison of neck length and offset in Standard neck and High Offset HO neck

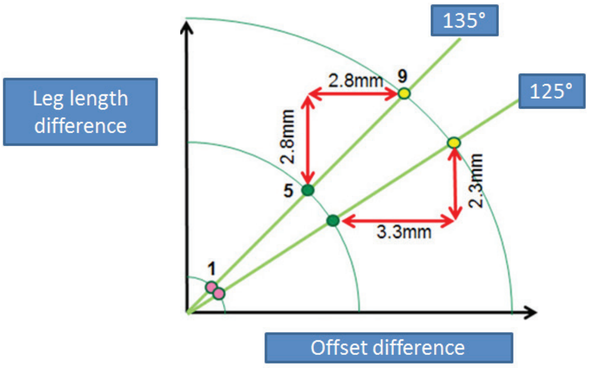

Figure 13
Graphic representation of the influence of head length and neck angle (CCD) on leg length and femoral offset. For example, if the head length is increased from 5 mm to 9 mm on a 125° neck the leg length will increase by 2.3 mm and the offset by 3.3 mm

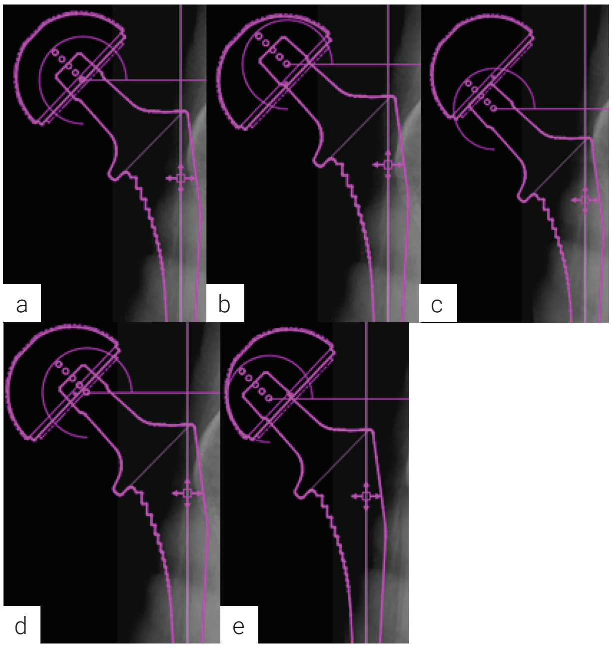

Figure 15
a) Preoperative templating without change of leg length or offset
b) Preoperative templating without change of offset but with lengthening of leg length
c) Preoperative templating without change of offset but with shortening of leg length
d) Preoperative templating without change of leg length but decrease offset
e) Preoperative templating without change of leg length but increase offset

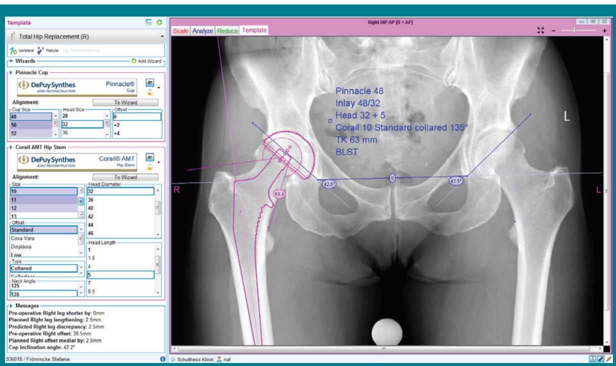

Figure 14
Screenshot of the various software template options for a standard hip prosthesis

Part 2: Narrative review of the key biomechanical aspects of total hip arthroplasty

Prevalence of leg length discrepancy

Small structural (also known as “anatomical” or “true”) LLDs up to about 5 mm are common in the general population and have negligible clinical impact [11]. According to Friberg [12], a certain degree of asymmetry in leg length should be considered normal, although there is no consensus about the magnitude of an acceptable LLD.
Knutson [11] reported that discrepancies in leg length of 10 mm or more affect 14.8 % of the normal population. Compatible with the findings of Knutson [11], Friberg [12] reported that 15.6 % (56 persons) from a cohort of 359 soldiers have a structural LLD of at least 10 mm.
They also noted that small LLD may only cause complications under certain conditions such as “(…) prolonged and/or repetitive loading”. Nonetheless, changes in leg length after THA-albeit small-might be perceived more strongly than pre-existing anatomical discrepancies. The perception of a LLD is associated with lower patient satisfaction and hip function [13].
A number of risk factors for LLD have been described such as congenital dysplasia and growth plate arrest as well as the history of a previous surgery, trauma and infection [14].

Functional versus structural LLD

There are several terms used to classify LLD. In this narrative review, the terms “structural” and “functional” LLD will be exclusively used.

Structural LLD, also known as the true or anatomical LLD, originates from bone shortening in any segment of the lower limb [15] or a difference in the height of the hip center of rotation (e.g. in severe hip dysplasia). Consequently, the distance between the femoral head (or a pelvic landmark) and the ankle mortise differs between legs [16]. We prefer the term “structural LLD” because it considers iatrogenic changes in bone structures (e.g. after THA) more clearly than the terms “anatomical LLD” or “true LLD”. Examples of structural LLD are presented in Figures 16-18.

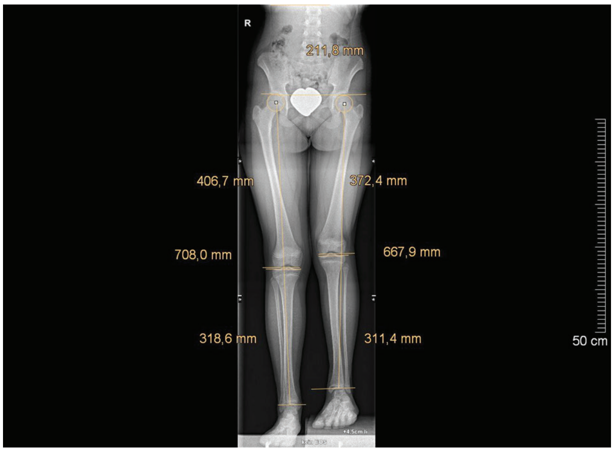

Figure 16
Full length AP view radiograph showing the LLD caused by congenital shortening of the left femur (372 mm vs. 407 mm)

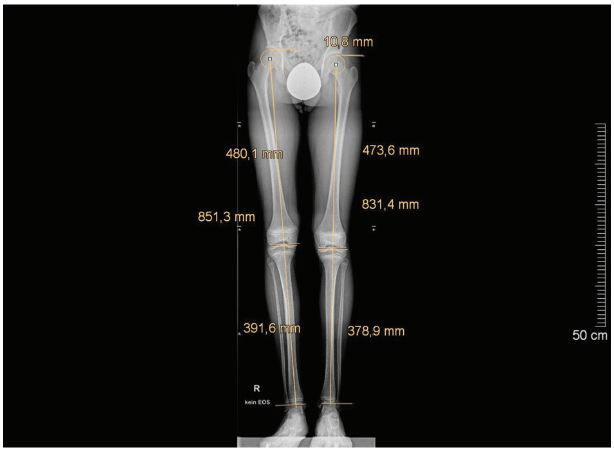

Figure 17
LLD caused by congenital shortening mainly of the left tibia (379 mm vs. 392 mm) with a slight discrepancy noted at the left femoral length (474 mm vs. 480 mm)

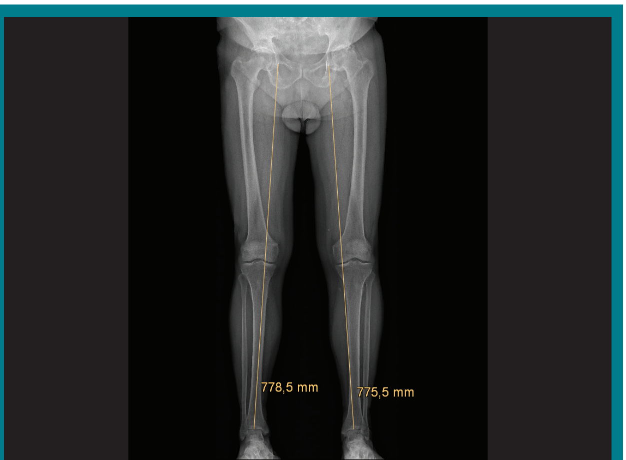

Figure 18
LLD caused by intra-articular shortening of the left hip joint

Functional LLD, or the "apparent LLD", is caused by alterations in lower limb mechanics such as static or dynamic axial malalignment (e.g. ligamentous laxity, joint contractures or muscle weakness) or pelvic obliquity due to scoliosis [15-17]. Functional LLD comprises all causes for LLD not directly related to structural differences in the lower limb. Functional LLD can be aggravated by structural LLD but can also exist independent of any anatomical changes. The most common causes for functional LLD which would lead to functional shortening are knee flexion contracture with or without concomitant hip flexion contracture as well as hip adduction contracture. Functional lengthening could result of hip abduction contracture as well as pes equinus gait which nearly always occurs in case of a structural leg length discrepancy of 3 cm and more.

Both structural and functional LLD may be congenital or acquired (i.e. iatrogenic, post-traumatic or degenerative) [17]. They are often present concomitantly and are not independent of each other. For example, structural leg lengthening leads to an increased abductor muscle tension, which in turn contributes to pelvic obliquity and hence, is considered a functional component of LLD.

To differentiate between functional and structural leg length discrepancy we recommend to examine the patient in supine position. In case of apparent LLD the patient should be re-checked in upright position. If in both examinations the LLD appears the same, structural leg length discrepancy is reasonable. In case of contradictory leg length in supine and upright position, it is due to functional LLD.

Pelvic obliquity is defined as a fixed (e.g. ankylosing spondylitis) or flexible condition caused by muscle contractures or as a compensating mechanism for structural LLD. A simple assessment for the distinction of these two types of pelvic obliquity includes an evaluation of the patient in both the standing and sitting positions. A flexible pelvic obliquity should resolve in the sitting position, whereas the fixed pelvic obliquity remains present [14].

Radiographic methods

There are two general methods used to record either structural or functional LLD. Radiological methods are associated with high inter- and intraobserver reliability and accuracy, whereas the clinical methods are easy to perform, cheap and can be carried out without radiation exposure. Radiological methods are the gold standard for measuring structural LLD, but often fail to detect functional problems [16, 18, 19]. As a primary imaging modality for the initial measurement of LLD, Sabharwal [19] recommend a standing full length AP view radiograph, whereas additional lateral full length views or even a CT scan may prove useful in more complex situations.

While the standing full length AP view provides information about angular deformities of the entire lower limb and is used to assess structural LLD [20], the standard AP view of the pelvis is used commonly to assess discrepancies of hip anatomy and for planning of the prosthetic component [1]. There is some deliberation as to which structures should be used for the measurement on the pelvic radiograph. Meermans [20] found the inter-teardrop line and center of the femoral head to be the most reliable landmarks for the pelvis and femur, respectively; the use of the bi-ischial line and lesser trochanter are therefore discouraged as reference points [20]. However, these landmarks can still be of use if the inter-teardrop line or center of the femoral head are difficult to identify.

Clinical measurement

Two types of clinical methods include direct and indirect assessments.

Direct clinical methods measure the distance between two palpated anatomical structures of the lower limb in supine position using a tape. Most commonly, the anterior superior iliac spine (ASIS) and medial malleolus are used for the measurement of structural LLD [16, 18, 19].

Indirect methods involve the palpation of bone landmarks such as the iliac crest or ASIS to assess the degree of levelness of these landmarks while the patient is standing. The most common indirect method is to place blocks of known thickness or book pages under the shorter limb until the palpated landmarks appear to be level [16, 18, 19]. Pes equinus posture as well as knee flexion posture on the contralateral side has to be eliminated to not falsify the result. This method measures functional LLD and takes into account the angular deformities of the lower limb [18, 19].

Several sources of error such as the difficulty in palpating the known bone landmarks and bone anomalies weaken the reliability and validity of the aforementioned clinical methods. Tape measurements have been especially criticized because they are associated with additional sources of error including differences in leg circumference and angular deformities [18, 19]. We recommend the indirect clinical method because it is slightly less prone to error and has been shown to better correlate with a patient's perception of LLD than the direct method [21, 22].

Since radiological and clinical measurements can be executed in a variety of ways, it is important to provide a clear definition or description of the measurements to be undertaken at the study outset. It should be noted that LLD "(…) is the result of a complex interaction of the lengths of bones, implants, and soft tissue contractures. No single measure adequately conveys all of this information" [20]. Accordingly, the surgeon should always combine radiological measurements with a thorough physical examination.

Influence of LLD on clinical outcomes

Leg length discrepancy has an important impact on clinical outcome scores and patient satisfaction after THA. However, there is no current consensus regarding the maximal acceptable LLD after THA [16, 20, 23].

A number of studies have focused on the outcomes of gait and/or stance, hip function (e.g. Harris Hip Score), pain and patient satisfaction. Synonyms for LLD such as limb length inequality, disparity or difference have been used in the literature.

LLD is a major cause of malpractice claims. Of 100 malpractice cases after primary THA, LLD (14/100) was the third most common malpractice claim after sciatic nerve injury (27/100) and joint instability (18/100) [24]. McWilliams [25] showed that neurological deficit is the most common cause for malpractice claims after hip surgery in England (14%), where 8.7% of these claims were made on account of LLD.

It is widely accepted that there is significant impact on gait deviation when a discrepancy of more than 10 mm exists, and this impact becomes greater as the LLD increases. Therefore, it has been suggested that surgeons should aim for an LLD of less than 10 mm. However, biomechanical changes on gait have been detected at LLD of only 5 mm and should not be ignored [17, 20, 26-28]. Overall, there is agreement that significant effects on gait begin at 10 mm LLD [29]. Yet most of the published data appear inconsistent and there is very little data concerning the correlation between the severity of LLD and its effects on standing or walking [30].

There are various ways in which a patient can compensate for LLD. In particular, Walsh [15] found that most of the candidates in a cohort of seven normal subjects with imposed LLD (via a shoe lift/raise) compensated their LLD of up to 20 mm through pelvic obliquity, which in turn was counterbalanced by a coronal compensation of the spine. Larger discrepancies of more than 20 mm are usually compensated through knee flexion with concomitant hip flexion and dorsiflexion in the upper ankle joint in the longer leg and sometimes pes equinus posture in the shorter leg.

Although pelvic obliquity and concomitant coronal spine compensation can result from structural LLD, both biomechanical changes can also be causal factors of functional LLD in the case of rigid scoliosis [31, 32]. Soft tissue tightness is a more common origin for functional LLD than structural malformations and can often be treated over time with stretching practices [32].

Sensitivity to LLD varies considerably among different patient groups. For example, patients with reduced mobility in the lumbar spine (e.g. after lumbar fusion, ankylosing spondylitis) are more sensitive to the effects of LLD because of their reduced capacity to compensate for the related biomechanical changes compared to those with hyperlaxity [12, 32].

Stefl [33] and Kanawade [34] found that normal and hypermobile lumbar spines are more tolerant of varied cup positioning regarding impingement and instability, whereas rigid or fused pelvises were associated with a higher risk for dislocation.

LLD and abductors

Abductor muscle strength and pretension are important factors for functional LLD. The strength of abductor muscles depends on muscle quality and volume, fiber length (i.e. pretension) and lever arms. Fiber length changes with alterations in leg length as well as offset, whereas lever arms almost entirely depend on offset [35].

Excessive muscle pretension occurring with leg lengthening and/or an increase in femoral offset may lead to abduction in the affected hip and pelvic obliquity, which in turn causes (additional) functional leg lengthening. In contrast, abductor weakness (e.g. caused by muscle damage or loss of pretension after offset reduction or leg shortening) may lead to functional shortening due to adduction in the affected hip. In the case of a structural variation in leg length, additional functional LLD might result from abnormal muscle tension [36, 37].

Ranawat and Rodriguez [32] reported that 14 out of 100 THA patients had a functional LLD with a sense of imbalance, leg lengthening and pelvic obliquity one month after surgery. This was most likely due to soft tissue tightness, since all affected patients noted an alleviation of their symptoms with stretching exercises by the 6-month follow-up. Persistent functional LLD are rare and mostly caused by degenerative diseases of the spine, protrusio acetabuli or structural joint malalignment of the leg [32].

Perception of LLD

In a series of 51 THA patients, one-third (18 people) perceived a discrepancy in leg length at the 12-month postoperative follow-up. Wylde [38] also found that 30 % (329 out of 1,114 patients) of THA patients reported a perception of unequal leg length, yet only 36 % of those with a self-rated perception of LLD had a confirmed structural LLD defined as a discrepancy of 5 mm or more. On the other hand, 17 % of the patients who did not perceive LLD were found to truly have a structurally leg lengths discrepancy [38].

Recording perceived LLD

Perceived LLD is measured as the patient’s subjective feeling of limb inequality (yes or no) or as a quantified value based on the clinical block test or radiographs taken in the standing position [39].

Subjective perception of LLD was found to occur more often in patients with a functional LLD compared to those with structural LLD [21, 22]. Furthermore, only poor correlation between orthoroentgenographic and patient‘s perception of the structural length of the femur was found [22, 40]. In contrast, Konyves and Bannister [41] reported that patients are more likely to perceive a LLD with increasing structural LLD; this specific cohort had a considerably large mean of leg lengthening (9 mm), which suggests that only larger structural discrepancies (> 5 mm) are actually perceived by patients.

Lazennec [42] reported that although there is no correlation with structural LLD, patient perception is associated with pelvic obliquity, genu flexum and the distance between the middle of the tibial plafond and the ground. Therefore, functional LLD may be the better predictor for perceived LLD than structural LLD because it takes into account additional factors such as malalignment of the lower limb and soft tissue contractures or rigid scoliosis resulting in pelvic obliquity [21, 43]. Accordingly, clinical measurement of functional LLD provides a better prognosis for the perception of postoperative LLD than the widely used pelvic AP radiographs [44].

These results are in line with the findings of Friberg [12, 32] and Ranawat [32] whereby patients with fewer compensatory mechanisms (e.g. spinal rigidity or muscle weaknesses) as well as patients with functional LLD tend to be more sensitive to perceiving LLD.

A study by O'Brien [27], which assessed imposed LLD, found that six patients from a cohort of 30 definitively felt an increase in the length of one leg by 5 mm which was artificially created. A majority (i.e. 20 out of 30) could definitely sense a discrepancy if it was raised to 10 mm, nine patients were unsure and only one felt nothing at all. With increased artificial leg lengthening above 10 mm, more and more patients were not only aware of a discrepancy but also began to feel physically uncomfortable. O'Brien stated that there is a definite relationship between the magnitude of imposed LLD and the subjective perception of inequality. However, there is no consensus regarding the threshold of maximal acceptable LLD after THA.

Perceived LLD and poor outcome

According to Iversen [13], patients who perceive a LLD are three times more likely to report a limp and almost twice as likely to fall in comparison to people who considered their legs to be of equal length. Also, Oxford Hip Scores were significantly worse for people who reported LLD after THA [38, 41, 43].

Risk factors for the perception of LLD

According to Sculco [14], there are three major risk factors for the perception of a postoperative LLD. As expected, a significantly large structural or functional LLD after THA is more likely to be felt by the patient. Further risk factors are preoperative LLD (symptomatic and asymptomatic) and fixed pelvic obliquity (e.g. after spinal fusion). Mavcic [44] observed patient-related risk factors for LLD and reported that body dimensions were the single most important predisposing factor. Independent of gender and age, smaller persons were more likely to perceive an LLD.

Satisfaction

There are very few data sources focused of the effect of LLD on patient-reported outcomes. The studies conducted so far are difficult to compare since a variety of outcomes have been measured. While some refer to patient satisfaction or quality of life, other studies focused only on pain, mobility or physical function as a surrogate for quality of life or satisfaction. According to Iversen [13], pain is the strongest predictor for postoperative dissatisfaction followed by the patient's awareness of a LLD. Röder [45] reported a significant correlation between postoperative leg lengthening of 10 mm and walking capacity, limping and general patient satisfaction, but not pain alleviation. For patients with 10 mm shortening of one leg, there was a significant association with limping, pain alleviation and patient satisfaction, but not with walking capacity. They could also show that the extent of discrepancy (shortening or lengthening) correlated to patient satisfaction and stated that even though leg lengthening is more common, leg shortening has a stronger impact on patient satisfaction.

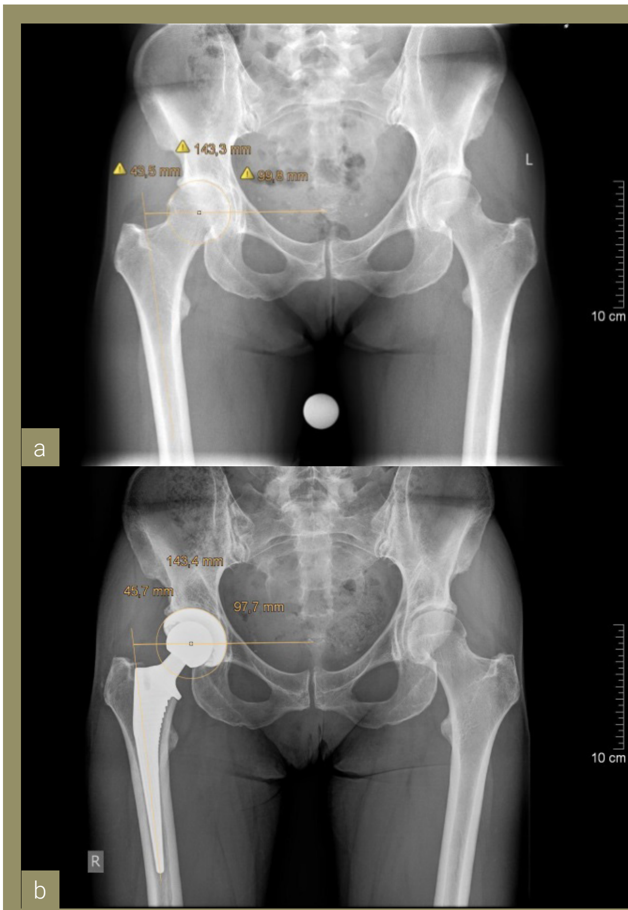

Figure 19
a) Preoperative global offset (143.3 mm) of the hip joint is the sum of femoral (43.5 mm) and acetabular offset (99.8 mm)
b) postoperative global offset (143.4 mm) remains unchanged, although changes in acetabular (reduced to 97.7 mm) and femoral offset (increased to 45.7 mm) are noted

On the other hand, several studies report a lack of significant correlation between LLD and patient satisfaction, quality of life and functional outcomes, which suggests that LLD has only negligible influence on satisfaction [28, 46, 47].

One must consider the weaknesses of these studies as well as the challenge to compare them. No information was given about the method used to measure leg length in the study of Röder [45]. For the following studies of Mahmood [28], Whitehouse [47] and White [46], different scores for satisfaction and/or quality of life were adopted and only structural LLD was measured. The latter can be misleading, since it has been shown that LLD perception does not correlate with structural LLD [42], but rather functional LLD. Iversen [13] reported the perception not only to correlate with poor physical function, but also with dissatisfaction six years after THA. Therefore, it is crucial to measure functional LLD as part of any work focused on the understanding and documentation of post-THA patient perception or satisfaction.

Femoral offset

Femoral offset is defined by the perpendicular distance between the center of the femoral head and the anatomical axis of the femur [48 – 50]. Changes in offset are correlated with changes in the muscle lever arms, which in turn have a direct impact on muscle and joint forces [48, 51]. The abductor muscle lever arm is defined as the distance between the center of the femoral head and line of action of the abductor muscles [49, 52], the latter of which is dynamic during hip motion and varies among patients. Hence, accurate quantification of the abductor moment arm is difficult. Yet femoral offset correlates with the abductor moment arm over a large range of motion and is easily quantifiable on a plain radiograph. Therefore, as an approximation, femoral offset is generally used as a parameter of abductor strength instead of the abductor moment arm itself.

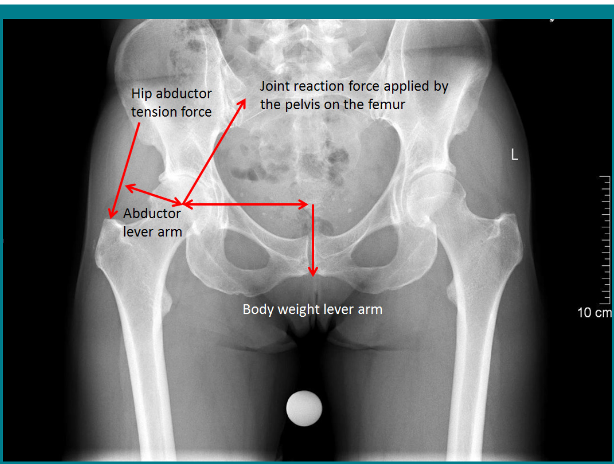

Figure 20
Biomechanical principles of the hip joint

Acetabular offset is the distance between the acetabular center of rotation and body plumb line. A large acetabular offset necessitates more abductor force to stabilize the pelvis during gait and vice versa. This is one of the reasons why most surgeons aim at medializing the cup in THA [53].

Global offset is the sum of the acetabular and femoral offset [49, 54] (Figure 19a). It is important that the global offset remains unchanged post-surgery. Nevertheless, surgeons often aim to increase femoral offset while decreasing the length of acetabular offset to optimize hip biomechanics (Figure 19b).

Center of rotation

Acetabular and femoral center of rotation may differ. Ideally, these two points are superimposed in a healthy hip or a normal functioning THA. These points may not be overlapping in case of subluxation. Of note, the acetabular as well as the femoral center of rotation may move during motion, e.g. in severe dysplasia or asphericity of the femoral head.

Biomechanical principles

The hip joint acts as a fulcrum on which the weight of the body and the opposing force of the abductors are balanced. Two lever arms of different lengths are at work in the hip. The shorter one covers the distance from the center of the femoral head to the line of action of the abductor muscles, whereas the longer lever arm is equivalent to the distance from the center of the femoral head to the body mass plumb line. Because abductor muscles act on the shorter lever arm and therefore have a mechanical disadvantage, they must be able to generate a force greater than the gravitational force of the body mass. These two forces (body mass and abductor) create a joint reaction force directed toward the hip center of rotation (Figure 20). Medialization of the rotational center of the hip joint by medial positioning of the socket with concomitant increase of femoral offset results in a load removal from hip abductors and a decrease of the joint reaction force (JRF). The lever arm of the abductor muscles increases while the lever arm of the body weight decreases.

In contrary, in case the length of the abductor lever arm decreases, the abductor muscles must generate more force to keep the pelvis horizontal, and hence the JRF increases [35, 48, 52].

Lengthening the femoral neck increases the abductor lever arm. However, this is accompanied by the direct proportional increase in leg length.

Decreasing the neck-shaft angle while keeping the neck length and stem size constant, effectively creates greater offset, but concomitantly shortens leg length. This might not only result in a LLD, but greater alteration of the implant's neck-shaft angle may increase stress on the neck and taper of the prosthesis.

In trochanteric osteotomy, the point of insertion of the abductor muscles is displaced laterally and distally to improve muscle tension, which provides a biomechanical advantage. However, this method comes with a considerable risk for complications and trochanteric pain.

Cup medialization with concomitant femoral offset increase is a well proven method with the benefits of maintaining a stable neck shaft angle and maintaining a constant global offset. Further benefits and disadvantages of this procedure are described in further detail below.

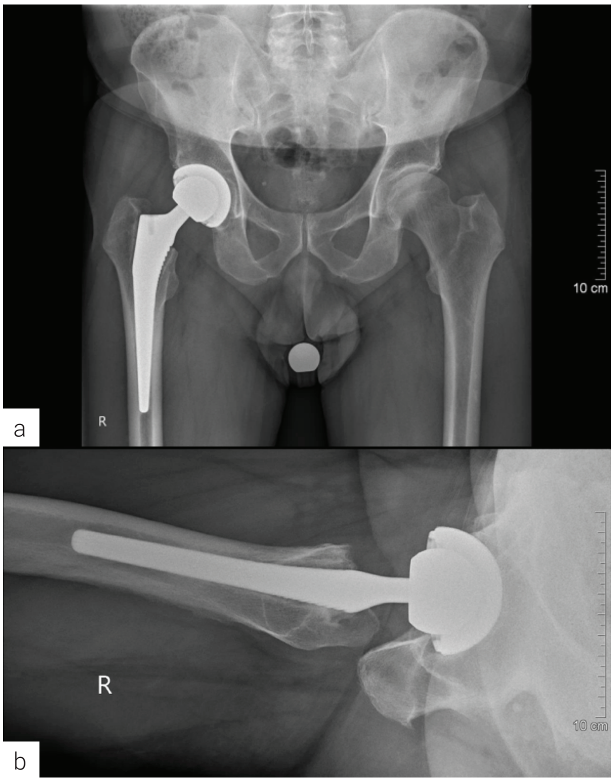

Figure 21
Inaccurately placed acetabular cup with retroverted cup in
a) AP view
b) axial view

Cup medialization

The goal of acetabular cup medialization is to alter both lever arms of the hip in such a way that the longer lever arm (acetabular offset) is shortened while the shorter lever arm (femoral offset) becomes longer. In a two-

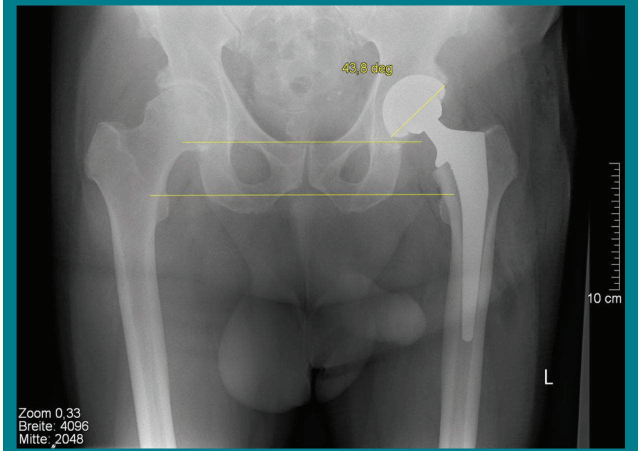

Figure 22
Measurement of the cup inclination angle in a postoperative plain AP radiographic control

dimensional model, such an alteration always results in lower joint reaction forces and released abductor muscles, while the global offset remains the same.

According to Terrier [53], there are nonetheless three major downsides of cup medialization. Because bone must be removed from the acetabulum, stability of the cup at the implant-bone interface and stem size may be compromised, especially for subjects with severe osteoporosis or subchondral sclerotic bone. In addition, the fixation of the cup can present some challenges in revision surgery. As a second disadvantage, joint reaction forces could be altered upon moving the center of rotation, which might have an effect on longevity of the implant. Thirdly, as the center of rotation is moved away from the anatomical position, the working length of the abductor muscle fibers is altered in a way that cannot be accurately predicted by a two-dimensional model. The effect of cup medialization on moment arms was shown to be consistently positive for abduction and adduction (change of lever arm: 10 to 85 %), whereas this effect was sometimes negative for flexion and extension (change of lever arm: -35 to 50 %) [53]; increasing moment arms through cup medialization was most effective in patients with low femoral anteversion. In common hip prosthesis templating, only two-dimensional changes are determined. In a three-dimensional model medialization of the center of rotation, by placing the cup more medial, actually results in shifting the center postero-supero-medial [67].

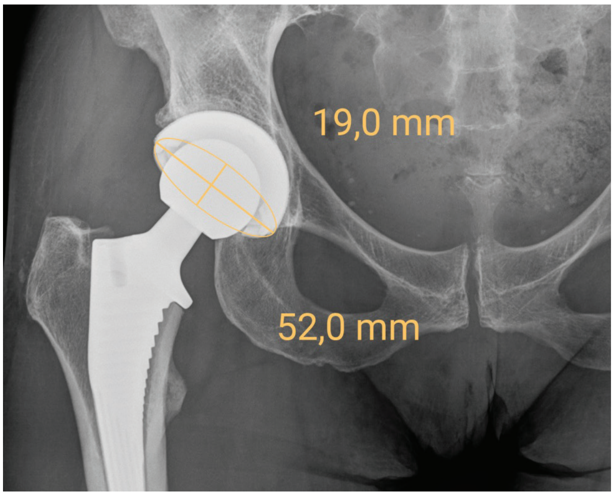

Figure 23
Projection of an open ellipsis representing cup version

Femoral anteversion

Femoral anteversion describes the forward rotation of the femoral neck with the femoral shaft as the center of rotation. An increase in femoral neck anteversion results in back displacement of the greater trochanter and therefore decreases the functional offset, the lever arm and gluteus medius strength [49]. In addition, increasing anteversion increases the length of gluteus minimus fibers and may cause postoperative peritrochanteric pain.

Measurement of cup anteversion and inclination

Inaccurately placed acetabular cups can cause impingement, reduced range of movement, accelerated wear as well as edge loading and instability [55, 56] (Figure 21).

Cup position is commonly defined by the acetabular anteversion and inclination, sometimes referred to as abduction angle (Figure 22). Cup inclination is commonly reported as the projected angle between the face of the cup (i.e. plain of the cup opening) and the transverse axis on the coronal plain. Cup anteversion can be calculated using the longest and shortest axis through the ellipse of the projected cup opening on the coronal plain using trigonometric methods as shown in Figure 23 below. A simplified method was proposed by Lewinnek [57]: arcsin (short axis/long axis). This method appears to be more accurate than, for example, the direct measurement of anteversion on a cross-table axial view [58]. For academic purposes, Murray [59] proposed three distinct ways to describe anteversion and inclination: radiographic, operative and anatomical. These definitions are based on the acetabular axis (i.e. the line through the acetabular center of rotation and pole of the cup), which is perpendicular to the cup opening. Radiographic anteversion and inclination are measured with reference to the coronal plain. On the other hand, operative and anatomical anteversion and inclination are measured with reference to the sagittal and axial (transversal) plains, respectively. For example, radiographic inclination is defined as the angle between the acetabular axis and longitudinal axis of the patient as projected on the coronal plain of an AP radiograph. The radiographic anteversion is defined as the angle between the acetabular axis and the coronal plain itself. These definitions are

Figure 24
Postoperative
a) plain AP
b) lateral radiographs after hip prosthesis replacement necessary because of pain resulting from incorrectly positioned cup

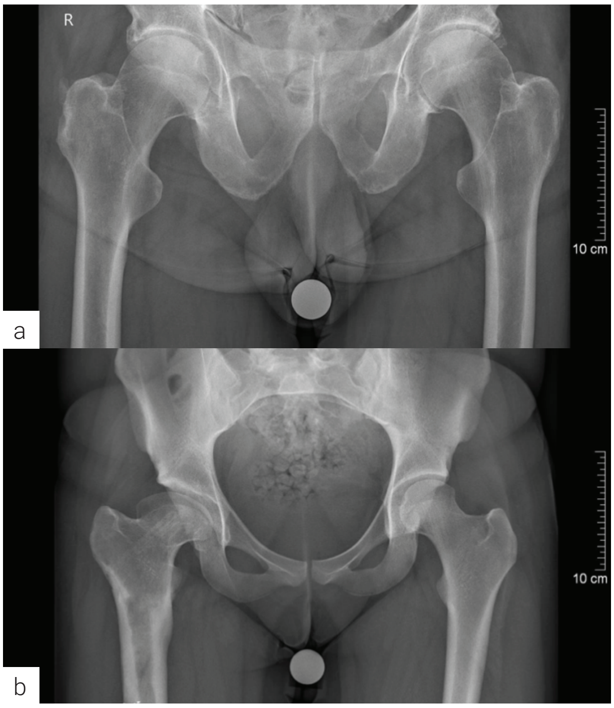

Figure 25
Plain AP radiographs showing a) pelvic reclination with overlapping of the coccyx and pubic symphysis as well as the freely visible obturator foramen; b) inclined pelvis with an increased distance between the coccyx and pubic symphysis, and the relatively small obturator foramen

not directly comparable. Therefore, it is essential to clearly define the terms of anteversion and inclination, whenever acetabular orientation is discussed [59].

Measurement of cup orientation on CT scans is proposed in two coordinate systems based on either the radiographic coronal plain (CT table) or anterior pelvic plain. The anterior pelvic plain is defined as the plain through the anterosuperior iliac spines and pubic tubercles [55]. The difference between the anterior pelvic and radiographic coronal plains is related to pelvic tilt and may be substantial in certain cases (i.e. ankylosing spondylitis). According to Malik [60], 1° of pelvic tilt measured on an AP radiograph causes an approximate change of 0.8° in cup anteversion. Posterior pelvic tilt increases anteversion and cup inclination in the coronal plain, while anterior pelvic tilt decreases the amount of anteversion and inclination [60]. Inclination on AP radiographs is less affected by pelvic tilt than anteversion [61]. Of note, it is not possible to distinguish between ante- and retroversion of the cup on the AP radiograph, as the projection of the cup opening appears with the same elliptical shape. A lateral (e.g. cross-table view) radiograph is therefore mandatory (Figure 23, 24) [55, 58].

Computer tomography scanning is considered to be the most accurate method for measuring cup orientation [55]. However, plain radiography continues to be widely used because of its accessibility, low cost and low exposure to radiation [55, 61].

Several studies compared the reliability (i.e. the agreement of measurement on plain radiographs) and validity (i.e. the proximity to equivalent measurements on CT scans) of AP radiographs to CT or computer-assisted radiography. In a study comprising 60 THA patients, Lu [55] reported excellent reliability for the measurement of anteversion and inclination on plain radiographs according to the method of Lewinnek [57]; interobserver reliability was 0.896 (95% CI, 0.846-0.933) for anteversion and 0.993 (95% CI, 0.989-0.996) for inclination. The mean difference of inclination and anteversion between the plain radiograph and CT was 2.3° (SD 1.8°; $p < 0.001$) and 0.6° (SD 3.1°; $p = 0.19$), respectively; both methods appear acceptable for clinical use.

In a study of 84 hips, Nomura [61] compared five different methods for evaluating anteversion on plain radiographs with CT measurements, calculated with the same definitions and around the same reference plain.

Intra- and interobserver reliability was excellent with 0.91 (95% CI, 0.88-0.94) and respectively 0.92 (95% CI, 0.89-0.95), respectively.

Cup orientation and placement is especially challenging in patients with either a fixed pelvic reclination or an anteverted pelvis. Both deformities can be identified on the plain pelvic radiograph by measuring the distance between the coccyx and pubic symphysis or the form of obturator foramina (Figure 25). Currently, there is no consensus regarding the preferred method of how to radiographically measure cup orientation.

Risks of cup malpositioning (Safety of traditional "safe zones")

To date, the positioning of the acetabular cup has been guided by the "safe zone" as described by Lewinnek [57], who claimed that fewer hip dislocations would occur inside the zone of 30° – 50° inclination and 5° – 25° of anteversion. However, the study reported only nine dislocations (in a total of 300 patients), whereby three were situated inside the "safe zone". In addition, cup orientation could only be assessed in 113 of the 291 patients without dislocations, and 35 patients of this subgroup were documented with the acetabular cup clearly outside the "safe zone".

There is, however, large variability in the results reported on the safety of this so-called "safe zone". Seagrave [56] concluded that the concept of the Lewinnek "safe zone" cannot be justified since only two of the eleven articles included in the systematic review presented statistically significant differences in the risk of dislocation. Furthermore, none of the alternate target zones proposed by several working groups [56], could not be identified as superior. Abdel [62] consider the traditional target values for cup positioning as useful, but note that these values do not represent a safe zone since the majority of dislocations (58 %) in their study were situated within the Lewinnek "safe zone". Hip stability is multifactorial [63] and the type of surgical approach might also be a risk factor for anterior or posterior dislocation [64]. In the case of a posterior approach, soft tissue damage and muscle weakness at the surgical site would be a predisposing for posterior dislocation. Therefore, Danoff [65] recommended an alternative target zone specifically for the posterior approach; their modified safe zone -with a tendency for greater anteversion (i.e. limits of anteversion of 10º – 25°)- was a better predictor for stable THAs than the Lewinnek safe zone. In line with the above mentioned reports, Biedermann [63] observed that patients with a posterior dislocation (anteversion 11°; inclination 42°) had a smaller mean of anteversion than patients with an anterior dislocation (anteversion 17°; inclination 48°). The relative frequency of anterior and posterior dislocation was the same at 15° of anteversion and the cup position was related to the direction of dislocation (e.g. less anteversion results in more posterior dislocations). Biedermann concluded that there is no safe zone for cup positioning, although an anteversion of 15° and an inclination of 45° was associated with the lowest risk of dislocation using the anterolateral approach [63].

Callanan [64] stated that even though a safe zone probably reduces the risk of dislocations, it might not be indicative of ideal positioning when considering other adverse events such as increased wear, impingement and movement restrictions. For example, since excessive inclination is related to increased wear and edge loading, Callanan recommended inclination values lower than 45°. In contrast, D'Lima [66] reported that inclination angles of less than 45° lead to decreased hip flexion and abduction. Higher angles of more than 45° resulted in a restricted range of adduction and rotation. Similarly, higher values of femoral and acetabular anteversion increased hip flexion and decreased hip extension. In light of this, D'Lima advocate an inclination angle lying between 45° and 55° to allow a good range of motion when combined with the appropriate femoral and acetabular anteversion.

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List of abbreviations

AP = anterior-posterior
ASIS = anterior superior iliac spine
CT = computer tomography
CCD angle = collum-caput-diaphyseal angle
HO = high offset
JRF = joint reaction forces
LLD= leg length discrepancy
MRI = magnetic resonance imaging
SD = standard deviation
THA = total hip arthroplasty