Leg length discrepancy and femoral offset after total hip arthroplasty
Clinical and radiological studies

Thesis for doctoral degree
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To my parents, thanks for love and support throughout my life.
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Abstract

Every year, about 1 million patients worldwide and 16000 patients in Sweden undergo total hip arthroplasty (THA). This surgical intervention is considered a successful, safe and cost-effective procedure to regain pain-free mobility and restore hip joint function in patients suffering from severe hip joint disease or trauma. Besides relieving the pain, restoration of biomechanical forces around the hip with appropriate femoral offset (FO), leg length and proper component position and orientation are important goals. The radiographic preoperative planning and postoperative evaluation of these parameters require good validity, interobserver reliability and intraobserver reproducibility. It remains controversial as to how much postoperative leg length discrepancy (LLD) and FO change are acceptable. Generally, lengthening of the operated leg ≥ 10mm and FO reduction of the operated hip > 5mm should be avoided by using preoperative radiological templating and intraoperative measurement methods. There is no consensus on the association between LLD and FO and outcome after THA.

The aims of this thesis were to:

1. To determine the influence of non-corrected LLD after THA on patients’ reported hip function and quality of life (QoL).
2. To study the association of global FO changes after THA with patients’ reported hip function, QoL and abductor muscle strength.
3. To evaluate the concurrent validity of the Sundsvall method of measuring postoperative global FO by comparing it to a standard method and to evaluate the interobserver reliability and intraobserver reproducibility of measurement of postoperative global FO, LLD and acetabular cup inclination and anteversion.
4. To analyse the postoperative radiographs of THA patients with leg lengthening and FO reduction to determine whether the problem is located in the stem, cup or both.
Study I: A prospective cohort study of 174 patients with unilateral osteoarthritis (OA), comparing patients with lengthening ≥ 10 mm, restoration (between 9 mm lengthening and 5 mm shortening) or shortening > 5 mm of the operated leg after THA. Follow up was 12–15 months. We found that a LLD of up to 20 mm did not influence the functional outcome (WOMAC) or QoL (EQ-5D). However, the lengthening group showed less improvement in WOMAC and more use of a shoe lift.

Study II: A prospective cohort study of 222 patients with unilateral hip OA, comparing patients with decreased global FO (> 5 mm reduction), restored FO (within 5 mm restoration), and increased FO (> 5 mm increment) after THA. Follow up was 12–15 months. The unadjusted results showed that the decreased FO group had a worse WOMAC index, less abductor muscle strength, and more use of walking aids. When these results were adjusted for possible confounding factors, only global FO reduction was statistically significantly associated with reduced abductor muscle strength. The incidence of residual hip pain and analgesics use was similar in the 3 groups.

Study III: A prospective cohort study of 90 patients with primary unilateral OA treated with THA. Global FO using the Sundsvall method, global FO (standard method), LLD, acetabular cup inclination and anteversion were measured on postoperative radiographs. The interobserver reliability and intraobserver reproducibility were tested using three independent observers. We found that the Sundsvall method is as reliable as the standard method and the evaluated radiographic measurement methods have the required validity and reliability to be used in clinical practice.
Study IV: A prospective cohort study of 174 patients with unilateral primary OA treated with THA. LLD and global FO were measured on postoperative radiographs. Patients with lengthening of the operated leg ≥ 10mm (n=41) and patients with reduction of global FO > 5mm (n=58) were further studied to investigate the amount of lengthening and global FO reduction that took place in the stem and in the cup compared with the contralateral side. The interobserver reliability and intraobserver reproducibility were tested using two independent observers. We found that post-THA lengthening of the operated leg ≥ 10mm was mainly caused by improper placement of the femoral stem, whereas a decrease of global FO > 5 was caused by improper placement of both acetabular and femoral components. The radiological measurement methods used showed substantial to excellent interobserver reliability and intraobserver reproducibility and are therefore clinically useful.

The main conclusions of this thesis are:

- LLD up to 20 mm and reduced global FO more than 5 mm did not influence the functional outcome or quality of life at 12–15 months postoperatively.
- Lengthening ≥ 10mm was associated with increased use of a shoe lift. A reduction of global FO more than 5 mm compared to the contralateral hip was associated with weaker hip abductor muscles and more use of walking aids. Therefore both should be avoided.
- The radiographic measurement methods of LLD, global FO, cup inclination and anteversion have the required validity and reliability to be used in clinical practice.
- Lengthening of the operated leg is mainly caused by improper femoral stem positioning while global FO reduction results from improper positioning of both acetabular and femoral components. Surgeons should be aware of these operative pitfalls in order to minimize component malpositioning.
Keywords
Total hip arthroplasty; leg length discrepancy; femoral offset; WOMAC; quality of life; complication; radiographic measurements; acetabular cup; inclination; anteversion.
Abstrakt på svenska (Abstract in Swedish)

Varje år opereras ungefär 1 miljon patienter runt om i världen och 16000 patienter i Sverige med en total höftledsprotes (THA). Operation med höftledsprotes anses vara en av de mest framgångsrika, säkra och kostnadseffektiva kirurgiska åtgärderna med syfte att för att återställa livskvalité. Målet är att smärtlindra och återställa rörligheten i den destruerade höftleden vid artros, reumatisk destruktion eller men efter exempelvis Perthes sjukdom. Vid operation med THA är det viktigt att återställa de biomekaniska krafterna runt höftleden med en adekvat så kallad femoral offset (FO), postoperativ benlängdsskillnad (BLS) och ett tillfredsställande komponentläge. Den preoperativa planeringen och den postoperativa bedömning av dessa parametrar kräver god tillförlitlighet, det vill säga validitet och reproducerbarhet både mellan olika bedömare och vid upprepade mätningar av samma bedömare. Det är fortfarande inte klarlagt hur mycket postoperativ förändring i FO och BLS som är acceptabla. I dagsläget är det acceptabelt om den postoperativa benförlängningen understiger 1 cm och förändringen i FO är under 5 mm. Det finns ingen konsensus huruvida det föreligger ett samband mellan BLS, FO och den patientrapporterade höftfunktionen och livskvalitén efter THA.

Syftet med denna avhandling var:

(1) Att studera effekten av icke-korrigerad BLS efter THA på den patientrapporterade höftfunktionen och livskvalitén.

(2) Att studera effekten av förändringen i FO efter THA på den patientrapporterade höftfunktion, livskvalitén och muskelstyrka i abduktion.

(3) Att utvärdera validitet och reliabilitet av en så kallad global FO genom att jämföra den med den gällande standard metoden samt studera tillförlitlighet av de radiologiska mätningar av postoperativa BLS, FO, cup inklination och anteversion efter THA.

(4) Att radiologiskt undersöka i vilken av komponenterna (stam eller cup) som förändringen i FO och BLS verkar vara förlagd.
**Studie I:** En prospektiv kohortstudie med 174 patienter som behandlats med THA för en primär unilateral koxartros. Patienterna delades in i tre grupper; de som fått en BLS förlängning över 10mm, återställning (mellan 9mm förlängning och 5mm förkortning) eller förkortning >5mm av det opererande benet efter THA. Uppföljning gjordes 12-15 månader postoperativt. Vi fann att BLS upp till 20mm påverkade inte höftfunktion (WOMAC) och livskvalité (EQ-5D), men den förlängda gruppen visade en mindre förbättring i WOMAC och rapporterade en mer frekvent användning av skoinlägg.

**Studie II:** En prospektiv kohortstudie med 222 patienter som behandlats med THA för en primär unilateral koxartros. Patienterna delades in i tre grupper; de patienter med förminskad FO (> 5mm minskning), återställd FO (inom 5mm) eller ökad FO (>5mm ökning). Uppföljning genomfördes efter 1 år med WOMAC, styrkemätning av höftens abduktorer och en frågeformulär. En minskad FO var associerade med en minskad styrka i höftens abduktorer. Det var ingen skillnad mellan grupperna gällande kvarstående höftsmärta och användning av analgetika.

**Studie III:** En prospektiv kohortstudie med 90 patienter som behandlats med THA på grund av primär unilateral koxartros. På de postoperativa röntgenbilderna uppmättes globala FO (Sundsvalls metodologi), globala FO (standard metod), BLS, cup inklination och anteversion. Reliabilitet och reproducerbarhet bedömdes mellan tre oberoende observatörer. Vi fann att global FO (enligt Sundsvalls metodologi) är lika tillförlitlig som den nuvarande standardmetoden och de utvärderade radiologiska mätmetoderna har hög validitet och reliabilitet och kan således användas i klinisk praxis.

**Studie IV:** En prospektiv kohortstudie med 174 patienter som behandlats med en THA för en primär unilateral koxartros. På de postoperativa röntgenbilderna uppmättes BLS och globala FO. Patienter med förlängning ≥ 10mm (n=41) och patienter med minskning av globala FO >5mm (n=58) studerades för att mäta förlängning och globala FO minskning som sitter i stammen eller i cup jämfört med kontralaterala sidan. Reliabilitet och reproducerbarhet bedömdes av två oberoende observatörer. Vi fann att en BLS över 10mm sitter framför allt i stamkomponenten i lårbenet medan en
minskning i FO över 5 mm sitter i båda stam och cup. De radiologiska mätmetoderna har hög reliabilitet och reproducerbarhet och kan således användas i klinisk praxis.

**De viktigaste slutsatserna i denna avhandling är:**

1. BLS med en förlängning upp till 20 mm och en minskning av globala FO mer än 5 mm påverkar inte patientrapporterad höftfunktion eller livskvalitet 1 år postoperativt.

2. BLS med en förlängning mer än 9 mm var associerad med mer användning av skoinlägg. En minskad FO med mer än 5 mm jämfört med den icke opererade höften var associerad med en sämre muskelstyrka i abduktion och ökat användning av gånghjälpmedel.

3. De radiologiska mätmetoderna av BLS, FO, acetabulära komponentens inklination och anteversion har hög validitet och reliabilitet, vilket kan användas i klinisk praxis.

4. En förlängning av det opererade benet orsakas främst av en positioneringen av stamkomponenten i lårbenet medan förlust av FO beror på otillfredsställande placering av både stam och den acetabulära komponenten. Kirurger bör vara medveten om dessa operativa fallgropar för att optimera det kirurgiska resultatet.
LIST OF PAPERS

This thesis is based on the following papers, which are indicated in the text by their Roman numerals (Studies I-IV).

I. Mahmood SS, Mukka SS, Crnalic S, Sayed-Noor AS. The Influence of Leg Length Discrepancy after Total Hip Arthroplasty on Function and Quality of Life: A Prospective Cohort Study. J Arthroplasty. 2015 Sep;30(9):1638-42.


IV. Mahmood SS, Al-Amiry B, Mukka SS, Crnalic S, Sayed-Noor AS. Leg lengthening and femoral-offset reduction after total hip arthroplasty: where is the problem located – stem or cup? Manuscript
## LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AP</td>
<td>Anteroposterior</td>
</tr>
<tr>
<td>CCD</td>
<td>Center collum diaphyseal angle</td>
</tr>
<tr>
<td>CI</td>
<td>Confidence interval</td>
</tr>
<tr>
<td>CLS</td>
<td>Cementless Spotorno stem</td>
</tr>
<tr>
<td>CT</td>
<td>Computed tomography</td>
</tr>
<tr>
<td>EQ-5D</td>
<td>EuroQol index</td>
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<tr>
<td>FO</td>
<td>Femoral offset</td>
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<tr>
<td>HHS</td>
<td>Harris hip score</td>
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<tr>
<td>HOOS</td>
<td>Hip Disability and Osteoarthritis Outcome Score</td>
</tr>
<tr>
<td>ICC</td>
<td>Interclass correlation coefficient</td>
</tr>
<tr>
<td>LLD</td>
<td>Leg length discrepancy</td>
</tr>
<tr>
<td>MCII</td>
<td>Minimal clinically important improvement</td>
</tr>
<tr>
<td>MRI</td>
<td>Magnetic resonance imaging</td>
</tr>
<tr>
<td>OA</td>
<td>Osteoarthritis</td>
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<tr>
<td>OHS</td>
<td>Oxford Hip Score</td>
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<td>PASS</td>
<td>Patient acceptable symptom state</td>
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<tr>
<td>PIHAQ</td>
<td>Personal Impact Health Assessment Questionnaire</td>
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<tr>
<td>QoL</td>
<td>Quality of life</td>
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<td>r</td>
<td>Person correlation coefficient</td>
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<td>PROs</td>
<td>Patient reported outcome</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>SD</td>
<td>Standard deviation</td>
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<tr>
<td>SF-12</td>
<td>12-Item Short Form Health Survey</td>
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<tr>
<td>SF-36</td>
<td>Short Form (36) Health Survey</td>
</tr>
<tr>
<td>THA</td>
<td>Total hip arthroplasty</td>
</tr>
<tr>
<td>VAS</td>
<td>Visual analogue scale</td>
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<tr>
<td>WOMAC</td>
<td>Western Ontario and McMaster Universities Osteoarthritis Index</td>
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1. Introduction

1.1 Background

Every year, about 1 million patients worldwide and 16000 patients in Sweden undergo total hip arthroplasty (THA). This surgical intervention is considered a successful, safe and cost-effective procedure to regain pain-free mobility and to restore hip joint function in patients suffering from severe hip joint disease or trauma. The number of people undergoing primary and revision THA is expected to increase further due to an ageing population, decreasing average age at the first operation and the limited lifespan of prostheses (Pivec et al 2012).

Since the introduction of modern low-friction THA by Sir John Charnley in the early sixties (Charnley et al 1961), there has been a continuous research evaluating prosthesis design and bearing, surgical technique and peri-operative care. This research aims to improve functional outcome and quality of life (QoL), increase prostheses lifespan and reduce complications. The large variety of prosthesis types and surgical approaches gives the surgeon great flexibility in choosing a suitable implant for each individual patient (Berry et al 2003, Chimento et al 2005) and to improve postoperative rehabilitation (Husted et al 2010, Larsen et al 2010).

Generally, the outcome of THA can be affected by factors related to the surgery or patient. Surgical factors include surgeon’s experience, surgical approach, prosthesis design and modularity and implant positioning. In this regard, restoration of the operated leg length and femoral offset (FO), and hence the peri-articular soft-tissue tensioning, represents an important goal. On the other hand, patient-related factors include physical and mental health status (Uwe et al 2012, Smith et al 2012).
1.2 Hip joint biomechanics

The hip joint acts as a fulcrum between body weight and the hip abductors (Bourne et al 2002) resulting in an equilibrium which maintains the pelvis level throughout the gait cycle and preventing a Trendelenburg lurch (Charles et al 2005). The lever arm between the center of the femoral head and the abductor muscles is less than that between the center of the femoral head and body weight, placing the abductor muscles at a mechanical disadvantage (Figure 1). Therefore, the abductors must generate a force that is larger than the body weight.

Gait analysis and free body diagrams have shown this discordant biomechanical relationship translates into a significantly higher joint reaction-force in THA without restoration of FO (Greenwald et al 2003). Conversely, an increase in FO increases the lever arm of abductor muscles, thereby reducing the abductor muscle force required for normal gait. This in turn minimizes the resultant reactive force across the hip joint and hence results in a lower rate of polyethylene wear. Furthermore, the lateralized position of the femoral shaft relative to the hip center tends to decrease the prevalence of femoro-acetabular impingement while concomitantly improving soft tissue tensioning (Charles et al 2005). A leg length discrepancy (LLD) ≥ 20 mm creates biomechanical changes to hip joint load both on the long and the short side and the effects seem to be larger on the short side. The increased stress may cause problems in the long term. Wretenberg et al (2008) found that the abduction peak moment was significantly increased on the short side but unaffected on the long side. The adduction moment decreased on the long side between 0 and 40 mm but was unaffected on the short side. The internal hip rotation moments were unchanged for both the long and short sides. The external rotation moment was unchanged on the short side and decreased between bare foot and 40 mm on the long side.
Figure 1: Illustration of the hip joint acting as a fulcrum, balancing the force of body weight with the force generated by the hip abductor.
1.3 Leg length discrepancy

Leg length discrepancy is a common complication of THA (Kitada et al 2011) with lengthening being more noticeable to the patient than shortening (Desai et al 2013). It is a major cause of litigation (McWilliams et al 2013) and it has been associated with patient dissatisfaction (Wylde et al 2009), gait disorder (Tanaka et al 2010), greater trochanter pain (Sayed-Noor et al 2006), nerve palsy (Hofmann et al 2000), low back pain and increased oxygen consumption and heart rate (Clark et al 2006). LLD can be the result of improper stem and/or cup positioning e.g. high positioning of the stem in the femoral canal secondary to high osteotomy cut or poor component version that obliges the surgeon to increase soft tissue tension for stability with resulting lengthening (McWilliams et al 2013).

The incidence of LLD after primary THA has been reported to range from 1% to 27% (Desai et al 2013) varying from 6 to 35 mm (White et al 2002, Maloney et al 2004). However, the degree of clinically significant LLD is still a matter of debate (Benedetti et al 2010, Meermans et al 2011). Generally, LLD < 10 mm is considered acceptable by most clinicians. O’Brien et al (2010) suggested that LLD after THA should be kept to less than 10 mm as healthy people were aware of LLD more than this. Benedetti et al (2010) showed that LLD in the range of 1–20 mm did not impair the symmetry of time-distance parameters and of hip kinematics and kinetics during gait and stairs walking. Also, Gurney et al (2002) concluded that in older adults, a LLD of between 20 and 30 mm is the critical limit above which there is increased pulmonary, cardiac and neuromuscular physiological loading. Perception of LLD after THA is reported in one third of operated patients and affected patients report lower functional outcome (Wylde et al 2009). Plaass et al (2011) reported negative marginal effect of LLD after THA with more pain in patients with lengthening and more limping in patients with shortening. Konyves and Bannister et al (2005) found that lengthening after LLD was associated with lower functional outcome up to 12 months postoperatively.
1.4 Femoral offset

The FO is an important parameter in THA. It is defined as the distance from the center of rotation of the femoral head to a line bisecting the long axis of the femur (Lecerf et al 2009). Charnley et al (1979) described different methods for optimizing the FO, such as, avoiding excessive anteversion of the femoral component, medializing the acetabular component, choosing a narrower neck-shaft angle and trochanteric advancement. The FO is also influenced when the stem is placed in varus or valgus.

1.5 Radiological evaluation in THA

In THA, radiographic preoperative planning and postoperative evaluation of LLD, FO and component positioning are essential and require good validity, interobserver reliability and intraobserver reproducibility. Computed tomography (CT) and magnetic resonance imaging (MRI) have been shown to be the gold standard in this regard (Wines et al 2006, Sabharwal et al 2008, Pasquier et al 2010). But concerns such as high cost, radiation exposure and availability in relation to the huge number of planned THA operations make their routine use impractical and limited to selected cases. Therefore, surgeons use plain radiographs for this purpose and rely on proper standardisation of radiographs and measurement techniques to minimise their shortcomings.

Regarding LLD, different plain radiographic measurement methods can be used. One method is the ortho-roentgenogram, which involves a single exposure of the leg including hips and ankles. It has the advantage of requiring only one exposure, but is subject to distortion by parallax error (Gurney et al 2002). Another method is the scanogram, which uses three exposures, one for the hip, one for the knee and one for the ankle, and negates the magnification error, but increases the time, cost and radiation exposure of the patient. In clinical practise, an anteroposterior (AP) plain radiograph showing the pelvis and proximal femurs is used to measure LLD in most cases. With this method, the LLD can be measured as the difference between the perpendicular distance between a line passing through the lower edge of the teardrop points (inter-teardrop line) (Figure 2) or the lower edge of ischial tuberosities (bi-ischial line) (Figure 3) and the tip of the lesser trochanter on each side (Meermans et al. 2011). Radiographic LLD measurement has been found to be more accurate than clinical measurement by different investigators (Clarke et al 1972, Lampe et al 1996, Cleveland et al 1988 Terry et al 2005).
**Figure 2:** Radiographic measurement of the LLD as the difference in perpendicular distance in millimetres between a line passing through the lower edge of the teardrop points to the corresponding tip of the lesser trochanter.

**Figure 3:** Radiographic measurement of the LLD as the difference in perpendicular distance in millimetres between a line passing the lower edge of ischial tuberosities to the corresponding tip of the lesser trochanter.
Regarding **FO**, it is commonly measured as the radiological distance between the center of rotation of the femoral head and long axis of the femur (Lecerf et al 2009). However, this measurement does not take into account the changes caused by the differing positioning of the acetabular cup. The latter is usually measured separately as the distance between the center of the femoral head to a perpendicular line passing through the medial edge of the ipsilateral acetabular tear drop. This is referred to as the cup offset (Loughead et al 2005). By adding the cup offset to the FO, the global FO is determined (Kjellberg et al 2009, Lecerf et al 2009, Dastane et al 2011) (Figure 4).

The Sundsvall method is another way to measure the global FO on plain radiographs. It is the distance between the femoral axis to the midline of the pelvis at the height of the lateral tip of the greater trochanter (Kjellberg et al 2009) (Figure 5).

**Figure 4:** Radiographic measurement of FO, cup offset and global FO.
Figure 5: The Sundsvall method of FO measurement carried out on the AP view of the pelvis as the horizontal distance between the femoral axis and the midline of the pelvis at the height of the lateral tip of the greater trochanter.

Acetabular cup positioning

The orientation of the acetabular component is defined by inclination, which is the angle between the face of the implant and the transverse axis and version, which is the angle between the axis of the component and the coronal plane of the patient (Nho et al 2012). The optimal orientation of the cup has been proposed as $15 \pm 10^\circ$ of anteversion and $40 \pm 10^\circ$ of inclination, based on the method of Lewinnek (Lewinnek et al 1978, Murray et al 1993, Sarmiento et al 2006, Yoon et al 2008). Whereas inclination can easily be measured on AP radiographs, version is more difficult to measure. Version of the acetabular component can be measured accurately using CT scans, and there are a variety of methods of measuring it on plain AP or cross-table lateral radiographs (Nho et al 2012). An ideal method should be both accurate and reproducible.
1.6 THA outcome measures

THA outcome was traditionally evaluated by objective clinical methods that are based on the assessment of pain and functional disability scored by the surgeon (Bryant et al 1993, Garellick et al 1999). The Merle d’Aubigne and Postel score (Charnley et al 1972) and the Harris hip score (HHS) (Harris et al 1969) remain two of the most widely used methods. An inherent difficulty of most surgeon-based scoring systems that assess outcome is that they are composite scores, which include clinical and radiological data together with patient-based subjective information. Also, there is sometimes a substantial disagreement between surgeons and patients about health status (Janse et al 2004). Thus, patient-reported outcomes (PROs) should be the mainstay in assessing postoperative patient’s satisfaction and health-related QoL.

Commonly used generic scales include the EuroQol index (EQ-5D) (Dawson et al 2001) and the Medical Outcomes 36-item and 12-item Short-Form Health Surveys (SF-36 and SF-12) (Ware et al 2006, Busija et al 2008). On the other hand, disease-specific scores that assess functional outcome include the Western Ontario and McMaster University Osteoarthritis Index (WOMAC) (Bellamy et al 1988), Oxford Hip Score (OHS) (Dawson et al 1996) and Hip Disability and Osteoarthritis Outcome Score (HOOS) (Nilsdotter et al 2003).

THA outcome measures should be interpreted carefully because a statistically significant change in a PRO score does not necessarily represent a clinically important improvement (McLeod et al 2011). Also, these PROs are not patient-specific and do not provide information about what is important to the individual patient and whether their preoperative expectations have been met. One important point in PRO evaluation is the minimal clinically important improvement (MCII); a change in the score defined as the minimal change representing a clinically important improvement from the patients’ perspective (Tubach et al 2009). Another point is the patient-acceptable symptom state (PASS); a value of the postoperative PRO score found acceptable by
patients. This is defined as the overall health status at which patients consider themselves to be feeling well (Maksymowych et al 2010). Both MCII and PASS estimations will be of future importance in research and clinical practice because they focus on the patients’ perspective of THA.

The Personal Impact Health Assessment Questionnaire (Hewlett et al 2002) was developed to assess the individual effect of disability in patients with rheumatoid arthritis. A similar personalised scoring system is being developed and validated for people with osteoarthritis (Wylde et al 2006). Wright et al (1994) have used a somewhat cumbersome patient completed questionnaire that identifies the main concerns of the individual and how these are affected by surgery. Methods to assess the personal effect on disability will not only expose any adverse events or failures associated with surgery but also identify whether realistic expectations, discussed preoperatively, have been achieved postoperatively. These instruments truly indicate the patients’ assessment of outcome.
1. Aims

**Study I**
To determine the influence of uncorrected LLD after THA on patients’ reported hip function and QoL.

**Study II**
To determine the association of global FO changes after THA with patients’ reported hip function, QoL and abductor muscle strength.

**Study III**
To evaluate the concurrent validity of the Sundsvall method of measuring postoperative FO by comparing it to a standard method. To evaluate the interobserver reliability and intraobserver reproducibility of measurement of postoperative global FO, LLD, acetabular cup inclination and anteversion.

**Study IV**
To analyse the postoperative radiographs of THA patients with leg lengthening and global FO reduction to determine whether the problem is located in the stem, cup or both.
2. Hypotheses

**Study I**
Uncorrected leg lengthening $\geq 10$ mm after THA is associated with lower functional outcome and QoL.

**Study II**
Reduction of global FO by $>5$ mm on the operated hip compared to the contralateral side, after THA is associated with lower functional outcome, QoL and abductor muscle strength.

**Study III**
The Sundsvall method for measurement of global FO is as reliable as the standard method. Radiographic measurement of LLD, global FO, cup inclination and anteversion methods have the required reliability to be used in clinical practice.

**Study IV**
Leg lengthening $\geq 10$ mm and reduction of global FO $>5$ mm after THA are the result of improper stem positioning.
3. Patients and methods

The studies of this thesis are based upon a prospective cohort of patients that were recruited at Sundsvall Teaching Hospital in Sweden between September 2010 and December 2013. A total of 222 patients with unilateral primary osteoarthritis (OA) treated with THA were recruited (Figure 6). Patients with secondary OA, previous spinal, pelvic, or lower limb injuries or fractures were excluded. The regional ethics committee at Umeå University approved the studies and informed consent was obtained from all patients.

Patients’ preoperative function and QoL were assessed with the WOMAC index and EQ-5D respectively. The WOMAC index is a patient-reported outcome measure developed to assess pain, stiffness, and physical function in patients with hip and/or knee OA (Bellamy et al 1988). It consists of 24 items divided into 3 subscales: pain (5 items), stiffness (2 items) and physical function (17 items). Response options are on 5-point scale ranging from none to extreme, and produce a total score of 0-96 (best to worse). The EQ-5D is a generic QoL instrument. It consists of a questionnaire and visual analogue scale (VAS) (Dawson et al 2001). The questionnaire comprises the following 5 dimensions: mobility, self-care, usual activities, pain/discomfort and anxiety/depression. Each dimension has 3 levels: no problems, some problems, and extreme problems. The mean of the EQ-5D is equivalent to 1.0 for a completely healthy person and 0 for death. Some negative values, corresponding to a state worse than death can occur. The EQ-VAS records the respondent’s self-rated health on a vertical, visual analogue scale where the endpoints are labeled and range from (0-100) where 100 is the best health state and 0 is the worst health state.

One of ten specialist orthopedic surgeons, or an assistant directly under their supervision, performed the operations using either a cemented Lubinus SP II system (Link, Germany) or cementless Spotorno (CLS) stem and Triology cup (Zimmer, U.S.A.). The Lubinus stem has one center-collum diaphyseal (CCD) angle (126°), 32
mm head and three neck lengths (47.5 mm, 51.5 mm and 55 mm) while the CLS stem has one CCD angle (125°), 32 mm head and four neck lengths (-4, 0, 4 and 8). The posterolateral approach was used in all operations.

Preoperative radiological templating using the Mdesk™ system (RSA Biomedical, Umeå, Sweden) was performed in most cases. Intraoperative assessment of leg length was done by evaluation of the soft-tissue balance and manual assessment of relative leg lengths by comparing it with the contralateral side. No intraoperative assessment of FO was done. Patients were mobilized at the first postoperative day with full weight bearing allowed. All patients followed the same postoperative exercise and rehabilitation program.

LLD and global FO were measured in each patient on plain radiographs within 3 months before the THA and at the second postoperative day. Radiographs were taken using a standardized protocol. The AP hip radiograph was made with the patient supine and both legs internally rotated 15 degrees and the X-ray beam centered on the pubic symphysis with a film focus distance of 115 cm. The lateral radiographs were made with the patient supine with the contralateral hip flexed and externally rotated with the X-ray beam angled at 45° inferomedial to superolateral through the hip joint. Acceptable radiographs were centered, straight (equal-sized obturator foramina) and included the proximal one-third of the femora (Frank et al 2007). Measurements were calibrated to a radiopaque standardised metal sphere to assess the degree of magnification. A 1 mm precision scale was used.

Patients were followed-up at 12 - 15 months postoperatively with the WOMAC index and EQ-5D questionnaire in addition to a clinical assessment. Patients completed an additional questionnaire (Table 1) enquiring about any residual problems such as the use of a walking aid, awareness of LLD, the need for a shoe lift, residual pain around the operated hip or use of analgesics for hip pain. During the clinical assessment, measurement of the abductor muscle strength was undertaken. Dislocation events were also recorded.
Figure 6: Diagram showing the flow of patients into the studies.

Sep 2010 - Dec 2013
Unilateral THA
n= 286

Excluded
n=21

Included in the study n=250

Declined to participate
n=15

Died during follow-up n=6
Drop-out n=22

Completed follow-up
N=222

Study I
n=174

Study II
n=222

Study III
n=90

Study IV
n=174
Table 1: The additional questionnaire sent to the patients at 12-15 months follow-up.

<table>
<thead>
<tr>
<th>Question</th>
<th>Options</th>
</tr>
</thead>
</table>
| How long after the operation did you use a walking aid e.g. crutches, walker etc.? | a- few weeks  
b- less than three months  
c- more than three months |
| Have you had a problem with your legs’ length after the operation?       | a- no  
b- yes, but it went away  
c- yes, still have the problem |
| Have you used shoe lifts (or something similar) to correct your legs’ length after the operation? | a- no  
b- yes, but I don’t use it now  
c- yes, I still use it. |
| Do you still have pain or discomfort around the operated hip?            | a- no  
b- yes, I have pain or discomfort in the groin or thigh  
c- yes, I have pain on the outer side of the hip  
d- yes, I have pain in the buttock region |
| Do you take any analgesic medications for hip pain?                      | a- no  
b- yes, only occasionally  
c- yes, regularly |
4.1 Study I

Between September 2010 and April 2013, a total of 225 consecutive patients with unilateral primary OA were considered for inclusion into the study. The primary outcome measure was the WOMAC Index. The secondary outcome measures were the EQ-5D, including the VAS scale, use of walking aid, awareness of LLD, use of shoe lift, residual hip pain, dislocation and the implant type (cemented vs. uncemented).

The LLD on radiographs was defined as the difference in perpendicular distance in millimeters between a line passing through the lower edge of the teardrop points to the corresponding tip of the lesser trochanter (Woolson et al 1999, Konyves et al 2005) (Figure 2). A positive LLD value was obtained when the affected limb was longer than the contralateral side, whereas a negative value indicated the opposite. Depending on the postoperative measurement, patients were divided into three groups: (1) the shortening group where the operated leg was more than 5 mm shorter compared with the contralateral side, (2) the restoration control group where the operated leg was within 5 mm shortening and 9 mm lengthening compared with the contralateral side and (3) the lengthening group where the operated leg became more than 9 mm longer compared with the contralateral side. According to the protocol of our department, postoperative LLD within 20 mm was left uncorrected.

Statistical methods

Statistical analysis was carried out using SPSS for Windows version 20.0 (SPSS Inc., Chicago, Illinois). To calculate the required sample size, a priori power analysis was performed using G*Power software (Faul et al 2009) based on comparing the means of the primary outcome WOMAC index of each group. With a power of 0.80 and a significance level (alpha) of 0.05, a minimum of 32 patients were needed in each group to detect a clinically significant 10 points difference (standard deviation SD 20) in
WOMAC index among the groups. Before using parametric tests, data was tested for normality using the Kolmogorov-Smirnov test. Demographic data were presented as means and standard deviation (SD).

The paired sample t-test was used to determine significance between preoperative and postoperative outcome scores for the whole cohort. Based on our hypothesis that uncorrected postoperative LLD, as a single variable, would influence the postoperative primary outcome parameter (WOMAC index) among the three studied groups (shortening vs. restoration vs. lengthening), ANOVA was used to compare the influence of LLD on functional outcome, QoL and health status VAS among the three groups. The Bonferroni correction included in this measurement would control the family wise error rate and counteract the problem of multiple comparisons. A series of Tukey’s post-hoc tests to compare each of the two groups was performed. The comparison of residual problems with the use of walking aid, awareness of LLD, the need for a shoe lift, residual pain or discomfort around the operated hip among the three groups was evaluated with Fisher’s exact test for more than two groups. Statistical significance was set at 0.05.
4.2 Study II

Between September 2010 and December 2013, a total 286 patients with unilateral primary OA were considered for inclusion. The primary outcome measure was the WOMAC index. The secondary outcome measures were the EQ-5D, including health status VAS, use of walking aid, residual hip pain, use of analgesics, dislocation and hip joint abductor muscle strength measured using an electronic dynamometer.

The global FO was measured by the addition of the distance between the longitudinal axis of the femur to the center of the femoral head and the distance from the center of the femoral head to a perpendicular line passing through the medial edge of the ipsilateral teardrop point of the pelvis (Lecerf et al 2009) (Figure 7). The measurement was repeated bilaterally to compare the global FO of the operated side to the non-operated hip. A positive value was used when the FO of the operated hip was greater than the contra-lateral side while a negative value indicated the opposite. Depending on the postoperative measurement, patients were divided into three groups: 1) the decreased FO group, where the global FO of the operated side was reduced by more than 5 mm compared with the contralateral side, 2) the restored FO group, where the global FO of the operated side was within 5 mm restored, compared with the contralateral side, and 3) the increased FO group, where the global FO of the operated side was increased by more than 5 mm compared with the contralateral side.

**Measurement of abductor muscle strength**

A single observer conducted isometric abductor muscle strength measurements in all patients at the outpatient department according to the method described by others (Yamaguchi et al 2004, Asayama et al 2005). Before measurement, information about the test was given to patients to allow them to become familiarized with it. While the patient was in the supine position with straight legs on a padded table, the pelvis was
immobilized with a band across the iliac spines. An electronic dynamometer (MAV Prüftechnik GMBH) was used. The pad of the compression arm was centered at the lateral aspect of the thigh just below the midpoint between the greater trochanter and knee joint. The patient was then asked to maximally abduct the thigh against the pad. The non-operated side was tested first. Two trials for each side were made with a one-minute rest in between. We documented the higher strength measure of the two trials for each side and then calculated the percentage of the operated side in relation to the contralateral side.

**Statistical methods**

Statistical analysis was carried out using SPSS for Windows version 20.0 (SPSS Inc., Chicago, Illinois). To calculate the required sample size, a priori power analysis was performed using G*Power software (Faul et al 2009) based on comparing the means of the primary outcome WOMAC index of each group. With a power of 0.80 and a significance level (alpha) of 0.05, a minimum of 65 patients was needed in each group to detect a clinically significant 7 points difference (SD 20) in WOMAC index among the groups. Before using parametric tests, data was tested for normality using the Kolmogorov-Smirnov test. Demographic data was presented as means and SD.

A two-tailed paired t-test was used to test hypotheses about change in pre- and postoperative outcome scores. Based on the null hypothesis that an FO reduction of more than 5 mm would not be associated with a worse postoperative WOMAC index (as a single outcome), ANOVA was used to test this hypothesis. Separate ANOVAs were also used to test any association between global FO and any of the following: WOMAC pain, WOMAC stiffness, and WOMAC physical activity, EQ-5 D, health status VAS, and abductor muscle strength. Tukey’s post-hoc tests were then used to compare 2 groups at a time.
The comparison of residual problems of using a walking aid, residual pain around the operated hip, use of analgesics, and dislocation in the 3 groups was evaluated with Fisher’s exact test. The unadjusted results of these comparisons were further adjusted for possible confounding factors, when statistically significant associations were found, in order to determine whether or not these associations were causal. We chose age, sex, and preoperative WOMAC index as a priori selection for possible confounding factors since it was expected that these variables would relate both to exposure and outcome and that they would not be in the causal pathway between the potential risk factor and the outcome (Shrier et al 2008). In all tests, any p-value < 0.05 was considered to be statistically significant.

**Figure 7:** Measurement of FO with the standard method as the distance between the longitudinal axis of the femur to the centre of the femoral head plus the distance between the femoral head to a perpendicular line passing through the medial edge of the ipsilateral teardrop point of the pelvis.
4.3 Study III

A total of 90 consecutive patients with primary unilateral OA who underwent THA between September 2010 and June 2012 were recruited into the study. The LLD on radiographs was defined as the difference in perpendicular distance in millimetres between a line passing through the lower edge of the teardrop points to the corresponding tip of the lesser trochanter (Woolson et al 1999, Konyves et al 2005) (Figure 2). A positive LLD value was obtained when the operated limb was longer than the contralateral side, whereas a negative value indicated the opposite.

Measurement of FO using the Sundsvall method was carried out on the AP view of the pelvis as the horizontal distance between the femoral axis (a line drawn through the centre of the femoral shaft) and the midline of the pelvis at the height of the lateral tip of the greater trochanter (Kjellberg et al 2009) (Figure 5). The measurement was performed bilaterally to compare the femoral offset on the operated side to the non-operated hip. A positive value was used when the FO of the operated hip was greater than the non-operated side, while a negative value indicated the opposite.

Measurement of FO with the standard method was carried out on AP view as the addition of the distance between the longitudinal axis of the femur to the centre of the femoral head and the distance from the centre of the femoral head to a perpendicular line passing through the medial edge of the ipsilateral teardrop point of the pelvis (Lecerf et al 2009). Once again, the measurement was repeated bilaterally to compare the FO of the operated side to the nonoperated hip. A positive value was used when the FO of the operated hip was greater than that of the contralateral side, while a negative value indicated the opposite (Figure 7).
Cup inclination was measured on the AP view as the angle in degrees between a line drawn along the angle of the rim of the cup and the transischial line (a line drawn between the most inferior point of the ischial tuberosities) (Wylde et al 2012) (Figure 8). Acetabular cup anteversion was measured on the lateral radiograph as the angle formed by intersection of a line drawn across the face of the acetabulum and a line perpendicular to the horizontal plane, according to the Woo and Morry method (Woo et al 1982) (Figure 9).

**Assessment of reliability and validity**

The interobserver reliability of global FO, LLD and cup inclination and anteversion was assessed from measurements made by three independent observers (an orthopaedic surgeon, orthopaedic resident and radiologist). All measurements were made without any knowledge of the patients’ clinical information or the findings of the other observers. After 8–10 weeks, the orthopaedic surgeon and the radiologist repeated the same measurements and the intraobserver reproducibility was measured by comparing the first to the second measurements.

The results of the three observers using the Sundsvall method of global FO measurements were compared with the results using the standard method to measure the validity of the Sundsvall method. The observers were blinded to their previous results when they made the measurements. Furthermore, we measured the degree of prediction of the three observers, i.e. the percentage of correct prediction for each observer of whether the FO was of positive (the operated hip had increased in FO) or negative (the operated hip had decreased in FO) value.
Statistical analysis

Statistical analysis was carried out using SPSS for Windows, version 20.0 (SPSS Inc., Chicago, IL) and statistical significance was set at 0.05. To calculate the required sample size, a priori power analysis was performed using Bonett’s approximation (Bonett et al 2002) for three observers. Using a minimum value of 0.7 for the interclass correlation coefficient (ICC) and a 95% confidence interval (CI) width of 0.2, a sample size of 68 hips was required. Therefore, we chose to include 90 patients with unilateral THA in order to provide a safe margin of error.

The ICC (with 95% CI) was used to evaluate the interobserver reliability of the obtained measures among the three observers and to evaluate the intraobserver reproducibility between the first and second measurements done by the two observers. To determine the concurrent validity of the Sundsvall method, we used the Pearson’s correlation coefficient ($r$) to measure its correlation with the standard method. The paired t-test was also used to compare the means of the measurements of the Sundsvall to the standard methods. This was done to assess whether there would be a significant difference between the two methods, which could mean an over- or underestimation of FO as measured by the Sundsvall method. For both ICC and Pearson’s correlation coefficient a value of 0.00 to 0.20 was considered slight, 0.21 to 0.40 was considered fair, 0.41 to 0.60 was considered moderate, 0.61 to 0.80 was considered substantial and 0.81 to 1.00 was considered excellent (Landis et al 1977).
**Figure 8:** Acetabular cup inclination is measured in degrees between a line drawn along the angle of the rim of the cup and transischial line (a line drawn between the most inferior point of the ischial tuberosities).

**Figure 9:** Acetabular cup anteversion is measured on the lateral radiograph as the angle formed by the intersection of a line drawn across the face of the acetabulum and a line perpendicular to the horizontal plane.
4.4 Study IV

Between September 2010 and April 2013, 174 patients with unilateral primary OA treated with THA were included in the study. LLD and global FO were measured in each patient at the second postoperative day using a standardized protocol.

The LLD on radiographs was defined as the difference in perpendicular distance in millimeters between a line passing through the lower edge of the teardrop points to the corresponding tip of the lesser trochanter (Woolson et al 1999, Konyves et al 2005). A positive LLD value was obtained when the affected limb was longer than the contralateral side, whereas a negative value indicated the opposite. Patients whose operated leg became ≥ 10 mm longer compared with the contralateral side (n=41) were further studied to investigate the amount of lengthening that took place in the stem (stem length) and in the cup (cup length) compared with the contralateral side. This was done using the method described by McWilliams et al (2012). The stem length at the operated side was measured as the distance between the lesser trochanter and teardrop and the cup length as the distance between the teardrop and the center of rotation. The stem and cup lengths were compared with those of the contralateral side (Figure 10).

The global FO measurement of the operated side was carried out on the postoperative pelvic AP view. It was calculated by adding the distance between the longitudinal axis of the femur to the center of rotation (stem offset) and the distance from the center of rotation to a perpendicular line passing through the medial edge of the ipsilateral teardrop point of the pelvis (cup offset) (Lecerf et al 2009). Once again, the measurement was repeated bilaterally to compare the FO of the operated side to the non-operated hip. A positive value was used when the FO of the operated hip was greater than the contra-lateral side while a negative value indicated the opposite. Patients with reduction of the global FO at the operated side of more than 5 mm (n=58) were further studied to investigate the amount of global FO reduction that took place in
the stem (stem offset) and in the cup (cup offset) compared with the contralateral side (Figure 7).

To test the interobserver reliability of the foregoing measurements on the 41 patients with leg lengthening and the 58 patients with global FO reduction, we compared the measurements made by an orthopaedic surgeon with the measurements made by a radiologist. The two observers were blinded to each other’s results. To test the intraobserver reproducibility, the radiologist repeated the same measurements after 8 weeks and his two measurements were compared to each other. He was blinded to his own previous measurements when he repeated them. The two observers were trained in making the measurements before starting the study and a set of 5 patients from the leg lengthening group and 5 patients from the FO reduction group were measured by the whole research group in order to reach a consensus.

**Statistical methods**

The radiological measurements were presented as means and SD. A two-tailed paired student t-test was used to compare the stem length and offset and the cup length and offset with the contralateral side. The ICC was used to evaluate the interobserver reliability (between the two observers) and intraobserver reproducibility (comparing each observer’s first and second measurements). An ICC of 0 to 0.20 was considered slight, 0.21 to 0.40 was considered fair, 0.41 to 0.60 was considered moderate, 0.61 to 0.80 was considered substantial and 0.81 to 1.00 was considered excellent (Landis et al 1977). Statistical analysis was carried out using SPSS for Windows version 20.0 (SPSS Inc., Chicago, Illinois) and statistical significance was set at \( p < 0.05 \).
Figure 10: A is the cup length at the operated side and A1 at the contralateral side, while B is the stem length at the operated side and B1 at the contralateral side.
5. Results

5.1 Study I

A total of 225 consecutive patients were eligible for inclusion in the study. At the end of the study a complete set of results for 174 patients (77.3%) was available (90 females and 84 males with a mean age at surgery of 68 years, SD 10) (Figure 11). The comparisons of the preoperative WOMAC index, EQ-5D and health status VAS among the three groups showed no statistically significant differences (p>0.05). All three groups had significant improvements (p<0.001) in the postoperative WOMAC index, EQ-5D and health status VAS compared with those preoperatively.

Comparisons of the postoperative WOMAC index, EQ-5D and health status among the three groups also showed no statistically significant differences (Table 2). The Tukey’s post-hoc tests to compare each of the two groups showed that the lengthening group had less favorable WOMAC index compared to the shortening group, with a tendency towards statistical significance [18.3 (SD 16.3) vs. 13.8 (SD 12.7), p=0.09] (Table 3). Regarding the implant type among the three groups, 47% (15/32) of implants were uncemented in the shortening group compared to 22% (22/101) in the restoration group and 7% (3/41) of the lengthening group. This difference was statistically significant (p=0.001).

Analysis of the additional questionnaire for residual problems showed that the use of a shoe lift was more common in the lengthening group (22% vs. 12.5% vs. 7%, p=0.04). Furthermore, the use of walking aids, awareness of LLD, and residual hip pain were all more common in the lengthening group, but without statistical significance (Table 2). The incidence of postoperative dislocation among the three groups was comparable.
Figure 11: Diagram showing the flow of patients in the study.

- Sep 2010 - April 2013
  - Unilateral THA
  - n=225
  - Excluded
  - n=16
  - Declined to participate
  - n=15
  - Included in the study
  - n=194
  - Died during follow-up
  - n=4
  - Drop out
  - n=16
  - Completed the study
  - n=174
  - Lengthening group
  - n=41
  - >10 mm
  - Restoration group
  - n=101
  - -5 to 9 mm
  - Shortening group
  - n=32
  - > -5 mm
**Table 2:** Patients’ demographic data and comparison of the pre- and post-operative WOMAC Index, EQ-5D, health status VAS and additional questionnaire among the three groups.

<table>
<thead>
<tr>
<th></th>
<th>Shortening group &gt; -5 mm</th>
<th>Restoration group -5 to 9 mm</th>
<th>Lengthening group &gt;10 mm</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>32</td>
<td>101</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>-6 to -20 mm (SD 10.5)</td>
<td>-5 to 9 mm (SD 2.5)</td>
<td>10 to 20 mm (SD 10.9)</td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>65 years (SD 10.8)</td>
<td>67 years (SD 10.7)</td>
<td>70 years (SD 9)</td>
<td>0.91</td>
</tr>
<tr>
<td>Sex</td>
<td>12 females (40%)</td>
<td>55 females (54%)</td>
<td>23 females (56%)</td>
<td>0.22</td>
</tr>
<tr>
<td>Uncemented</td>
<td>(15) 47%</td>
<td>(22) 22%</td>
<td>(3) 7%</td>
<td><strong>0.001</strong></td>
</tr>
<tr>
<td>Preoperative WOMAC</td>
<td>59.8 (SD 14.0)</td>
<td>59.5 (SD 14.3)</td>
<td>58.6 (SD 11.9)</td>
<td>0.92</td>
</tr>
<tr>
<td>Preoperative EQ-5D</td>
<td>0.39 (SD 0.28)</td>
<td>0.49 (SD 0.35)</td>
<td>0.47 (SD 0.28)</td>
<td>0.31</td>
</tr>
<tr>
<td>Preoperative health status VAS</td>
<td>46 (SD 18)</td>
<td>45 (SD 21)</td>
<td>44 (SD 19)</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Postoperative WOMAC</td>
<td>13.8 (SD 12.7)</td>
<td>17.0 (SD 18.3)</td>
<td>18.3 (SD 16.3)</td>
<td>0.41</td>
</tr>
<tr>
<td>Postoperative EQ-5D</td>
<td>0.87 (SD 0.13)</td>
<td>0.84 (SD 0.19)</td>
<td>0.82 (SD 0.19)</td>
<td>0.50</td>
</tr>
<tr>
<td>Postoperative health status VAS</td>
<td>81.1 (SD 18)</td>
<td>79.1 (SD 17)</td>
<td>79.7 (SD 19)</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use of walking aid &gt;3 months</td>
<td>3 (9%)</td>
<td>22 (21%)</td>
<td>11 (27%)</td>
<td>0.17</td>
</tr>
<tr>
<td>Awareness of LLD</td>
<td>5 (15.5%)</td>
<td>16 (16%)</td>
<td>12 (29%)</td>
<td>0.16</td>
</tr>
<tr>
<td>Use of shoe lift</td>
<td>4 (12.5%)</td>
<td>7 (7%)</td>
<td>9 (22%)</td>
<td><strong>0.04</strong></td>
</tr>
<tr>
<td>Residual pain</td>
<td>2 (6%)</td>
<td>7 (7%)</td>
<td>5 (12%)</td>
<td>0.53</td>
</tr>
<tr>
<td>Dislocation</td>
<td>1 (3%)</td>
<td>2 (2%)</td>
<td>1 (2.5%)</td>
<td>0.92</td>
</tr>
</tbody>
</table>
**Table 3:** Comparisons of postoperative WOMAC Index, EQ-5D and health status VAS between each of two groups using Tukey’s post-hoc tests.

<table>
<thead>
<tr>
<th></th>
<th>EQ-5D</th>
<th>Health status VAS</th>
<th>WOMAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lengthening vs. Restoration</td>
<td>p=0.68</td>
<td>p=0.97</td>
<td>p=0.67</td>
</tr>
<tr>
<td>Lengthening vs. Shortening</td>
<td>p=0.21</td>
<td>p=0.64</td>
<td>p=0.09</td>
</tr>
<tr>
<td>Restoration vs. Shortening</td>
<td>p=0.34</td>
<td>p=0.54</td>
<td>p=0.36</td>
</tr>
</tbody>
</table>
5.2 Study II

A total of 286 consecutive patients were eligible for inclusion in the study. At the end of the study a complete set of results for 222 patients (78%) was available (107 females and 115 males) (Figure 12). A cemented prosthesis was used in 176 patients (79%) and a non-cemented prosthesis in 46 patients. Comparison of the preoperative WOMAC index, EQ-5D and health status VAS among the three groups showed no statistically significant differences (p>0.05) and all three groups had significant improvements (p<0.001) in the postoperative WOMAC index, EQ-5D and health status compared with that preoperatively.

Comparing the postoperative WOMAC index, EQ-5D, health status VAS and abductor muscle strength among the three groups (Table 4) showed a significant difference in the WOMAC index (mainly attributable to a lower physical activity score) and abductor muscle strength. Further analysis with the Tukey’s post-hoc tests revealed the difference to be present between the decreased FO group and the two other groups (p<0.05). Analysis of the residual problems questionnaire and examination for residual hip problems showed that the use of walking aids was more common in the decreased FO group than the restored and increased FO groups (32% vs. 21% vs. 15%, p=0.04) while the incidence of residual hip pain/tenderness, use of analgesics for hip pain and postoperative dislocation among the three groups was comparable (table 4).

When the unadjusted results for comparing the postoperative WOMAC indices, abductor muscle strength and walking aids use among the three groups were adjusted for possible confounding factors e.g. gender, age and preoperative WOMAC index, global FO reduction was only associated with abductor muscle strength (table 5).
Figure 12: Diagram showing the flow of patients in the study.

- Sep 2010 - Dec 2013
  - Unilateral THA
  - n=286

- Excluded n=21
- Declined to participate n=15

- Included in the study n=250

- Died during follow up n=6
  - Drop out n=22

- Completed the study n=222

  - Decreased FO group n=71
  - Restored FO group n=73
  - Increased FO group n=78
Table 4: Patients demography and unadjusted results of comparing pre and postoperative WOMAC index (primary outcome) and other parameters among the three groups. P-values were determined with ANOVA and Fisher’s exact test.

<table>
<thead>
<tr>
<th></th>
<th>Decreased FO group &gt; -5mm</th>
<th>Restored FO group -5 to 5mm</th>
<th>Increased FO group &gt;5mm</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>71</td>
<td>73</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>-12.8</td>
<td>-0.4</td>
<td>12.1</td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>71</td>
<td>68</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>Sex</td>
<td>33 females</td>
<td>35 females</td>
<td>39 females</td>
<td></td>
</tr>
<tr>
<td>Preoperative EQ-5D</td>
<td>0.44 (SD 0.26)</td>
<td>0.43 (SD 0.22)</td>
<td>0.51 (SD 0.66)</td>
<td>0.6</td>
</tr>
<tr>
<td>Preoperative health status VAS</td>
<td>42 (SD 20)</td>
<td>46 (SD 19)</td>
<td>41 (SD 19)</td>
<td>0.2</td>
</tr>
<tr>
<td>Preoperative WOMAC</td>
<td>61 (SD 13)</td>
<td>60 (SD 14)</td>
<td>61 (SD 13)</td>
<td>0.8</td>
</tr>
<tr>
<td>Postoperative EQ-5D</td>
<td>0.82 (SD 0.2)</td>
<td>0.86 (SD 0.17)</td>
<td>0.86 (SD 0.2)</td>
<td>0.3</td>
</tr>
<tr>
<td>Postoperative health status VAS</td>
<td>79 (SD 17)</td>
<td>78 (SD 20)</td>
<td>80 (SD 19)</td>
<td>0.9</td>
</tr>
<tr>
<td>Postoperative WOMAC</td>
<td>20 (SD19)</td>
<td>15 (SD 15)</td>
<td>15 (SD 14)</td>
<td>0.05</td>
</tr>
<tr>
<td>WOMAC pain</td>
<td>3.4 (SD 4.0)</td>
<td>2.4 (SD 3.3)</td>
<td>2.5 (SD 3)</td>
<td>0.1</td>
</tr>
<tr>
<td>WOMAC stiffness</td>
<td>1.8 (SD 2)</td>
<td>1.4 (SD 1.3)</td>
<td>1.2 (SD 1.4)</td>
<td>0.07</td>
</tr>
<tr>
<td>WOMAC physical activity</td>
<td>15 (SD 14)</td>
<td>11 (SD 11)</td>
<td>11 (SD 11.0)</td>
<td>0.05</td>
</tr>
<tr>
<td>Abductor muscle strength (% compared with contralateral side)</td>
<td>78 (SD 30)</td>
<td>90 (SD 38)</td>
<td>92 (SD 44)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Walking aids (%)</td>
<td>32</td>
<td>21</td>
<td>15</td>
<td>0.04</td>
</tr>
<tr>
<td>Residual hip pain (%)</td>
<td>12</td>
<td>11</td>
<td>9</td>
<td>0.9</td>
</tr>
<tr>
<td>Analgesics use (%)</td>
<td>16</td>
<td>9</td>
<td>7</td>
<td>0.3</td>
</tr>
<tr>
<td>Dislocation (%)</td>
<td>2.8</td>
<td>1.4</td>
<td>1.2</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Table 5: The adjusted results for factors associated with postoperative WOMAC index, abductor muscle strength and use of walking aids.

<table>
<thead>
<tr>
<th>Postop WOMAC index</th>
<th>Coef</th>
<th>95% CI</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>1.00</td>
<td>Ref</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>-5.96</td>
<td>-10.3 to -1.66</td>
<td>0.007</td>
</tr>
<tr>
<td>Age</td>
<td>0.40</td>
<td>0.18 to 0.63</td>
<td>0.001</td>
</tr>
<tr>
<td>FO groups</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decreased global FO group</td>
<td>1.00</td>
<td>Ref</td>
<td></td>
</tr>
<tr>
<td>Restored/Increased global FO group</td>
<td>-0.53</td>
<td>-3.4 to 2.3</td>
<td>0.7</td>
</tr>
<tr>
<td>Preop WOMAC index</td>
<td>0.12</td>
<td>-0.4 to 0.28</td>
<td>0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Abductor muscle strength</th>
<th>Coef</th>
<th>95% CI</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>1.00</td>
<td>Ref</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>-3.11</td>
<td>-10.2 to 0.97</td>
<td>0.4</td>
</tr>
<tr>
<td>Age</td>
<td>0.02</td>
<td>-0.36 to 0.38</td>
<td>0.9</td>
</tr>
<tr>
<td>FO groups</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decreased global FO group</td>
<td>1.00</td>
<td>Ref</td>
<td></td>
</tr>
<tr>
<td>Restored/Increased global FO group</td>
<td>11.0</td>
<td>57.1 to 121.3</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Preop WOMAC index</td>
<td>-0.06</td>
<td>-0.33 to 0.20</td>
<td>0.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Walking aids use</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>1.00</td>
<td>Ref</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>0.19</td>
<td>0.08 to 0.43</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Age</td>
<td>1.09</td>
<td>1.04 to 1.14</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>FO groups</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decreased global FO group</td>
<td>1.00</td>
<td>Ref</td>
<td></td>
</tr>
<tr>
<td>Restored global FO group</td>
<td>0.52</td>
<td>0.20 to 1.32</td>
<td>0.2</td>
</tr>
<tr>
<td>Increased global FO group</td>
<td>0.65</td>
<td>0.24 to 1.73</td>
<td>0.4</td>
</tr>
<tr>
<td>Preop WOMAC index</td>
<td>1.01</td>
<td>0.98 to 1.04</td>
<td>0.7</td>
</tr>
<tr>
<td>Abductor muscle strength</td>
<td>1.00</td>
<td>0.99 to 1.02</td>
<td>0.8</td>
</tr>
</tbody>
</table>
5.3 Study III

There were 46 males and 44 females with a mean age of 68 years (range 44 to 85). There were eight patients with low-quality images (mainly a malrotated pelvis and unclear lateral view) so these patients were re-examined with new radiographs to ensure adequate quality. The interobserver reliability of all measurements among the three observers was excellent, except for LLD, which was substantial (Table 6). The intraobserver reproducibility of measurement for the two observers was excellent (Tables 6). The validity of the Sundsvall method of global FO measurement when compared to the standard method was good with positive correlation. Pearson’s coefficient ($r$) for the three observers was excellent. The p-value comparing the means (SD) of the Sundsvall method and standard method was $> 0.05$ (Table 7), i.e. there were no significant differences among the measurements.
Table 6: The interobserver reliability of radiographic measurements among the three observers, intra observer reproducibility of observer 1 (orthopaedic surgeon) and intraobserver reproducibility of observer 2 (radiologist). ICC=Intraclass correlation coefficient, CI=confidence interval, LLD =leg length discrepancy, FO=femoral offset

<table>
<thead>
<tr>
<th></th>
<th>LLD</th>
<th>FO Sundsvall</th>
<th>FO standard</th>
<th>Cup inclination</th>
<th>Cup anteversion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inter-observer reliability</strong></td>
<td>ICC</td>
<td>0.79</td>
<td>0.92</td>
<td>0.88</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>95% CI</td>
<td>0.72–0.85</td>
<td>0.89–0.94</td>
<td>0.84-0.91</td>
<td>0.77–0.92</td>
</tr>
<tr>
<td><strong>Intra-observer reproducibility observer I</strong></td>
<td>ICC</td>
<td>0.90</td>
<td>0.94</td>
<td>0.93</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>95% CI</td>
<td>0.86-0.93</td>
<td>0.91-0.96</td>
<td>0.90-0.96</td>
<td>0.80-0.91</td>
</tr>
<tr>
<td></td>
<td>Pearson’s (r)</td>
<td>0.91</td>
<td>0.94</td>
<td>0.94</td>
<td>0.87</td>
</tr>
<tr>
<td><strong>Intra-observer reproducibility observer II</strong></td>
<td>ICC</td>
<td>0.87</td>
<td>0.94</td>
<td>0.94</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>95% CI</td>
<td>0.81-0.91</td>
<td>0.91-0.96</td>
<td>0.90-0.96</td>
<td>0.79-0.90</td>
</tr>
<tr>
<td></td>
<td>Pearson’s (r)</td>
<td>0.87</td>
<td>0.94</td>
<td>0.94</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Table 7: The validity of the Sundsvall method of FO measurement compared to the standard method using Pearson’s correlation coefficient and degree of prediction. SD: standard deviation, r: Pearson’s correlation coefficient.

<table>
<thead>
<tr>
<th>Observers</th>
<th>Sundsvall method Mean (SD)</th>
<th>Standard method Mean (SD)</th>
<th>Pearson’s (r)</th>
<th>Degree of prediction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.05 (10.5)</td>
<td>-0.80 (9.6)</td>
<td>0.93</td>
<td>87%</td>
</tr>
<tr>
<td>2</td>
<td>0.18 (10.5)</td>
<td>-0.20 (9.6)</td>
<td>0.90</td>
<td>88%</td>
</tr>
<tr>
<td>3</td>
<td>-0.12 (9.8)</td>
<td>-0.92 (8.6)</td>
<td>0.85</td>
<td>83%</td>
</tr>
</tbody>
</table>
5.4 Study IV

Leg lengthening group

There were 41 patients (24 females and 17 males, mean age 70.5 years SD 8.8) in this group. The mean lengthening of the operated leg was 12.8 mm (SD 2.5). The comparison of stem length and cup length with the contralateral side showed that the lengthening was located in the stem for the two observers (table 8).

FO reduction group

There were 58 patients (26 females and 32 males, mean age 72.2 years SD 8.5) in this group. The mean FO reduction was -13.3 mm (SD 6.2). The comparison of the stem offset and cup offset with the contralateral side showed that the FO reduction was located both in the stem and cup for the two observers (table 8).

The reliability and reproducibility of the measurements

Both interobserver reliability and intraobserver reproducibility were substantial to excellent (ICC ≥ 0.79). Tables (9, 10) show the obtained values.
Table 8: Demographic data and comparison of stem length and cup length, stem offset and cup offset between the two observers.

<table>
<thead>
<tr>
<th></th>
<th>Leg lengthening group</th>
<th>FO reduction group</th>
</tr>
</thead>
<tbody>
<tr>
<td>number</td>
<td>41</td>
<td>58</td>
</tr>
<tr>
<td>age</td>
<td>70.5 years (SD 8.8)</td>
<td>72.2 years (SD 8.5)</td>
</tr>
<tr>
<td>sex</td>
<td>24 female</td>
<td>26 female</td>
</tr>
<tr>
<td>mean</td>
<td>12.8 mm (SD 2.5)</td>
<td>-13.3 mm (SD 6.2)</td>
</tr>
</tbody>
</table>

**Observer I (radiologist)**

<table>
<thead>
<tr>
<th></th>
<th>Stem length operated 57.7 mm (SD 10.0)</th>
<th>Stem offset operated 49.2 mm (SD 9.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem length contralateral</td>
<td>50.9 mm (SD 10.4)</td>
<td>Stem offset contralateral 57.1 mm (SD 9.0)</td>
</tr>
<tr>
<td>p</td>
<td>0.003</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Cup length operated</td>
<td>19.0 mm (SD 4.4)</td>
<td>Cup offset operated 35.1 mm (SD 4.8)</td>
</tr>
<tr>
<td>Cup length contralateral</td>
<td>18.9 mm (SD 4.1)</td>
<td>Cup offset contralateral 39.9 mm (SD 5.2)</td>
</tr>
<tr>
<td>p</td>
<td>0.95</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

**Observer II (orthopaedic surgeon)**

<table>
<thead>
<tr>
<th></th>
<th>Stem length operated 59.5 mm (SD 9.8)</th>
<th>Stem offset operated 48.9 mm (SD 8.8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem length contralateral</td>
<td>50.9 mm (SD 10.5)</td>
<td>Stem offset contralateral 55.1 mm (SD 8.0)</td>
</tr>
<tr>
<td>p</td>
<td>0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Cup length operated</td>
<td>18.2 mm (SD 4.5)</td>
<td>Cup offset operated 35.5 mm (SD 4.7)</td>
</tr>
<tr>
<td>Cup length contralateral</td>
<td>18.8 mm (SD 4.2)</td>
<td>Cup offset contralateral 40.4 mm (SD 5.8)</td>
</tr>
<tr>
<td>p</td>
<td>0.90</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>
**Table 9:** The interobserver reliability between the two observers.

<table>
<thead>
<tr>
<th>Leg lengthening</th>
<th>Observer 1 (radiologist)</th>
<th>Observer 2 (orthopaedic surgeon)</th>
<th>ICC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem length operated</td>
<td>57.7 (SD 10.0)</td>
<td>59.5 (SD 9.8)</td>
<td>0.82</td>
</tr>
<tr>
<td>Stem length contralateral</td>
<td>50.9 (SD 10.4)</td>
<td>50.9 (SD 10.5)</td>
<td>0.86</td>
</tr>
<tr>
<td>Cup length operated</td>
<td>19.0 (SD 4.4)</td>
<td>18.2 (SD 4.5)</td>
<td>0.79</td>
</tr>
<tr>
<td>Cup length contralateral</td>
<td>18.9 (SD 4.1)</td>
<td>18.8 (SD 4.2)</td>
<td>0.85</td>
</tr>
<tr>
<td><strong>FO reduction</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stem offset operated</td>
<td>49.2 (SD 9.5)</td>
<td>48.9 (SD 8.8)</td>
<td>0.93</td>
</tr>
<tr>
<td>Stem offset contralateral</td>
<td>57.1 (SD 9.0)</td>
<td>55.1 (SD 8.0)</td>
<td>0.95</td>
</tr>
<tr>
<td>Cup offset operated</td>
<td>35.1 (SD 4.8)</td>
<td>35.5 (SD 4.7)</td>
<td>0.90</td>
</tr>
<tr>
<td>Cup offset contralateral</td>
<td>39.9 (SD 5.2)</td>
<td>40.4 (SD 5.8)</td>
<td>0.85</td>
</tr>
</tbody>
</table>

**Table 10:** The intraobserver reproducibility between the two measurements of the radiologist.

<table>
<thead>
<tr>
<th>Leg lengthening</th>
<th>First measurement</th>
<th>Second measurement</th>
<th>ICC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem length operated</td>
<td>57.7 (SD 10.0)</td>
<td>58.6 (SD 9.2)</td>
<td>0.95</td>
</tr>
<tr>
<td>Stem length contralateral</td>
<td>50.9 (SD 10.4)</td>
<td>49.3 (SD 11.2)</td>
<td>0.91</td>
</tr>
<tr>
<td>Cup length operated</td>
<td>19.0 (SD 4.4)</td>
<td>19.0 (SD 4.8)</td>
<td>0.88</td>
</tr>
<tr>
<td>Cup length contralateral</td>
<td>18.9 (SD 4.1)</td>
<td>19.7 (SD 4.2)</td>
<td>0.88</td>
</tr>
<tr>
<td><strong>FO reduction</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stem offset operated</td>
<td>49.2 (SD 9.5)</td>
<td>48.7 (SD 9.8)</td>
<td>0.96</td>
</tr>
<tr>
<td>Stem offset contralateral</td>
<td>57.1 (SD 9.0)</td>
<td>57.4 (SD 9.8)</td>
<td>0.96</td>
</tr>
<tr>
<td>Cup offset operated</td>
<td>35.1 (SD 4.8)</td>
<td>34.9 (SD 4.9)</td>
<td>0.92</td>
</tr>
<tr>
<td>Cup offset contralateral</td>
<td>39.9 (SD 5.2)</td>
<td>39.3 (SD 4.5)</td>
<td>0.92</td>
</tr>
</tbody>
</table>
6. Discussion

The studies of this thesis have shown that postoperative LLD up to 20 mm and reduced global FO more than 5 mm did not influence functional outcome or QoL at 12–15 months postoperatively. However, lengthening ≥ 10 mm was associated with more use of a shoe lift. Reduction in global FO > 5 mm, compared to the contralateral hip, was associated with weaker hip abductor muscles and more use of walking aids. Furthermore, the plain radiographic measurement methods of LLD, global FO, cup inclination and anteversion have the required validity and reliability to be used in clinical practice. These measurements have shown that lengthening of the operated leg ≥ 10 mm compared to the contralateral side was mainly caused by improper placement of the femoral stem, whereas a decrease of global FO > 5 mm compared to contralateral hip was caused by improper placement of both the acetabular and femoral components.

Regarding LLD, we chose different cut-off values for shortening and lengthening (shortening of the operated leg > 5 mm while lengthening of the operated leg ≥ 10 mm). This categorization was arbitrary as we thought that shortening was less common and less tolerated than lengthening. Also we chose to use radiological methods for LLD measurement rather than clinical methods because clinical methods are less accurate (Terry et al 2005) and could be affected by pelvic tilting and hip contracture. Regarding global FO changes, we chose the 5 mm cut-off to divide our patients into three groups because previous reports (Cassidy et al 2012, Sariali et al 2014) suggest this cut-off value affects outcome.

The WOMAC index and EQ-5D questionnaire are commonly used outcome measures in THA. Both of them are well validated including the Swedish version. We realize however that both measures have a ceiling effect (Marx et al 2005, Garbuz et al 2006) i.e. it is difficult to discriminate among patients with very good outcomes whose scores are at the top end of the scale. The WOMAC index, which is a patient-centered index,
might be more suitable to detect the influence of LLD and FO on patients reported functional outcome than other surgeon-based indexes such as the Harris Hip Score (white et al.2002).

In Study I, patients of the three LLD groups were comparable in age, sex and preoperative WOMAC index and EQ-5D. After the operation, all three groups showed clinically significant improvement in all measures and no statistically significant differences were detected among them. However, the shortening group scored a little better than the restoration and lengthening groups. When each of the two groups were compared with Tukey’s post-hoc tests, a difference with a tendency for statistical significance was noticed between the shortening and lengthening groups in the WOMAC index (13.8 vs. 18.3, p=0.09) (Table 3). However, this difference did not reach the usually used MCII of 10 points. No further analysis of these results e.g. with confounder factor adjustment were done because there was no statistically significant difference in WOMAC and EQ-5D postoperatively among the groups.

Five patients (12%) in the lengthening group had residual pain compared to 2 patients (6%) in the shortening group and 7 patients (7%) in the restoration group. One possible explanation for this observation is that before the THA operation most patients had shortening (and maybe contracture) secondary to the OA changes and this shortening could be long lasting. When the affected hip underwent THA, restoration of the original leg length or lengthening could give rise to over-tensioning of the soft tissue around the hip with possible biomechanical and gait disturbances. This could explain the residual pain as well as the increased risk for the need of shoe lifts, use of walking aids and LLD awareness (Tanaka et al. 2010) (Table 2). Farmer et al (2010) found that treatment of hip pain after THA in patients with LLD was more difficult than in those who had no LLD.

After study I was published, we looked at and compared the LLD among the three groups before the operation and found that the shortening group had LLD of -8.9 mm (SD 9.3), while the restoration group had LLD of -3.8 mm (SD 6.5) and lengthening
group of -1.3 mm (SD 5.3), p<0.01 (unpublished data). This could mean that patients with preoperative shortening get the best results if they continue with the shortening after the operation. The duration of OA and associated soft-tissue contracture might have a role in this regard, i.e. shortening due to long lasting OA is associated with more soft-tissue contracture. Restoration or lengthening of this shortening could give rise to over-tensioning and pain and hence worse function. Unfortunately, we did not record OA duration during our data collection. However, we plan to make this observation in the near future.

Previous studies have reported a variable effect of LLD on functional outcome. Beard et al (2008), for instance, showed that patients with LLD had a marginal deterioration in Oxford Hip Score at 3 years follow-up. This was not detected at earlier follow-ups. Konyves and Bannister et al (2005) showed that 62% of their patients were lengthened by a mean of 9 mm. The lengthening was perceived by 43% of patients at 3 months, but only by 33% of patients at 12 months. Wylde et al (2009), on the other hand, showed that 30% of patients perceived LLD after THA but only 36% of those had a true LLD on radiographic measurement. They also found that patients with perceived LLD had a worse outcome. Röder et al (2012) reported a negative effect of leg lengthening after THA on walking capacity, limping and patient satisfaction and of leg shortening, on hip pain, limping and patient satisfaction. Also, Edeen et al (1995) found that the extent of LLD correlated with the awareness of the problem, abnormal gait and the use of a shoe raise. Other studies reported no influence of LLD on the functional outcome after THA (White et al 2002, Benedetti et al 2010, Whitehouse et al 2013).

In study II, all three global FO groups showed a statistically and clinically significant improvement in postoperative WOMAC index, EQ-5D, and health status VAS. The unadjusted results showed an association between the decreased global FO group and worse WOMAC index and more use of walking aids compared to the restored and increased FO groups. Further analysis showed that this difference was mainly in the
WOMAC physical function subscore (Table 4). However, when the results were adjusted for age, sex, and preoperative WOMAC index, these associations were no longer apparent. On the other hand, the decreased global FO group had weaker hip abductor muscle strength compared to the other 2 groups, both in the crude results and the adjusted results (Table 5). This is most probably due to shortening of the lever arm of the operated hip, with subsequent loss of abductor muscle tension and power. These findings are in agreement with the results of Cassidy et al. (2012), who found a worse score for the WOMAC physical activity subscale in their decreased FO group and speculated that this was the result of abductor muscle weakness.

Other studies have shown positive correlations between FO restoration and both abductor muscle strength and hip range of motion (McGrory et al 1995, Yamaguchi et al 2004, Asayama et al 2005, Kiyama et al 2010). In contrast, Liebs et al (2014) found that decreasing FO by more than 5 mm was associated with the best improvement in score for the WOMAC pain subscale. The authors did not mention whether all the patients included had primary osteoarthritis and whether the same surgical approach was used, and no explanation was given for their results. Sariali et al (2014) studied the effect of modification of global FO after THA on gait. They found that a 6-12 mm decrease in FO after THA altered the gait, with lower swing speed and reduced range of motion at the knee when walking.

In studies I and II, the risk of dislocation was similar in the 3 groups (Table 2, 4). This means that decreasing global FO or shortening of the operated leg alone did not appear to compromise prosthetic stability. Indeed, this could emphasize the multifactorial aetiology of implant instability and indicate the importance of other parameters such as the state of soft tissue tensioning around the hip joint before operation, intra-operative implant positioning and patient compliance for prosthetic stability. Accordingly, we conclude that replacement of the diseased painful joint, keeping the leg length as it was before the operation or restoring to the contralateral leg length, restoring or increasing
global FO, with correct prosthetic positioning, is associated with the best WOMAC index and prosthetic stability.

The influence of LLD and global FO on QoL and health status VAS in the present studies seems to be negligible (Table 2,4). We found no differences among the three groups in the significant improvement of QoL and health status VAS that they achieved after THA. This agrees with the findings of White et al (2002), Cassidy et al (2012), Fujimaki et al (2013), Whitehouse et al (2013) and Liebs et al (2014) who used the SF-36 and SF-12 health survey questionnaires.

The distribution of implant types among the three groups in study I was another interesting finding. The uncemented implant type was more common in the shortening group (47%) while only 7% of the uncemented implant was used in the lengthening group. This might be caused by the tendency of the uncemented femoral stem to take a deeper position in the femoral canal than the broach. Konyves and Bannister et al (2005) reported that lengthening of the operated leg in 98% of cases was caused by improper positioning of the cemented femoral stem.

Another interesting observation would be the effect of different combinations of LLD and global FO changes e.g. lengthening with decreased FO versus lengthening with restored FO versus lengthening with increased FO versus restored leg length with decreased FO and so on. Unfortunately, this requires a large sample size and therefore cannot be investigated with this study data.

There are different radiological measurement methods for LLD, FO and cup positioning after THA using different bony landmarks (Gurney et al 2002, Sabharwal et al 2008, Kjellberg et al 2009, Patel et al 20011, Merle et al 2013). These methods e.g. plain radiographs, orthoroentgenogram, CT scanogram and MRI have different diagnostic accuracy, cost effectiveness, radiation dose and time consumption (Gurney et al 2002, Sabharwal et al 2008). CT and MRI are more accurate than plain
radiographs (Kjellberg et al 2009, Lecerf et al 2009, Sariali et al 2009, Pasquier et al 2010, Kjellberg et al 2012). The associated high cost, radiation exposure and limited availability make their routine use impractical and limited to selected cases. Therefore, plain radiographs are routinely used.

For measurement of LLD we used the Woolson method (inter-teardrop-lesser trochanter distance). This was found to be as reliable as the orthoroentgenogram and gave improved correlation with full-leg radiographs compared to the bi-ischial-lesser trochanter distance (Woolson et al 1999, Konyves et al 2005, Meermans et al 2011). The teardrop points have previously been found to be vertically and rotationally constant despite altered pelvic tilting/rotation (Kjellberg et al 2012). This could minimize the effect of pelvic position in plain radiographs. In study III, we found a substantial interobserver reliability and excellent intraobserver reproducibility of this method among the observers (Table 6). Our results are in agreement with those reported in the literature (Patel et al 2011, Kjellberg et al 2012, McWilliams et al 2012, Wylde et al 2012). However, these studies were not actually designed to evaluate the reliability but rather the effect of LLD after THA. Furthermore, study III was adequately powered regarding the number of included patients and observers compared to previous studies. Also, all patients had unilateral osteoarthritis and this factor increased the accuracy of the LLD measurements, as the reference side is unaffected.

In this thesis the global FO was measured as the sum of femoral offset and cup offset. This combined measurement takes account of the changes caused by implant design and the positioning of the stem within the femoral canal as well as the changes in the acetabular center of rotation caused by cup implantation (Loughead et al 2005, Kurtz et al 2010). The latter was found to be an essential factor in restoring the FO in THA (Dastane et al 2011) and to affect the incidence of bony impingement more than the stem offset (Kurtz et al 2010). We have also showed that this method for measuring global FO has a good interobserver reliability and intraobserver reproducibility (Table 6). However, the use of multiple reference points (femoral axis, centre of the
femoral head and teardrop point) may increase the risk of erroneous measurement. Also, in some cases the degree of osteoarthritic changes and/or the peroperative acetabular reaming is so extensive that the teardrop point becomes difficult to localise. Therefore, we advocated a new method, the Sundsvall method, to measure the global femoral offset (Fig.5).

In a previous pilot study, the Sundsvall method had an excellent correlation with the CT scan and standard method. A limitation of the study was its small sample size. In study III, we found a strong agreement between the Sundsvall and standard methods for all three observers (Table 7). This indicates good validity of the Sundsvall method. Furthermore, the interobserver reliability and intraobserver reproducibility of both the Sundsvall and standard method were excellent (Table 6). Therefore, we propose that the Sundsvall method could replace the standard method in measuring global FO. In cases where the evaluation of cup positioning or cup offset is needed, the standard method should be used.

The precise positioning of the acetabular cup is a crucial part of the surgical technique of THA. A number of studies have shown correlation of acetabular cup positioning with THA outcome (Little et al 2009, Moskal et al 2011). Improper positioning can also give rise to bone-bone or implant-implant impingement and/or prosthetic instability (Malik et al 2007, Dudda et al 2010). In clinical practice, the pelvis AP view is used to determine the inclination angle of the cup, while the lateral view is used to measure the anteversion angle of the cup. The accuracy of these measurements has been criticised owing to the difficulty in standardising pelvic tilting and rotation during imaging. Therefore, a CT scan is recommended as the method of choice, especially for cup anteversion evaluation. The high cost and radiation dose of CT scans are some of the disadvantages associated with their use. Bearing in mind the large number of THAs performed each year, surgeons still use plain radiographs for this evaluation.
We measured the acetabular cup inclination angle (in degrees) between a line drawn along the rim of the cup and transischial line (Figure 8). Kalteis et al (2006) found that this method had a good validity and reliability when compared with CT scans. Others (Kalteis et al 2006, Park et al 2009, Patel et al 2011, Wylde et al 2012, Lu et al 2013) have evaluated the reliability of this method in different patient categories, e.g. primary OA, dysplastic hips and femoro-acetabular impingement (Clohisy et al 2009), and found it to be good to excellent. This agrees with the results of the present study.

On the other hand, we measured the acetabular cup anteversion on the lateral view according to the Woo and Morry method (Woo et al 1982) (Figure 9). The cup ante- or retroversion is calculated in relation to the horizontal plane, assuming that the pelvis is parallel to this plane. Nunley et al (2011), Nho et al (2012) and McArthur et al (2012) have shown that this method has good validity compared with CT scans. However, any pelvic rotation/tilting may affect the accuracy of this measurement, especially in patients with contralateral hip or spine disease. In the present study, the included patients had no contralateral hip disease, a factor that could decrease this bias. We found the interobserver reliability and intraobserver reproducibility of this method to be excellent among the observers (Table 6). This agrees with the results found by others (McArthur et al 2012, Nho et al 2012, Lu et al 2013).

Based on the findings of studies I and II, we chose to assess the site of leg lengthening ≥ 10 mm and global FO reduction > 5 mm in study IV. McWilliams et al (2012) has studied the reliability of four methods for measurement of LLD including the Woolson method (Woolson et al 1999), Willamson method (Williamson et al 1978), the transischial line-lesser trochnater, center of rotation of femoral head-lesser trochanter (CFR–LT) method and center of rotation of femoral head-teardrop-lesser trochnater (CFR–T–LT) method. It was found that all of them had a comparable inter and intraobserver reliability but the CFR–T–LT method had the advantage of being able to distinguish between LLD caused by cup position, stem position or both. This might help surgeons determine the site of LLD (stem, cup or both). Konyves et al (2005) used
the CFR–T–LT method in a study of the effect of LLD on hip function in 90 THA patients. They found that femoral stem positioning was associated with 82% of lengthening. This finding is in agreement with the results of study IV and this may indicate that cup positioning has no or minimal contribution to LLD after THA. Therefore, the measurement of cup length could possibly be omitted from the LLD measurement. Indeed, this omission is common in clinical practice.

We have used the standard method for global FO measurement. This method takes into account the changes caused by implant design and the valgus/varus positioning of the stem within the femoral canal as well as the changes of the acetabular center of rotation caused by cup implantation (Loughead et al 2005, Kurtz et al 2010). Dastane et al (2011) found that cup offset is an essential factor in restoring the global FO in THA and affects the incidence of bony impingement more than the stem offset (Kurtz et al 2010). This was in agreement with our results that also showed that a decreased FO > 5 mm was caused by malpositioning of both the femur stem and acetabular cup. The measurements included in study IV showed substantial to excellent interobserver reliability and intraobserver reproducibility and are therefore clinically useful (Tables 8-10).

Preoperative templating is an important factor for optimal implant positioning. It decreases postoperative LLD and improper global FO restoration. Templating allows the surgeon to calculate several vital parameters such as hip joint bone stock, component size, expected depth of seating of the femoral component within the femoral canal, position of the acetabular component, potential LLD and optimal level of proximal resection. The majority of patients in our study were templated with Mdesk™ digital templating system. Bertz et al (2012) showed that this system had a good validity and reliability compared with other templating systems used in clinical practice. Furthermore, intra-operative evaluation of LLD and FO restoration should be considered and practiced in THA surgery. This evaluation can include clinical tests, the use of anatomical landmarks, the use of intraoperative mechanical devices, radiological

All patients in our study were assessed with leg-to-leg comparison although the accuracy of this test is not adequately documented. Also, numerous intraoperative mechanical devices have been described. Perhaps the most commonly used is the pin method, which measures the distance between a fixed point in the iliac bone and greater trochanter. This distance is measured intraoperatively before and after the placement of trial implant components and adjusted according to the required leg length restoration measured preoperatively (McGee et al 1985, Woolson et al 1985, Bourne et al 2002, Takigami et al 2008). The position of the leg should however be identical before and after the placement of trial implant components to avoid erroneous measurements. Another modality for intraoperative LLD and FO is computer navigation. This technique has generally reported good to excellent accuracy (Murphy et al 2006, Murphy et al 2007, Kitada et al 2011) in spite of the influence of the surgeon’s experience on the achieved results.
6.1 Limitations and strengths

The studies in this thesis have a few limitations. Radiographic measurements made on the pelvic AP view are susceptible to error since horizontal dimensional parameters are influenced by variation in the positioning of the pelvis and the divergence of the X-ray beams (Rubin et al 1992, Lecerf et al 2009, Varghese et al 2011). Although a standardized positioning protocol was used for obtaining the radiographs, patient position remains a possible source of error. A CT scan is superior to a plain radiograph in measurement of LLD and FO. Plain radiographs might also underestimate the actual change compared with a CT scan. However, this underestimation should be negligible as we calculated the difference between the operated and the contralateral side. Furthermore, plain radiographs are the commonly used method to measure FO and LLD after THA in clinical practice owing to their availability and acceptable radiation exposure.

To evaluate the validity of the Sundsvall method, we compared the results with those obtained using the standard method on plain radiographs. To achieve a more precise evaluation of the validity of the Sundsvall method, comparison with a CT scan is desirable. However, the standard method is an appropriate method for the measurement of perioperative FO in THA and this comparison should give an indication about the validity of the Sundsvall method. Another limitation is the ceiling effect of the WOMAC index and EQ-5D questionnaire (Marx et al 2005, Garbuz et al 2006). This could mask some of the differences between patients with good outcome.

The above limitations are counterbalanced by the strengths of the study data, which is a prospective cohort with adequate sample size, consisting of patients with unilateral hip OA. The latter eliminates the risk of radiological and clinical measurement bias caused by the effect of eventual OA changes in the contralateral hip. Furthermore, the observer that made the radiological measurements and followed-up the patients was not involved in their management. We had preoperative hip function and QoL data
available. This allowed us to compare the preoperative status of the studied groups as well as to compare the preoperative with the postoperative hip function and QoL for the whole cohort as well as for each studied group per se.

The evaluation of hip abductor muscle strength was done by a valid method using an electronic dynamometer. The outcome instruments used (WOMAC index and EQ-5D questionnaire) have good validity and will allow comparison of our results with other studies. The observers who did the radiological measurements were from two different specialties and experiences. This would make the obtained results more generalizable and therefore applicable in routine clinical practice.
7. Conclusions

The functional outcome, QoL and health status of patients undergoing THA show a statistical and clinical improvement regardless of postoperative LLD up to 20 mm and global FO reduction > 5 mm. However, lengthening ≥ 10 mm was associated with more use of a shoe lift. Reduction of global FO > 5 mm compared to the contralateral hip was associated with weaker hip abductor muscles and more use of walking aids, and both should therefore be avoided. Furthermore, the plain radiographic measurement methods of LLD, global FO, cup inclination and anteversion have the required validity and reliability to be used in clinical practice. These measurements have shown that lengthening of the operated leg was mainly caused by improper placement of the femoral stem, whereas a decrease of global FO > 5 mm was caused by improper placement of both the acetabular and femoral components. Surgeons should be aware of these operative pitfalls in order to minimize component malpositioning.
8. Future implications

1. Further analysis of the included data is warranted to evaluate whether the total change in LLD and global FO between the preoperative and postoperative measurement affects functional outcome and QoL in a more apparent way compared with the postoperative measurements.

2. The influence of preoperative function and QoL and degree and duration of OA on postoperative outcome is an interesting issue. It can affect our decision about the timing of THA.

3. Measurement of THA component positioning using low-dose CT scan can provide meticulous evaluation with minimal radiological exposure. Validity and reliability studies of this new modality are needed.

4. The influence of body mass index (BMI) and surgical approach on leg length and FO restoration and component positioning is interesting to investigate. It will broaden our understanding of the factors affecting positioning.
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10. References


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11. Appendix

The Western Ontario and McMaster Universities Arthritis Index (WOMAC)

Smärta
Följande frågor rör den höftsmarta du eventuellt upplevt den senaste veckan. Ange graden av smarta du har kant i följande situationer.

1. Gå på jämnt underlag
   Ingen  Lätt  Måttlig  Svår  Mycket svår

2. Gå upp eller ner för trappor
   Ingen  Lätt  Måttlig  Svår  Mycket svår

3. Under natten i sängläge (smärta som stör sömnen)
   Ingen  Lätt  Måttlig  Svår  Mycket svår

4. Sittande eller liggande
   Ingen  Lätt  Måttlig  Svår  Mycket svår

5. Stående
   Ingen  Lätt  Måttlig  Svår  Mycket svår

Stelhet
Följande frågor rör ledstelhet (inte smarta). Stelhet innebar svårighet att komma igång eller ökat motstånd vid rörelser i höftleden. Ange graden av stelhet du har upplevt i din höft den senaste veckan.

1. Hur stel har din höft varit när du just har vaknat på morgonen?
   Ingen  Lätt  Måttlig  Svår  Mycket svår

2. Hur stel har din höft varit efter att du suttit eller legat och vilat
   Ingen  Lätt  Måttlig  Svår  Mycket svår
Fysisk funktion
Följande frågor rör din fysiska funktion. Ange graden av svårighet du har upplevt den senaste veckan vid följande aktiviteter på grund av dina höftbesvär.

<table>
<thead>
<tr>
<th>Aktivitet</th>
<th>Ingen</th>
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<td>4. Stå stilla</td>
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<td>5. Böja dig, tex för att plocka upp ett föremål från golvet</td>
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<td>6. Gå på jämt underlag</td>
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<td>7. Stiga i och ur bil</td>
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<td>9. Ta av strumpor</td>
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<td>10. Stiga ur sängen</td>
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<td>12. Ligga i sängen (vända dig, hålla höften i samma läge under lång tid)</td>
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<td>13. Stiga i och ur badkar/dusch</td>
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<td>14. Sitta</td>
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<td>15. Sätta dig och resa dig från toalettstol</td>
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<td>16. Utföra tungt hushållsarbete (snöskottning, golvtvätt, damsugning etc)</td>
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<td>17. Utföra lätt hushållsarbete (matlagning, damning etc)</td>
<td>Ingen</td>
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<td>Mycket svår</td>
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Formulär EQ-5D

Rörlighet
1. Jag går utan svårigheter
2. Jag kan gå men med viss svårighet
3. Jag är sängliggande

Hygien
1. Jag behöver ingen hjälp med min dagliga hygien, mat eller påklädnings
2. Jag har vissa problem att tvätta eller klä mig själv
3. Jag kan inte tvätta eller klä mig själv

Huvudsakliga aktiviteter (t ex arbete, studier, hushållssysslor, familje- och fritidsaktiviteter)
1. Jag klarar av mina huvudsakliga aktiviteter
2. Jag har vissa problem med att klara av mina huvudsakliga aktiviteter
3. Jag klarar inte av mina huvudsakliga aktiviteter

Smärtor/besvär
1. Jag har varken smärtor eller besvär
2. Jag har måttliga smärtor eller besvär
3. Jag har svåra smärtor eller besvär

Oro/nedstämdhet
1. Jag är inte orolig eller nedstämd
2. Jag är orolig eller nedstämd i viss utsträckning
3. Jag är i högsta grad orolig eller nedstämd

Generellt hälsotillstånd
Ditt bästa tänkbara hälsotillstånd markerats med 100 och Ditt sämsta tänkbara hälsotillstånd med 0.
Vi vill att Du på denna skala markerar hur bra eller dåligt Ditt hälsotillstånd är, som Du själv bedömer det. Gör detta genom att dra en linje från nedanstående ruta till den punkt på skalan som markerar hur bra eller dåligt Ditt nuvarande hälsotillstånd är.

0---------------------------------50---------------------------------100
Questionnaire about additional Residual Problems

- Hur länge fick du använda gånghjälpmedel(t ex käpp,kryckor,rollator ....ect) efter operation?
  a) Några vekor
  b) Mindre än 3månader
  c) Mer än 3månader

- Har du haft problem med skillnad i benlängden efter operation?
  a) Nej
  b) Ja, men det gick över
  c) Ja, har fortfarande det problemet

- Om du haft problem med benlängdsskillnad, har du använd skoinlägg eller liknande?
  a) Nej
  b) Ja, men slutade med det
  c) Ja, har det fortfarande

- Har du fortfarande smärtor eller besvär kvar i eller runt den opererade höften?
  a) Nej
  b) Ja, smärtan/besvär ligger i ljusken/låret
  c) Ja, smärtan/besvär ligger på utsidan av höften
  d) Ja, smärtan/besvär ligger i skinkan

- Äter du fortfarande smärtlindande tabletter för höftsmärtan?
  a) Nej
  b) Ja, bara ibland
  c) Ja, regelbundet