Osteoarthritis of the Hip and Uncemented Total Hip Arthroplasty

Effects of Immediate Weight Bearing on Implant Stability, Bone Mineral Density, and Body Composition.

OLOF WOLF
Abstract

The initial recommendation for the postoperative regime after uncemented total hip arthroplasty (THA) was 6-12 weeks of partial weight bearing (PWB) to obtain a stable implant position during bone ingrowth. In recent years patients with uncemented THA have increasingly practiced full weight bearing (FWB) after surgery, which has largely been based on clinical experience rather than on scientific evidence. The aim of this thesis was to investigate the effects of FWB versus PWB for 3 months on the stability of the implants and on bone mineral density (BMD), as well as body composition (BC) of the lower extremities.

We used radiostereometric analysis (RSA) to measure implant micromotion and dual X-ray absorptiometry (DXA) to measure BMD and BC. Forty-six patients with strictly unilateral osteoarthritis of the hip (OAH) received uncemented THA. These patients were then randomized to the FWB or PWB groups and followed for 5 years.

In a preoperative cross-sectional study the BMD of the hip and heel were compared between the OAH-affected side and the healthy side. The study showed an increase of BMD at the femoral neck and a decrease at the total hip and trochanter. The results of a RSA study of cup stability showed that there might be minimal movement in medial and proximal directions during the first postoperative week. These results indicate that the RSA baseline investigation of uncemented cups should be performed as early as possible after the first postoperative day. FWB had no adverse effects on the stability of the uncemented press-fit cups or the uncemented cementless Spotorno (CLS) femoral stems after a 5-year follow-up. There was no difference in periprosthetic BMD around the CLS stem regardless of the postoperative weight bearing regime. All zones around the femoral stem indicated a recovery in BMD toward baselines, except the calcar region, which showed progressive loss in BMD to -22% at 5 years post-surgery. FWB had no effect on the changes in BC after surgery.

In conclusion, FWB is safe in uncemented THA in terms of stability, BMD and BC. Furthermore, THA apparently counteracts age-related changes in BC but not in BMD.

Keywords: Osteoarthritis of the hip, uncemented, total hip arthroplasty, stability, RSA, BMD, DXA, body composition, weight bearing

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ISSN 1651-6206
urn:nbn:se:uu:diva-131092 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-131092)
To Ninna,
and our wonderful children

Clara, Elsa, and Max

Pain is temporary
Glory is forever
List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I  Wolf, O., Ström, H., Milbrink, J., Larsson, S., Mallmin, H. Differences in hip bone mineral density may explain the hip fracture pattern in osteoarthritic hips. *Acta Orthopaedica*; 2009; 80(3):308–313


III Wolf, O., Mattsson, P., Milbrink, J., Larsson, S., Mallmin, H. Effects of different weight bearing regimes on stability of press fit cups. A randomized study with 5 years of follow-up using radiostereometry. *Submitted*


V Wolf, O., Mattsson, P., Milbrink, J., Larsson, S., Mallmin, H. Effects of postoperative weight bearing on body composition and bone mineral density of the legs after uncemented unilateral total hip arthroplasty. A randomized study with 5 years of follow-up. *Manuscript*

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### Abbreviations

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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>BMC</td>
<td>Bone mineral content</td>
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<tr>
<td>BMD</td>
<td>Bone mineral density</td>
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<tr>
<td>CI</td>
<td>Confidence interval</td>
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<tr>
<td>CLS</td>
<td>Cementless Spotorno (femoral stem)</td>
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<tr>
<td>CN</td>
<td>Condition number</td>
</tr>
<tr>
<td>DXA</td>
<td>Dual X-ray absorptiometry</td>
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<tr>
<td>EBRA</td>
<td>Ein-Bild-Roentgen-Analyse</td>
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<td>FM</td>
<td>Fat mass</td>
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<td>FN</td>
<td>Femoral neck</td>
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<tr>
<td>FWB</td>
<td>Full weight bearing</td>
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<tr>
<td>HA</td>
<td>Hydroxyapatite</td>
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<td>LM</td>
<td>Lean mass</td>
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<td>OAH</td>
<td>Osteoarthritis of the hip</td>
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<td>PWB</td>
<td>Partial weight bearing</td>
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<tr>
<td>QCT</td>
<td>Quantitative computed tomography</td>
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<tr>
<td>QoL</td>
<td>Quality of life</td>
</tr>
<tr>
<td>PMMA</td>
<td>Polymethylmetaacrylate (bone cement)</td>
</tr>
<tr>
<td>RCT</td>
<td>Randomized controlled trial</td>
</tr>
<tr>
<td>ROI</td>
<td>Regions of interest (regional DXA analysis)</td>
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<tr>
<td>RSA</td>
<td>Radiostereometric analysis</td>
</tr>
<tr>
<td>TB</td>
<td>Total body</td>
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<tr>
<td>TH</td>
<td>Total hip</td>
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<td>THA</td>
<td>Total hip arthroplasty</td>
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<td>TR</td>
<td>Trochanter</td>
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Introduction

This thesis has focused on the effect of weight bearing on implant stability, bone mineral density (BMD), and body composition for patients with unilateral osteoarthritis of the hip (OAH) treated with uncemented total hip arthroplasty.

Osteoarthritis of the hip

Osteoarthritis is a disease affecting the joint cartilage and subchondral bone (Figure 1). The disease is now considered to involve the entire joint, including ligamentous and muscular changes, as well as synovial inflammation. Patients describe symptoms that include joint pain, stiffness, and decreased range of motion. The prevalence of OAH is highest in the age group older than 85 years, with 10% of patients in this age group having the disease. Not all patients with early radiographic OAH present symptoms. Moreover, symptoms come and go in a cyclic pattern. OAH is equally common in both sexes and is bilateral in one third of the cases. The first line of treatment consists of patient education, analgesics, weight loss, and physiotherapy. Although there are surgical options, such as osteotomies and arthrodesis, the ultimate contemporary surgical solution for severe OAH is total hip arthroplasty (THA). THA results in pain relief, functional recovery, and improved quality of life (QoL), often within 3 months after surgery. Since 1979, almost 300000 primary THAs have been performed in Sweden (9 million inhabitants) according to the annual report 2008 from the Swedish Hip Arthroplasty Register. As a curiosity, there were six reported THAs in 1967. More than 180000 of these operations have been performed during the past 15 years. Cemented THA is still more common, but uncemented THA is gaining in popularity. In 2008, about 20% of the stems and 15% of the cups were uncemented. In total, 14451 primary THAs were performed in 2008. About 1800 were uncemented THAs, about 1400 were reversed hybrids with an uncemented femoral stem, and about 200 were hybrid THAs with an uncemented cup. The annual incidence of THA per 100000 in the Nordic countries varied between 217 (Finland) and 309 (Iceland) in the age group 50-89 years in 1996-2000. Since 2005, more than 80% of all primary THAs in Sweden were operated because of primary OAH. Fractures, the vast majority being femoral neck fractures, are the cause in 10% of the
cases. The effectiveness of the new pharmaceutical drugs against inflammatory joint diseases is documented in the decreasing part of THAs because of this diagnosis ⁵.

![Figure 1. Preoperative X-ray of pelvis with right-sided osteoarthritis of the hip (OAH) (left). Note the difference in rotation is demonstrated by the visualization of the lesser trochanter on the OAH side.](image)

**Total hip arthroplasty**

**History**

At the end of the 1880s, the first described prosthetic procedures by Themistocles Gluck were performed ⁶¹. He used ivory to construct the prosthetic parts of a hinged knee prosthesis to replace a tuberculous knee in a 17-year-old female ⁶¹. Jules Emile Péan used rubber and platinum in shoulder prosthesis in the 1890s ¹³².

The materials and methods changed during the first half of the 20th century. Marius Nygard Smith-Petersen introduced mould arthroplasty in 1923¹⁴⁹, first with molds of glass, and in 1938 with molds of vitallium.

The design and fixation of prostheses, as well as materials, evolved during the mid 20th century. Philip Wiles introduced a stainless steel prosthesis
fixated through the femoral neck and attached to the lateral part of the femur with plate and screws and an acetabular component screwed into the pelvis in patients with juvenile rheumatoid arthritis \(^\text{180}\). In the 1940s, Austin-Moore \(^\text{116}\) and Thompson \(^\text{167}\) independently introduced hemiarthroplasties made of vitallium with an intramedullary stem.

In 1946, polymethylmetaacrylate (PMMA) was used by the Judet brothers, Robert and Jean, when they replaced the femoral head with a knob of PMMA attached to the femoral neck by a slim stem \(^\text{88}\). In the 1950s, McKee introduced metal on metal arthroplasties \(^\text{111}\), which later were modified in collaboration with Watson-Ferrar \(^\text{112}\). Clinical results from these early arthroplasties were sometimes good; however, there were serious causes of THA failure, including loosening, implant failure, and short-term satisfaction.

The modern era of arthroplasty may be traced to John Charnley of Wrightington, Manchester, England in the 1960s. He initially used PMMA to secure Moore stems and Teflon cups \(^\text{47}\). The aim of striving toward better outcomes resulted in the introduction of more resistant, high-density polyethylene cups \(^\text{48}\). Stem designs and concepts further evolved. Major initial problems concerned the infection rate, aseptic loosening, osteolyses, and bone resorption because of debris particles.

### Uncemented THA

Because of initial problems involving the loosening of cemented implants, Judet and Lord experimented in the early 1970s with other modes of fixation. Stable implants were achieved by bone ingrowth, either into a porous metal surface \(^\text{89}\) or into a rough irregular surface made by casting of a multitude of tiny balls to the surface \(^\text{102}\). Porous coatings of cobalt-chrome, stainless steel, and titanium were introduced, with all showing signs of bone ingrowth \(^\text{66, 134}\). Initial stability, adequate pore size, thickness of surface layer, and gap between bone and implant were all requisites for bone ingrowth \(^\text{33, 34, 44, 103, 134}\). Although polymers were also tested as surface material, they did not show bone ingrowth but showed instead a rather fibrous fixation with less biomechanical strength \(^\text{122, 154, 169}\). Fibrous fixation was also seen around implants without good initial stability \(^\text{135, 152}\). To better predict bone ingrowth and to produce a better initial stability materials acting more like bone, i.e. calcium phosphates, were introduced as surface material on hip implants in the 1980s \(^\text{64, 67, 126}\). Hydroxyapatite (HA), being one of these new materials, showed better bone ingrowth that could overcome larger bone-to-implant gaps \(^\text{151}\). HA-coated implants showed a better and faster fixation than non-coated uncemented implants \(^\text{152}\). Two kinds of common complications with these early implants were noted. First, osteolyses was observed in non circumferential coated implants, which is due to joint fluid and debris entering the medullary canal \(^\text{165}\). Second, proximal
periprosthetic osteolyses was found because of loading only of the distal periprosthetic bone in the early fully coated stems 56, 58, 83.

Cobalt-chromium and titanium are the most frequent used materials. Bone ingrowth occurs into the porous surface of both materials 11, 43. Titanium has no adverse effects on tissue, is not known as a carcinogen, and allows for direct bonding with bone 11, 43, 136.

Contemporary designs include press-fit stems with 25 and without 155 proximal coating. The fully porous coated metal cancellous cementless Lübeck prosthesis showed distal fixation with proximal stress-shielding 74. The press-fit collarless CLS has a three-dimensional taper design and ribs for increased rotational stability. The tip of the stem is slim in order not to fill the diaphysis, which would prevent stress-shielding 155. The CLS is a grit-blasted titanium stem and has no porous coating 155. To better preserve the proximal bone stock newer designs with a shorter stem (or no stem at all) are being evaluated, but no long-term data exist 68, 142.

The type of and degree of coating varies 59. The proximal 30% of the Bi-Metric stem is porous-coated and HA-sprayed in order to have the coated region extend into the proximal cortical region of the femur 7. The adding of HA-tricalcium phosphate coating on the titanium proximally porous coated Multilock femur stem resulted in a lower loss of proximal BMD 163. The ABG-I prosthesis is proximally HA-coated 25. The ABG-II prosthesis has an undersized and even shorter distal part to prevent distal bonding 15. HA-coated stems in combination with a tapered design increase the femoral fixation and result in less stress-shielding and better proximal remodeling of bone 46, 105. However, HA coating was found to be a risk factor (RR 1.7) for aseptic loosening in acetabular cups in a recent registry study 100.

**Stress-shielding**

The load put on the leg while weight bearing is transferred over the joint to the femoral implant and further transferred to the femoral bone. This event, according to Wolff’s law, will lead to adaptive bone remodeling depending on the type of fixation used to hold the implant in place 183.

Distally fixated stems transfer excessive load distally, bypassing the proximal part and potentially leading to loss of proximal bone mass 74. The change to coating of the proximal part of the stem is intended to overcome this mechanism of disuse of the proximal femur 32. Proximal coated stems showed less stress-shielding than fully ingrown stems and more than cemented stems, but still calcar stress-shielding is a matter of concern 82.

The stiffness of the material is of importance for longevity. Titanium stems are more flexible (have a lower mode of elasticity) than cobalt-chromium and thus can transfer stress more optimally, resulting in less cortical bone loss 43, 136.

Signs of stress-shielding include calcar resorption, calcar round-off, and distal cortical hypertrophy 10, 57. Many studies have shown proximal pe-
riprosthetic bone loss, with a decrease of about 20% 1 year after surgery. The calcar bone loss continues progressively up to 14 years with the Bi-Metric and up to 10 years with the ABG-I prosthesis.

Design and fixation are crucial for bone preservation, as illustrated by the change in design introduced in the ABG-II prosthesis (a slight anterioposterior metaphyseal flare and a shorter and slimmer distal part), which resulted in a lower loss of BMD in the proximal femur. Minimizing the inevitable stress-shielding in uncemented THA is the keystone in preserving the bone stock of the proximal femur and in facilitating a possible future revision.

Postoperative rehabilitation and weight bearing

The original postoperative regime with the Thompson hemiarthroplasty (implanted uncemented) was 9 months with crutches. Later, Charnley proposed using a cane for 4 weeks after surgery in order not to avulse the attached trochanter, but full weight bearing was allowed. For the past decades, full postoperative weight bearing in cemented arthroplasties has been clinical praxis at several centers, although without supporting scientific evidence.

For uncemented THA, Lord reported full weight bearing on the sixth or seventh postoperative day in the madreporique arthroplasty. Four to 6 weeks of partial weight bearing (PWB) were recommended for the first HA-coated implants. Woolson et al. found no adverse clinical or radiographic effects of full weight bearing (FWB) when compared with PWB in a consecutive series of patients receiving a porous-coated stem. Contrary to this finding, Rao et al. found significantly more subsidence, but equal clinical scores, in the FWB group in a study with the half porous-coated Taperloc stem without a collar. However, none of these studies was randomized.

Standard postoperative rehabilitation programs do not really exist as a result of clinical trials but rather as a result of clinical experience. A survey to orthopedic surgeons in the U.S. in 2005 about postoperative rehabilitation showed that cemented THAs are recommended to perform FWB at 4 weeks versus 6 weeks for uncemented THAs. However, this was the personal recommendation from the surgeons answering the survey and not based on any clinical trials. In a randomized controlled trial (RCT) of 80 patients with a THA physiotherapy combined with 10-day postoperative treadmill training with partial body weight restored independent walking better than physiotherapy alone. In addition, patients with additional resistance training of the quadriceps three times a week for 12 weeks had an increased muscle mass and strength, as well as shorter length of hospital stay than patients with only the standard at-home 1 hour/ day physiotherapy program. Surprisingly, a 6-week arm exercise program with an ergometer showed longer walking distance and a better clinical score 1 year after surgery.
To limit postoperative weight bearing is difficult. PWB in trials usually allows loads between 15 and 30 kg on the operated leg. Several techniques to limit or measure weight bearing exist. Since patients with uncemented implants seemed to do well even if they did not perform PWB as the surgeon told them, the question of immediate FWB postoperatively has been a growing issue for the past decade.

In the past years randomized controlled trials of controlled weight bearing after THA and radiostereometric analysis (RSA) to study micromotion have been published. No adverse effect of FWB after THA was seen for either of the two uncemented stems up to 1 and 2 years after the operation. Thien et al. used a sole that, after calibration, gave auditory feedback when exceeding or reaching the calibrated load. Another study used the same technique but studied subsidence on radiographs and concluded there was no evidence of an adverse effect of FWB. This technique of limiting weight bearing is easy to use as long as the shoe is on the foot, but gives no exact measurement of the actual load. There is also a technique where the soles measure the actual load put on each step, but this technique gives no feedback. Two studies showed that patients have difficulties complying to weight bearing of 10% of body weight or 15 kg, but that they limit their weight bearing compared with groups of FWB.

In a recent review by Hol et al. the evidence-based recommendation for postoperative rehabilitation after an uncemented stem in THA was full immediate weight bearing. The majority of the supporting studies had used RSA to measure subsidence of the femoral stem. The focus of the rehabilitation should be a symmetrical and limp-free gait pattern. This pattern can be achieved by the use of crutches, or a cane for shorter distances at home, as well as treadmill training to activate the right muscle groups. Caution should be taken with stair climbing during the first postoperative weeks.

Bone densitometry

Historical methods include single-photon absorptiometry (SPA) and dual-photon absorptiometry (DPA).

Dual X-ray absorptiometry

The change of energy source to X-ray led to faster and more accurate values with dual X-ray absorptiometry (DXA). The beam from X-ray tubes spans a wide range of photon energies and modification of the beam is done to produce the two photoelectric peaks necessary to separate bone from soft tissue and to allow the separation of fat from lean tissue. The precision of DXA is superior to that of DPA. The radiation dose is extremely low, 1-5 μSv for a
DXA scan of the proximal hip or lumbar spine. The areal BMD is reported as g/cm².

The World Health Organization definition of osteoporosis is based on a gender-specific T-score of -2.5 or below using DXA. The T-score is expressed relative to a healthy reference population of young adults. The age- and gender-matched Z-score is more appropriate for comparisons between younger age groups. DXA is mainly used for diagnosing osteoporosis, assessing the risk of fracture, and monitoring the response to treatment in trials. The most common sites of measurement are the lumbar spine and hip. It is also possible to measure peripheral sites, such as the heel or distal radius or even bone surrounding hip implants.

Bone mineral density

DXA-derived BMD is used in clinical praxis to diagnose osteoporosis. Two meta-analyses have shown that a decrease in BMD can predict the risk of future fractures. Perimenopausal women in the lowest quartile of hip BMD showed a 2.2 higher risk of any fracture than perimenopausal women in the highest quartile. In 80-year-old women each SD decrease in hip BMD increased the risk of hip fracture by 2-2.4, and 1.8-2.6 times when adjusted for age, weight, and participating center. The relative risk of a hip fracture is 2.6 and the risk of any fracture is 1.6 for each SD decrease in hip BMD. For vertebral fracture, it is 2.3 for each SD decrease in spine BMD. The risk gradient (relative risk/SD decrease in BMD) of hip fracture is age dependent with a gradient of 3.7 at 50 years and 1.9 at 85 years. Positioning of the patient and rotation of the hip can influence the measurement. To obtain reliable and accurate measurements it is necessary to use reproducible standard positions and control the rotation of the hip.

Quantitative computed tomography

Quantitative computed tomography (QCT) is a technique that provides a full three-dimensional measurement of the bone. Bone mineral density is measured as g/cm³. QCT allows for a volumetric measurement of bone, lean mass, and fat mass. It separates cortical and trabecular bone.

DXA versus QCT

DXA gives an areal BMD and is size dependent; QCT gives a volumetric BMD and is not dependent on the size of the bone. QCT can separate cortical from trabecular bone and QCT-derived measures, such as lower percent cortical volume, smaller minimal cross-sectional area, and lower trabecular BMD are independently correlated to increased hip fracture risk. Because
of the ability to monitor the trabecular microstructure, QCT provides a possibility for monitoring changes in bone structure in response to pharmacological interventions.\textsuperscript{118}

As mentioned previously, the diagnosis of osteoporosis is based on DXA\textsuperscript{1}. All large prospective epidemiological studies of osteoporosis and fracture risk assessment are based on DXA, i.e. all reference data are DXA based\textsuperscript{50,78}. Moreover, all interventional studies of pharmaceuticals (phase I, II, and III) have had DXA included in the study protocol (e.g., alendronate\textsuperscript{28}, zoledronic acid\textsuperscript{29}, risedronate\textsuperscript{141}, and raloxifene)\textsuperscript{60}. So, at present DXA is the gold standard for fracture prediction and has the ability to identify patients who will respond to anti-fracture treatment\textsuperscript{30}.

A comparison study of hip structural analysis from DXA images and volumetric QCT measurements concluded that DXA might derive valid geometrical measurements of the proximal hip\textsuperscript{137}. The two-component limitation of DXA (separating two tissues) is argued by Bolotin to lead to inconsistencies in \textit{in vivo} measurements of BMD as compared with \textit{in vitro}, where there are not different surrounding soft tissues in the region of interest\textsuperscript{37}. However, volumetric QCT measurements might also be misleading because of alteration in bone marrow composition.

The radiation of QCT is considerably higher than that of DXA. Three-dimensional QCT of central sites, such as the hip (~2.5-3 mSv) or the spine (~1.5 mSv), have similar radiation as the yearly background radiation (UK, 2.7 mSv) and is acceptable in patients\textsuperscript{6}, whereas DXA exposes the patients to 1-5 \textmu Sv for the same scans. Peripheral QCT has negligible radiation and thus can be used in normal subjects to study growth of the skeleton.

Body composition

Total body (TB) scans with DXA, in addition to quantify the bone mineral content (BMC), allow for measurement of fat mass (FM) and lean mass (LM) in the TB or selected regions. Lean mass quantifies the muscle mass in the selected area. QCT measures soft tissues as volumes.

Other techniques can assess body composition indirectly from derived fat mass and fat free mass using mathematical calculations. Bioelectrical impedance assessment shows significant correlations to DXA in assessing body composition but may overestimate BMC\textsuperscript{65}. In addition, bioelectrical impedance assessment may encounter technical problems in severely obese patients (a BMI > 35 kg/m\textsuperscript{2})\textsuperscript{38}. Underwater weighing (or hydro densitometry), TB potassium counting, and anthropometry (skinfold and circumference measurements) are other techniques used\textsuperscript{22}. Whole body magnetic resonance imaging is a non-ionizing technique and can accurately assess body fat in different compartments, but its use in body composition measurements is still limited because of accessibility\textsuperscript{49}.
However, in the clinical setting DXA-derived body composition has become the gold standard because of its excellent accuracy and precision, fast acquisition, comfort level, non-invasive, low radiation, and good availability. Furthermore, it allows for regional analysis of different anatomical sites (Figure 2).

![Figure 2. Total body (TB) dual X-ray absorptiometry (DXA) scan with manually adjusted regions](image)

**Implant stability**

**Radiostereometric analysis**

Roentgen stereophotogrammetry is based on radiographic examinations of calibration cages and object markers implanted in the skeleton. Accurate measurements of radiographs and computer-assisted calculations can provide a three-dimensional motion analysis. *Kärrholm, 1989*<sup>97</sup>

Radiostereometric analysis, initially called roentgen stereophotogrammetric analysis<sup>146</sup>, is a high precision technique enabling measurements of three-dimensional movements between two segments. Introduced more than 35 years ago by Selvik, RSA has been widely used in orthopedic research (e.g., in assessing THA<sup>99</sup>, movement of the talocrural joint<sup>104</sup>, stability of femo-
ral neck fractures, spine surgery, elbow prostheses, and cruciate ligaments). In 1979, Baldursson et al. introduced this technique to evaluate joint prosthesis.

The RSA technique is based on implantation of small spherical markers (diameter 0.5, 0.8, or 1.0 mm) of tantalum (atomic number 73) on implant (e.g., femoral stem, cup, or cruciate ligament) and surrounding bone (e.g., femur, acetabulum, or tibia). No complications of the implanted tantalum markers have been documented. However, there has been one reported case of chronic urticaria 10 months after implantation of tantalum staples during femoral vein stripping.

To study movement in hip arthroplasty the patient is placed supine on the examination table and two ceiling mounted X-ray tubes, angled 40º to each other, are simultaneously exposed. A calibration cage, which differs in appearance depending on which investigation is being done, is placed beneath the examination table. After this, the tantalum markers are numbered in a preplanned fashion, which nowadays is made digitally, but was formerly performed manually.

The RSA calculation software then uses the two-dimensional values from the X-rays to calculate the three-dimensional position of the tantalum markers by using the calibration cage markers as references. At each examination, each segment’s position in relation to the calibration cage (absolute motion) is measured along (translation) and around (rotation) the X-, Y-, and Z-axis. Therefore, changes in position between subsequent examinations will be described three-dimensionally as translations and rotations along and around these three axes (Figure 3).

![Figure 3](image.png)

Figure 3. Radiostereometric analysis enables the measurement of motion along three axes, as well as rotation around these axes.

Loose markers, inadequately visualized markers because of, e.g., hindering metal, or incorrect identification of markers will all lead to measurement errors. The three-dimensional distribution of markers in each segment, i.e.
the rigid body, is compared between examinations and measured as mean error of rigid body fitting \(^{97, 146}\). Further, the distribution of markers in the investigated implant or bone, i.e. scattering, is important. The condition number (CN) describes how well scattered the markers are in each segment \(^{188}\). A low CN indicates a good scatter of markers, whereas a high CN indicates markers close to each other or on a straight line.

After the absolute motions are known, RSA software enables calculation of the relative motions of the implant measured. Thus, movement over time of the implant (e.g., subsidence or rotation of the femoral stem) in THA, wear of the plastic insert in total knee arthroplasty, or wear of the polyethylene in the cup (movement between femoral head and cup) can be measured. Depending on type of implants being evaluated, one can measure movements of individual markers, the center of the femoral head, a reconstructed point on radiographs, or the center of gravity in the rigid body. To compare movements of individual implants the point used should always be stated. In THA the center of gravity of the rigid body is often used and the femoral stem is often marked by the manufacturer in a standardized pattern.

Other techniques

Ordinary radiographs have been used to measure subsidence \(^{184}\). Several software systems have been combined with X-rays to increase the accuracy e.g. Ein-Bild-Roentgen-Analyse (EBRA) \(^{26}\), AccuGrid \(^{140}\), and UMA \(^{54}\). Moreover, CT and software using volume merging allows for assessing migration \(^{123}\).

Precision and accuracy

The precision of the RSA study setting is calculated as the difference in the three-dimensional position of the rigid body between double examinations on the same day, preferably after repositioning of the patient. The precision is determined individually for each translation and rotation around the three axes. Typically, the precision for subsidence is 0.1-0.2 mm. The accuracy of RSA can be 10-250 \(\mu\)m and 0.03-0.6 ° \(^{97}\) as compared with the specific radiographic software (AccuGrid) accuracy of 0.25 mm used in the study by Rao et al. \(^{140}\), 1.5 mm for EBRA \(^{26}\), and 2.5 mm for UMA \(^{54}\). In a comparison of conventional radiographs to RSA the accuracy of detecting subsidence on radiographs was found to be from 4 mm to more than 1 cm \(^{108}\). The accuracy for the semi-automated software in combination with CT was 1 mm in cup translation \(^{123}\). The precision of cup translations is 0.1-0.3 mm and 0.4-0.8 ° \(^{143, 144}\). The accuracy or precision of RSA varies between different laboratories and depends on various factors, including the laboratory used, the calibration, and the number and distribution of markers \(^{97}\).
SF-36

Standardized questionnaires have long been used to evaluate the patient’s view of health and life. The Short Form-36 (SF-36) was developed to provide a short alternative that with eight scales would represent the patient’s well-being in different dimensions. There is a validated Swedish translation of SF-36, which makes the use in research purposes easier. The scales include evaluation of physical functioning, role limitation because of physical problems, bodily pain, general health perceptions, vitality, social functioning, role limitations due to emotional problems, and mental health (Table 1). The answers to the questions were transformed into a scale from 0 (worst possible state) to 100 (best possible state) for all SF-36 scales.

Table 1. The eight dimensions of the short form-36 (SF-36) along with their common abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF</td>
<td>Physical functioning</td>
</tr>
<tr>
<td>RP</td>
<td>Role physical</td>
</tr>
<tr>
<td>BP</td>
<td>Bodily pain</td>
</tr>
<tr>
<td>GH</td>
<td>General health</td>
</tr>
<tr>
<td>VT</td>
<td>Vitality</td>
</tr>
<tr>
<td>SF</td>
<td>Social functioning</td>
</tr>
<tr>
<td>RE</td>
<td>Role emotional</td>
</tr>
<tr>
<td>MH</td>
<td>Mental health</td>
</tr>
</tbody>
</table>
Aims

The general aim of this thesis was to evaluate the effect of full postoperative weight bearing in comparison with PWB on uncemented THA. We used RSA to assess the stability of the implants and DXA to examine BMD, BMC, FM, and LM.

The specific aims of the papers were:

I To evaluate the influence of unilateral OAH on BMD of the proximal femur, BMD at the heels, and body composition of the lower limb.

II To measure the possible migration of uncemented acetabular cups during the first week after surgery.

III To determine whether immediate FWB compared with PWB affects the stability of acetabular press fit cups over a 5-year period. To analyze the pattern of micromotion of uncemented press fit cups over 5 years.

IV To determine whether immediate FWB compared with PWB affects the periprosthetic BMD or the implant stability over a 5-year perspective.

V To investigate the influence of immediate FWB compared with PWB on the body composition of the lower extremities and on the BMD of the heels. Another aim was to examine the BMD of the unaffected contralateral hip and the change in TB composition and weight for 5 years after unilateral THA.
Patients and Methods

Study population

Forty-five patients (Figure 4) were included in a randomized controlled study with the primary inclusion criteria of unilateral OAH (Figure 5). After scrutinizing the patient charts, two patients were found with avascular necrosis of the femoral head, one after surgical treatment of a femoral neck fracture, and one after cortisone treatment for lymphoma. Three patients underwent surgery on the contralateral hip within the follow-up period of 5 years (3, 6, and 38 months postoperatively). These patients were excluded because of our aim to follow-up unilateral OAH.
In total, 40 patients met the inclusion criteria set up for the initial study. One of these patients received a cemented femoral stem because of an intra-operative decision by the surgeon and was only included in the first study. One patient died within 3 months postoperatively because of pulmonary embolism and was only included in the first study. One patient (randomized to PWB), additional to the initial 45 patients, took part only in the RSA examinations and was included in Study II and III.

Study I
Forty patients (20 men) with unilateral OAH from the initial group were eligible for this study. Their mean age was 55 (SD±8.8) years, mean weight 80 (SD±13) kg, and mean length 172 (SD±8.8) cm.

To control the influence of rotation on hip BMD 21 patients (five men, 42 proximal femurs in total) were included from a first routine visit to the Uppsala Osteoporosis Unit. Their mean age was 64 (SD±12) years, mean weight 72 (SD±14) kg, and mean height 167 (SD±9.9) cm.

Study II
Twenty-eight of the 41 patients (one with RSA only) with unilateral OAH underwent RSA examination within 1 hour after skin closure. For the purpose of increasing the study population in this early RSA study, we included the two patients with avascular necrosis. Thus, 30 patients were analyzed.

After exclusions, the study group consisted of 24 patients (14 men) with a mean age of 54.1 (SD±9) years, a mean weight of 79.9 (SD±12) kg and a mean height of 172.7 (SD±10) cm.

Study III
From the initial 41 patients (one with only RSA), one died, one received a cemented implant, one received an unmarked cup and one received a Tril-
ogy cup. Seven of the remaining 37 patients could not be analyzed by RSA because of technical problems.

Hence, 30 patients (14 men) with either Interop (n= 13) or Allofit (n= 17) cups were followed for 5 years. Their mean age was 54 (SD±10) years, mean weight 79 (SD±14) kg, and mean height 171 (SD±9) cm.

Study IV
Thirty-eight patients (20 men) with a mean age of 54 (SD±9) years, mean weight of 80 (SD±13) kg, and mean length of 172 (SD±9) cm were followed for 5 years to evaluate the periprosthetic BMD and stability of the stem.

Study V
Body composition and DXA measurements were performed on 38 patients. Two patients were excluded from the initial 40 patients: one died postoperatively and one received a cemented implant. For demographics, see Study IV.

The implants
All patients received the uncemented CLS stem (Figure 6). The CLS stem is a collarless straight titanium alloy available in 13 sizes. It is designed as a three-dimensional taper with a trapezoidal cross-section for press-fit implantation and with anterior and posterior ribs for increased rotational stability. The design as a press-fit stem is thought to avoid stress-shielding by proximal load transfer to the femur. The CLS stem is by far the most common uncemented femoral stem in Sweden. In 2008, the CLS stem was used in 8.7% of all primary THAs (cemented, hybrids, and uncemented) in Sweden according to the annual report from the Swedish Hip Registry. Survival of the CLS stem at 17 years was 88% and survival with aseptic loosening as endpoint was 94% in 257 hips evaluated in a retrospective review of 354 hips. Another 17-year follow-up of 70 (80 hips) out of 94 consecutive patients (107 hips) with the CLS stem reported a stem survival of 98.8% for revision for any reason. If considering all patients lost to follow-up as failures, the 17-year survival would still be 84%.
The initial study included the uncemented Interop cup (Figure 7) that includes a hemispherical porous shell with sealed screw holes. For reasons of manufacturing problems with oil-contaminated shells, this product was withdrawn from the market. In total, 19 Interop cups were used. The withdrawal forced us to change the study protocol and the majority of the remaining patients received the Allofit cup (n=24) without screw holes (Figure 8). Two patients received a Trilogy cup with cluster holes.

One patient in each cup group was excluded because of bilateral surgery within the follow-up period. The two patients excluded because of avascular necrosis of the femoral head had received Interop cups. The patient with the cemented stem had also received an Interop cup; the patient that died post-operatively had received an Allofit cup; and the patient who was followed only by RSA also received an Allofit cup.

All cups (Centerpulse, Bern, Switzerland, acquired by Zimmer Inc., Warsaw, IN) are press-fit cups. No additional screws were used for stability. The Interop cup has a roughened titanium cancellized back surface, whereas the Allofit cup has a grit-blasted titanium surface. These cups were combined with a polyethylene hooded insert. The Trilogy cup has a hemispheric titanium alloy shell with fiber mesh and cluster holes. The Trilogy cup was
Figure 7. The Interop cup. Without the sealed screw hole (left) and with tantalum markers (arrows) in the polyethylene insert (right).

Figure 8. The Allofit cup.
combined with a polyethylene liner with a 10° elevated rim. All patients received a 28-mm cobalt-chromium femoral head.

The surgical procedure

Five experienced surgeons performed all operations in a standardized manner using an anterolateral modified Hardinge approach. The surgeons were blinded to the postoperative rehabilitation regime. All operations were performed under spinal anesthesia. The patients were given three doses of 1 g intravenously administrated Kloxacillin. Antithrombotic prophylaxis was given with low-molecular-weight heparin for 7-10 days. Postoperative pain was relieved with paracetamol and morphine.

Figure 9. Postoperative X-ray of the cementless Spotorno (CLS) stem and Allofit cup from the radiostereometric analysis (RSA) laboratory. The implants and the surrounding bone are marked with tantalum markers.
Randomization

Directly after surgery, the patients were randomized with a closed and numbered envelope technique to either FWB or PWB condition on the surgically treated leg.

The patients in the PWB group used crutches and were instructed to load approximately 15 kg on the operated side for 3 months after surgery. They received a written program with exercises focused on mobility to be performed at home after discharge from the hospital.

The FWB group of patients could use crutches if needed. The patients in the FWB group were instructed to perform unrestricted FWB. In addition, they received intensive supervised physiotherapy. For the first weeks after surgery, they performed active exercises to increase mobility. From 4-6 weeks after surgery, water training 2-3 times a week was added. From 7-12 weeks, exercises on an ergometer bicycle and specific active exercises were performed under close supervision of the physiotherapist in the gym.

Radiostereometry

During surgery, tantalum markers were inserted into the proximal femur, pelvis, and acetabular cup in a preplanned fashion (Figure 9). The stems were marked by the manufacturer with five tantalum markers, one at the tip, two on each side of stem, and the remaining two proximal to each side of the hump distal to the neck. Cups were marked with 5-8 tantalum markers at the outer rim of the polyethylene hooded insert. In addition, the titanium shells were preoperatively marked with one tantalum marker on the central button at the bottom in a similar fashion for both the Interop and Allofit cups.

A specially trained radiology research nurse performed all radiostereometric examinations. The first postoperative examination was initially performed within 5-7 days after surgery. During the study period, an amendment to the initial study protocol was performed by adding a baseline examination within 1 hour after surgery in 30 patients and a repeated measurement on the first postoperative day (Study II, p. 38). The follow-up examinations were performed at 1 and 3 months and after 1, 2, and 5 years.

The set-up included the uniplanar technique with the patients in supine position using the calibration cage 43 positioned under the examination table. Ceiling mounted x-ray tubes were positioned with 40° angle and with separate generators for true simultaneous exposure 99, 172. Initial radiographs were digitized by a scanner (UMAX, Umeå, Sweden). Because of modernization of the RSA X-ray laboratory, digital x-ray was introduced during the study period.
Table 2. The precision of our radiostereometric analysis (RSA) laboratory during this study

<table>
<thead>
<tr>
<th>Type of motion</th>
<th>Stem (n=42)</th>
<th>Cup (n=33)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translation (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse axis (x)</td>
<td>0.12</td>
<td>0.27</td>
</tr>
<tr>
<td>Longitudinal axis (y)</td>
<td>0.11</td>
<td>0.23</td>
</tr>
<tr>
<td>Sagittal axis (z)</td>
<td>0.31</td>
<td>0.34</td>
</tr>
<tr>
<td>Rotation (degrees)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse axis (x)</td>
<td>0.42</td>
<td>0.87</td>
</tr>
<tr>
<td>Longitudinal axis (y)</td>
<td>1.06</td>
<td>1.17</td>
</tr>
<tr>
<td>Sagittal axis (z)</td>
<td>0.12</td>
<td>0.54</td>
</tr>
</tbody>
</table>

95% prediction interval about zero for significant motions based on double examinations.

The precision of our RSA measurements in this study set-up was based on 33 double examinations of cups and 42 double examinations of stems (Table 2). Micromotion of the cup and stem was measured as rotations around three axes and as translations of the center of the rigid body along these three axes. For all measurements and calculations, we used UmRSA Analysis 6.0 (RSA Biomedical, Umeå, Sweden).

Figure 10. The pencil beam DPX-L scanner at work in a total body (TB) scan.
Dual X-ray absorptiometry

Bone densitometry at the proximal femur bilaterally and TB composition measurements were performed with a pencil-beam TB DXA scanner, DPX-L (Lunar Co, Madison, WI, USA) (Figure 10). Three regions of interest (ROIs) at the proximal femur were analyzed for areal BMD (g/cm²): femoral neck (FN), trochanter region (TR), and total hip (TH) (Figure 11). Furthermore, we analyzed BMC and projected bone area in these regions. Total body scans were made for TB composition and regional analysis. These regional analyses of the body composition measurements were analyzed for body and total limb mass (g), FM (g), LM (g), and BMC (g), and given separately for both lower limbs. Such absolute values are likely to be strongly influenced by the manually defined lower limb ROIs, since even small differences will affect the results. In an effort to reduce these influences we chose to compare body composition relations as percentage of total limb mass, i.e. FM%, LM%, and BMC%. A spine phantom was scanned regularly during the study period and the long-term precision, expressed as CV% for L2-L4 BMD, was <1.5%.

Figure 11. Dual X-ray absorptiometry (DXA) of the proximal femur with regions of interest (ROIs).
Bone densitometry of the contralateral proximal femurs and TB were performed before the operation (both proximal femurs) and at 3 months and then 1, 2, and 5 years after the operation. The TB scan was also performed within one week after surgery in a subset of the cohort.

The heels were measured with cone-beam DXA equipment, PIXI (Lunar Co, Madison, WI, USA). A manufacturer defined ROI of the calcaneus was analyzed for areal BMD (g/cm²).

To control the influence of rotation on hip BMD 21 patients (totally 42 proximal femurs) without any hip joint disease were, as a part of a first routine visit to the Uppsala Osteoporosis Unit, Uppsala University Hospital, measured bilaterally at the proximal femur with a short fan beam DXA scanner (Prodigy, GE-Lunar Co, Madison, WI, USA) and analyzed for FN, TR, and TH. The proximal femurs were first scanned at the recommended standard position with the foot in approximately 10-15° internal rotation, i.e. the FN in 0° and perpendicular to the X-ray beams (Figure 12). The second position was chosen to simulate a neutral position of the femur (often seen in patients with OAH), with the FN in 10-15° of external rotation because of the anteversion of the FN (Figure 1). Comparisons between the two positions of rotations were made for BMD of the three ROIs, i.e., FN, TH, and TR.
BMD around the hip implant (orthopedic hip implant software) was analyzed for each of the seven Gruen zones (Figure 13), with no offset to include every amount of bone outside the prosthesis during the first postoperative week and then at 3, 12, 24, and 60 months.

Figure 13. The seven Gruen zones surrounding the femoral implant.

Hip abductor strength

Hip abductor strength was measured with a dynamometer, CSD 400™ (Chatillon Inc, New York, NY, USA). Measurements were repeated five times at each examination and the mean value in kilograms was used for statistical analysis. The physiotherapist performed all examinations preoperatively, after 1 week, 3, and 6 months, and then after 1 and 2 years.

Weight bearing

Weight bearing preoperatively was measured using shoes with sensor-equipped soles and analyzed by the F-scan system (Tekscan™ Inc, MA,
USA). Mean value in kilograms based on three recordings, each including five steps, was used.

After randomization and instructions from the physiotherapist the registration was repeated 1 week and 3 months after surgery in an attempt to follow the patients’ compliance to the instructed weight bearing. Full weight bearing was allowed immediately after surgery for the patients in the FWB group and after 3 months for the patients in the PWB group. Weight bearing was also recorded at visits to the physiotherapist at 6 months and then at 1 and 2 years.

**Merle d’Aubigné and VAS**

The patients’ pain, walking ability, and range of motion were scored by a Merle d’Aubigné protocol. In addition, pain at rest and during weight bearing exercises was evaluated by a visual analog scale. These evaluations were performed during ordinary visits to the physiotherapist.

**Grading of OAH**

The degree of OAH was classified by two observers (HM and JM) independently from each other from the preoperative radiographs according to the Kellgren/Lawrence global grading scale. The radiographic classification included the presence of osteophytes, narrowing of the joint cartilage associated with subchondral sclerosis, pseudocystic areas, and the altered shape of the femoral head. The degree of OAH is divided into five grades: 0 (no OAH) – 1 (doubtful) – 2 (minimal) – 3 (moderate) – 4 (severe).

**SF-36**

The patients reported their QoL on touch screen computers with the installed Swedish SF-36 form. This evaluation was performed at ordinary visits to the physiotherapist preoperatively, at 3 months and after 1 and 2 years. The results were compared with an age-matched Swedish reference population.
Statistical analysis

All statistical calculations were performed using Statistica versions 7.1-9 (StatSoft Inc, Tulsa, OK). Groups were described with standard descriptive statistics (mean, standard deviation).

Evaluations of differences between groups were performed with Student’s t-test for quantitative data and the Mann-Whitney U-test for continuous variables. Evaluations of differences between dependent values, such as sides in patients, were performed with the paired t-test or Wilcoxon signed rank test. Non parametric tests were used for non-normally distributed data. To detect changes over time we used Friedman’s ANOVA for related samples. Changes from baseline in Study 5 were given as the mean proportion with 95% confidence interval (CI).

In Study II we used the unsigned (absolute) values for micromotion and calculated the median and 95% CIs for the median. Confidence intervals for the median were based on order statistics (ranks) as described by Hahn and Meeker 76. These calculations were performed using SAS 9.1.3 software (SAS Institute Inc., Cary, NC). Only p-values < 0.05 were considered significant.

We used statistical assistance and advice from the Uppsala Clinical Research Center.

Power analysis

A power analysis was done before the beginning of the study to estimate the sample size necessary to detect a significant difference in subsidence of the femoral stem between the two groups (FWB and PWB). It was determined that a group of 20 patients would be sufficient with alpha = 0.05 and beta = 0.20 (i.e. a power of 0.8). The study protocol was decided to include and randomize 46 patients to FWB or PWB.
Results and Discussion

Study I. Unilateral OAH and proximal femoral BMD

The aim of Study I was to investigate the effect of OAH on BMD at the proximal femur. A further aim was to determine whether OAH would affect the BMD at the heels and body composition of the legs. The 40 patients of this study were examined preoperatively before receiving an uncemented THA.

Since OAH affects the range of motion at the hip, we examined how rotation affects the measurement of BMD. To address this issue a second group of 21 patients without hip disease was recruited from a scheduled routine bilateral proximal femur DXA measurement at the Osteoporosis Unit at our hospital. These patients were scanned twice: in a correct position with the femoral neck perpendicular to the DXA beams, i.e. 10-15° internal rotation of the femur; and in a position often seen in OAH with the proximal femur in neutral rotation with the foot in vertical position (Figure 12).

Table 3. Bone mineral density (BMD) of the proximal femurs and heels

<table>
<thead>
<tr>
<th></th>
<th>OAH limb</th>
<th>Healthy limb</th>
<th>Difference</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMD FN</td>
<td>1.05 (±0.14)</td>
<td>1.01 (±0.13)</td>
<td>4.1 %</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>BMD TR</td>
<td>0.82 (±0.14)</td>
<td>0.89 (±0.13)</td>
<td>-8.3 %</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>BMD TH</td>
<td>1.01 (±0.14)</td>
<td>1.06 (±0.14)</td>
<td>-4.6 %</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>BMD heel</td>
<td>0.54 (±0.08)</td>
<td>0.55 (±0.09)</td>
<td>-1.7 %</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Values are mean (±SD), g/cm², p=p-value, paired t-test; FN=femoral neck, TR=trochanter, TH=total hip

Our data show 4% higher BMD at the FN and 8% and 5% lower at the TR and TH, respectively (Table 3). There was no difference in BMD between the OAH-affected heel and the healthy heel. When we scrutinized our DXA scans, it became evident that almost half of the OAH patients were scanned with the OAH side in the neutral position as opposed to the healthy side, which was scanned in the correct position with internal rotation of the femur, as could have been expected because of the restricted range of motion.

The correct scanning position of the proximal femur, allowing perpendicular X-ray beams, led to a 2.4% lower BMD at the TR compared with the position often (half of our OAH patients) seen in OAH (Table 4).
Table 4. The effect of rotation of the proximal femur on bone mineral density (BMD) of the hip

<table>
<thead>
<tr>
<th>ROI</th>
<th>Correct position</th>
<th>Neutral position</th>
<th>Difference</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>FN</td>
<td>0.87 (±0.13)</td>
<td>0.87 (±0.13)</td>
<td>0.3 %</td>
<td>0.7</td>
</tr>
<tr>
<td>TR</td>
<td>0.72 (±0.12)</td>
<td>0.74 (±0.12)</td>
<td>-2.4 %</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>TH</td>
<td>0.88 (±0.13)</td>
<td>0.88 (±0.13)</td>
<td>-0.5 %</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Values are mean (±SD), g/cm², p=p-value, paired t-test; FN=femoral neck, TR=trochanter, TH=total hip, Correct position=10-15° internal rotation of femur, Neutral position=femur in neutral position as often seen in osteoarthritis of the hip (OAH).

The main findings in this study are the differences in BMD of the proximal femur. The influence of rotation of the proximal femur on BMD at the trochanter indicates that we might have overestimated the BMD at the TR in our OAH patients. Consequently, the reduction in BMD at the TR in the OAH group would have been even larger if the matter of rotation would have been addressed. The optimal position can be achieved by using block and foot straps ⁷⁰, but in the clinical setting it might be difficult to precisely control for this, especially in patients with restricted range of motion (e.g., OAH patients) ⁶⁹. Finally, this difference in DXA results underlines the importance of evaluating the DXA images before making conclusions.

The 8% decrease in BMD at the trochanter and almost 1 SD lower Z-score than the FN indicates that the trochanteric region might be the weaker part of the proximal femur in OAH. It is speculated that a fall on the hip will not lead to a femoral neck fracture if the trochanteric region cannot withstand the blow and transfer the impact on to the femoral neck ⁶⁵. This decrease in BMD could be one explanation for the fact that trochanteric, and not femoral neck, fractures are often seen in osteoarthritic patients ¹¹³, ¹⁵⁶, ¹⁷⁶. Other factors that affect hip fracture risk include age, sex, BMI, tendency to fall, other diseases, and infections. The geometry of the proximal femur has also been shown to contribute to the risk of hip fracture ²⁴, ¹⁷¹. A new add-on tool, called hip structural analysis (HAS), for DXA has the ability to measure geometric contributions to bone strength as opposed to BMD alone ²¹, ³⁹. However, HAS has not been proven better than DXA in predicting fractures ²¹, ³⁹.

Study II. Cup stability during the first postoperative week

The aim of this study was to investigate whether any significant micromotion of uncemented press-fit cups occurs during the first postoperative week. In the clinical setting it has been routine to perform baseline RSA examinations 5-7 days after surgery. Our investigation of micromotion during the first week after surgery would state whether this routine is safe.
Thirty of the patients performed their first RSA examination within the first postoperative hour while still under spinal anesthesia. Twenty-four patients had cups that could be analyzed; the other patients were excluded because of technical problems with visualization of the markers.

To answer the question whether any micromotion occurred regardless of direction we used the unsigned (absolute) values to calculate the absolute median and the 95% CIs of the median. The limit of significant motion was the precision limits of the RSA setting. An upper limit of the 95% CI below the precision limit indicates no significant motion.

The 95% CI for proximal/distal and medial/lateral micromotion exceeded the precision limit at 1 week (Table 5). The absolute median values for micromotion were all below the precision limit. Mean (signed) values for micromotion in the medial (0.31 mm) and the proximal direction (0.27 mm) were barely above the precision limit.

Table 5. Micromotion of the uncemented cups at 1 day (n=22) and 1 week (n=23) compared with radiostereometric analysis (RSA) baseline at 1 hour.

<table>
<thead>
<tr>
<th>Translation (mm)</th>
<th>Mean (range)</th>
<th>Median (abs)</th>
<th>95% CI (abs)</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medial(+)/lateral(-)</td>
<td>0.27</td>
<td>0.086</td>
<td>0.035-0.211</td>
<td>0.27</td>
</tr>
<tr>
<td>1 day</td>
<td>0.21 (-0.15-1.35)</td>
<td>0.086</td>
<td>0.035-0.211</td>
<td>0.27</td>
</tr>
<tr>
<td>1 week</td>
<td>0.31 (-0.59-1.36)</td>
<td>0.213</td>
<td>0.058-0.576</td>
<td>0.23</td>
</tr>
<tr>
<td>Proximal(+)/distal(-)</td>
<td>0.23</td>
<td>0.034</td>
<td>0.026-0.134</td>
<td>0.23</td>
</tr>
<tr>
<td>1 day</td>
<td>0.14 (-0.03-0.89)</td>
<td>0.034</td>
<td>0.026-0.134</td>
<td>0.23</td>
</tr>
<tr>
<td>1 week</td>
<td>0.27 (-0.13-1.10)</td>
<td>0.115</td>
<td>0.064-0.371</td>
<td>0.34</td>
</tr>
<tr>
<td>Anterior(+)/posterior(-)</td>
<td>0.34</td>
<td>0.078</td>
<td>0.042-0.170</td>
<td>0.34</td>
</tr>
<tr>
<td>1 day</td>
<td>-0.07 (-0.51-0.22)</td>
<td>0.078</td>
<td>0.042-0.170</td>
<td>0.34</td>
</tr>
<tr>
<td>1 week</td>
<td>-0.09 (-0.51-0.40)</td>
<td>0.128</td>
<td>0.053-0.290</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Mean (range) are signed values; median and 95% confidence interval (CI) are unsigned/absolute (abs) values.

The mean values indicated medial and proximal micromotion, i.e. in the direction of loading. The mean values barely exceeded the precision limit at 1 week, whereas the absolute median values did not. The upper limit of the 95% CI is above the precision limit, indicating that a significant micromotion might have occurred in the medial and proximal direction.

The reason of the timing for the often applied baseline RSA examination is unclear. The conclusion from a RSA study of hip revisions with bone graft was that the baseline examination should be performed as early as possible, preferably on the first or second postoperative day. Contrary to this finding, the 1-week examination was found to be safe in a study of the first week’s micromotion of the CLS stem. However, the bone quality in a revised acetabulum is probably inferior to that seen in primary THA, especially if bone grafting and packing were used.
Based on our results, we conclude that the baseline examination should be performed as early as possible after the first postoperative day as illustrated by more individual translations exceeding the precision in the medial (Figure 14) and proximal (Figure 15) direction.

*Figure 14. Individual translations along the X-axis for 24 cups at 1 day and 1 week. The precision limit is indicated.*
Study III. Postoperative weight bearing and cup stability over 5 years

The aim of this study was to compare the effect of full versus partial postoperative weight bearing on the stability of press-fit cups over a 5-year period. Thirty of the 39 eligible patients included in the study could be evaluated with RSA within 5-7 days after surgery. Examinations were repeated at 1 and 3 months and after 1, 2, and 5 years. Twenty-seven of the 30 patients completed the 5-year examination.

Our data show a difference in the inclination of cups (rotation around the Z-axis) between the weight bearing regimes at 1 month and at 2 years, but not after 5 years (Figure 16). The movement was of equal amount in both the FWB and PWB groups, but in the opposite directions. At 2 years, the inclination increased by 0.8° in the FWB group and decreased by 0.6° in the PWB group.

There were no differences in translation, retro/anteversion or anterior/posterior tilt, of the cups at any time point. At 5 years, there were no differences at all between the groups. The only micromotions that exceeded the precision limit of the RSA settings were inclination and proximal trans-
lation in the FWB group. No difference in micromotion whatsoever was observed between the Interop and the Allofit cups (data not shown). We treated all cups together as press-fit titanium cups.

At 5 years, all cups pooled together displayed a mean micromotion of 0.05 (±0.6) mm in the medial, 0.3 (±0.5) mm in the proximal, and 0.1 (±0.5) mm in the anterior direction. There was a mean anterior tilt of 0.2 (±0.9) °, a mean retroversion of 0.3 (±1.4) °, and a mean increase in inclination of 0.3 (±1.4) °.

Only one prospective RCT has evaluated the effect of FWB versus PWB on micromotion of uncemented cups with RSA. Although the follow-up was considerably shorter (1 year), FWB was found to be safe. The micromotion recorded in our study was of the same magnitude as in their study, except for higher values for proximal migration (0.5 mm in our study versus 0.1 mm in their study at 1 year) and inclination (0.6° in our study versus 0° in their study at 1 year). Most of the micromotion occurred during the first year in both studies.

The micromotions recorded in our randomized study agree with findings in other RSA studies of uncemented cups with PWB for 6-8 weeks and of cemented cups.

In our randomized study we found no adverse effect of FWB on the stability of the studied press-fit titanium cups. The detected micromotions are small; most of them being within the precision limit, and had no clinical impact over 5 years.
Figure 16. Mean change in inclination (rotation around Z-axis). Full weight bearing (FWB) versus partial weight bearing (PWB) (also without the revised patient, >-8° at 1 year). Significant difference at 1 month and 2 years between groups.

**Study IV. Postoperative weight bearing and periprosthetic BMD and CLS stem stability over 5 years**

Thirty-eight patients received an uncemented CLS stem and were randomized to the FWB or PWB group and followed for 5 years. The aim of this study was to investigate if FWB would affect the periprosthetic BMD or the stability of the CLS stem.

DXA scans of the proximal femur were done at 5-7 days, 3 months, 1, 2 and 5 years. BMD was calculated for all seven Gruen zones surrounding the stem. RSA examinations were done at the same time points, as well as at 1 month. Using the Swedish SF-36, a physiotherapist evaluated the QoL of the patients. The physiotherapist informed all patients about weight bearing and patient compliance and adherence to the instructions was controlled using the F-scan system at visits before surgery, and at 1 week, 3, 6, 12, and 24 months after surgery.
Weight bearing did not affect BMD in any Gruen zone at any time point (Figure 17). At 3 months, an 8-15% reduction was observed in BMD in all Gruen zones for both groups. BMD was restored toward baselines in all Gruen zones, except zone seven. For all patients in both the PWB and FWB groups, BMD decreased progressively to -22% in zone seven (i.e. the calcar region) at 5 years (Figure 18).
We found no difference in micromotion of the CLS stem between the groups at 5 years (Table 6). At 5 years, the mean subsidence of all stems was 1.7 (±2.7) mm, mean retroversion 3.0 (±8.2) ° and mean varus tilt 0.4 (±1.1) °.

Table 6. Micromotions of the cementless Spotorno (CLS) stem at 5 years in the full weight bearing (FWB) versus partial weight bearing (PWB) group.

<table>
<thead>
<tr>
<th>(+) / (-)</th>
<th>FWB (n=16)</th>
<th>PWB (n=17)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Translation (mm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medial/lateral</td>
<td>-0.11 (±0.5)</td>
<td>0.07 (±0.3)</td>
<td>0.4</td>
</tr>
<tr>
<td>Proximal/distal</td>
<td>-2.13 (±3.2)</td>
<td>-1.33 (±2.1)</td>
<td>0.1</td>
</tr>
<tr>
<td>Anterior/posterior</td>
<td>-0.36 (±1.3)</td>
<td>-0.13 (±0.3)</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Rotation (degrees)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior/posterior tilt</td>
<td>0.36 (±1.4)</td>
<td>0.23 (±0.8)</td>
<td>1.0</td>
</tr>
<tr>
<td>Retro-/anteversion</td>
<td>4.90 (±11.6)</td>
<td>1.26 (±1.8)</td>
<td>0.1</td>
</tr>
<tr>
<td>Valgus/varus tilt</td>
<td>-0.62 (±1.5)</td>
<td>-0.16 (±0.3)</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Values are mean (SD); p=p-value, Mann-Whitney U test.

There were no differences in the SF-36 dimensions between the groups. Before the THA, the scores for general health and mental health were similar to those of a Swedish age-matched reference population, but the other dimension scores were lower in the study group. At 3 months, there were still lower scores in physical functioning and role limitations due to physical
functioning. At 1 and 2 years, all SF-36 dimension scores were equal to those of the age-matched reference population (Figure 19).

Whereas we found no differences in periprosthetic BMD or stability between the FWB and PWB groups, the only other randomized trial of 20 patients operated on with the HA-coated BiMetric stem showed larger bone loss in zones 1, 4, and 5 in the PWB group at 3 months. At 2 years, the PWB group still showed a larger bone loss in zone 1. Contrary to our finding of a restoration of BMD in all zones except zone seven, they found no restoration in zones one and seven. The reason for this discrepancy could be the effects of different stem designs and surface properties.

Thien et al. found no differences in stability when assessed with RSA of the uncemented ABG-I stem in their randomized study with a follow-up period of 1 year. This result is consistent with our findings, although we found a difference in anterior/posterior translation at 3 months, this difference disappeared after a longer period.

THA is an effective treatment for symptomatic OAH. Our finding of restored dimension scores of SF-36 at 1 year is supported by the work of Nils-
dotter et al. who found that at least 1 year is needed to reach all benefits from the THA.\textsuperscript{119}

In conclusion, we see no adverse effects of FWB on periprosthetic BMD or implant stability with a follow-up of 5 years.

Study V. Effects of weight bearing on body composition and BMD after unilateral THA

Thirty-eight patients received an uncemented CLS stem. Of the 38 patients, 18 were randomized to FWB, and 20 to PWB and then followed for 5 years. The aim of the study was to investigate the effects of FWB and PWB on body composition and BMD of contralateral hip and heels. Furthermore, we wanted to investigate the changes in TB composition, BMD, and weight during the 5 years after a unilateral THA.

Preoperative DXA was performed for TB composition measurements and BMD of the contralateral hip and heels. Follow-up measurements were performed at 3 months, 1, 2, and 5 years.

Preoperatively, the OAH side contained more FM\% and less LM\%, whereas there was no difference in BMC\%.

At 3 months and 1 year after THA, postoperative weight bearing had no effect on the change in body composition regarding FM\%, LM\%, or BMC\%. Moreover, there were no differences between FWB and PWB on changes in BMD at the contralateral hip or heels. Because no differences were detected, we followed all OAH patients as one group to measure changes over 5 years.

Table 7. Five-year values of total body (TB) and contralateral hip bone mineral density (BMD), body composition, and weight. Changes are from preoperative baseline.

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>5 years</th>
<th>% change from baseline</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total body</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FM%</td>
<td>32</td>
<td>33.9 (±8.9)</td>
<td>2 (±14)</td>
<td>0.3</td>
</tr>
<tr>
<td>LM%</td>
<td></td>
<td>62.5 (±8.5)</td>
<td>-1 (±7)</td>
<td>0.7</td>
</tr>
<tr>
<td>BMC%</td>
<td></td>
<td>3.6 (±0.5)</td>
<td>-5 (±6)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td></td>
<td>DXA-derived</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FN</td>
<td>33</td>
<td>79.8 (±13)</td>
<td>1 (±6)</td>
<td>0.5</td>
</tr>
<tr>
<td>BMD (g/cm²)</td>
<td></td>
<td>FN</td>
<td>0.967 (±0.1)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>TR</td>
<td></td>
<td>0.866 (±0.1)</td>
<td>-2 (±5)</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>TH</td>
<td></td>
<td>1.021 (±0.1)</td>
<td>-3 (±4)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Total body</td>
<td>32</td>
<td>1.202 (±0.1)</td>
<td>-3 (±3)</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Values are mean (SD); p=p-value, Wilcoxon Rang sign test/paired t-test (DXA values) from baseline.

At 5 years (Table 7), there was a decrease of 5\% in TB BMC\%, as well as a decrease in BMC\% of both legs. The decrease in the operated leg’s BMC\%
was larger (9% versus 4%), which is probably due to the femoral head extraction at surgery. There were no changes in FM% or LM% in either TB or the legs. The BMD of the contralateral hip was 3, 3, and 2% lower at the FN, TH, and TR, respectively, at 5 years, whereas the TB BMD was 3% lower. There was no change in BMD at the heels or in body weight.

In a community-based study of 273 men and women there was an annual decrease of 1-2% in TB LM and a 2-7% in TB FM% in patients older than 50 years 90. An annual decrease of 0.3-1.5% in BMD at the FN was found in several large population-based studies 87, 90, 147.

Our findings of a loss of BMD at all ROIs of the proximal femur, as well as a 3% loss in TB BMD at 5 years are in good accordance with these findings. However, we found no changes in FM% or LM% in the TB or in the legs at 5 years. This finding might reflect the return to activity after THA, counteracting the age-related changes otherwise seen 90. Age-related fatty infiltration that is associated with muscle weakness 72 and poor lower extremity performance 181 can be diminished by physical activity 73.

To conclude, we found no effects of FWB on change in body composition or BMD of the legs at either 3 months or 1 year after an uncemented unilateral THA. With these findings in mind, we can recommend FWB after unilateral THA. We also found a decrease in TB BMC% and BMD 5 years after unilateral THA. On the other hand, the age-related changes in TB FM% and TB LM% did not materialize in this study. THA seems to allow for physical activity and may counteract the expected age-related changes in body composition but not in BMD.
General discussion

Uncemented THA – the future?
The survival of cemented implants in younger patients has been disappointing\(^\text{150}\). Cementless stems are becoming increasingly common even in older patients (the mean age of patients receiving uncemented THA in Sweden in 2008 was 57 years)\(^5\). Cementless fixation was used in more than 60% of all THAs in Australia in 2008\(^4\) and in more than 70% in Canada 2006-2007\(^3\), whereas only 30% of the stems in Sweden were uncemented in 2008\(^5\).

The CLS stem used in this thesis has an excellent long-term survival rate. In patients younger than 55 years (mean age 47) the overall survival at 12 years was 97%\(^14\) and 92% in patients with a mean age of 57 years\(^12\). At 17 years, the overall survival rate was 88% in this older patient group and 94% with aseptic loosening as the endpoint\(^13\).

The use of uncemented THA may be advantageous in the sense that it decreases the incidence of complications (e.g., thromboembolic disease and fat embolism) and significantly reduces operative time\(^186\). With this knowledge in hand, it is tempting to use uncemented THA or even uncemented hemiarthroplasty in elderly patients with hip fractures. However, in patients older than 75 years there is a significantly higher revision rate for uncemented THA than for uncemented and hybrid fixation\(^4\). Arguments against uncemented THA would also be thigh pain\(^20,45\), increased heterotopic bone formation\(^43\), and intraoperative femoral fractures\(^23,77\).

However, when considering all necessary costs, there were no substantial differences in cost between cemented and uncemented implants\(^186\). In Sweden, uncemented stems performed better than cemented in terms of survival, whereas cemented cups outperformed uncemented as a whole; although in a study of all THAs between 1992 and 2007, the five most common uncemented cups had a survival equal to that of the uncemented cups\(^77\).

How to control weight bearing?
Theoretically, all patients would benefit from early rehabilitation with FWB. For instance, there would be less loss of muscle and bone mass with early activation of muscles and stimulation of bone. A faster discharge from hos-
pital and a quicker return to walking ability have been reported with early rehabilitation.

The question with uncemented THA is whether a good primary fixation is achieved by press-fit implantation, which is necessary to withstand the forces of early rehabilitation and weight bearing. Some patients have probably in all times not followed the recommendations of weight bearing and thus loaded their operated hips more (or less) than recommended. The best restraining factor is most likely pain. The effectiveness of prescribed weight bearing has been questioned since the patients were unable to comply with instructions. To perform studies with randomized weight bearing it is essential to control for compliance to the weight bearing instructions. The ideal situation would be an around-the-clock system with an auditory feedback mechanism.

The system closest to this is probably the auditory feedback system used by Thien et al. and by Bodén et al. This system includes a pressure-activated auditory advice in the soles of the shoes emitting a buzzer sound at a calibrated load. Of the FWB groups, only the one in Bodén et al.’s study received instructions using the feedback system in the hospital before discharge. This way, they were encouraged to perform FWB, which our patients had difficulties in doing during the first postoperative week. The PWB groups had instructions to load either 10% of their body weight or 30 kg. Of course, the effect of this feedback system vanishes at home while walking without shoes.

The F-scan system used in this thesis measures the actual load during walking but there is no direct feedback system. The PWB group was instructed to load 15 kg on the operated hip. Measurements at visits to the physiotherapist showed FWB on the OAH-affected side before surgery (64 kg in PWB versus 67kg in FWB). The PWB group loaded 26 kg at 1 week and 32 kg at 3 months, whereas the FWB group was able to load 39 kg at 1 week and 70 kg at 3 months. The measurements indicate that the PWB group had difficulties in obeying the weight bearing restrictions given as described earlier, but the mean values of weight bearing were much lower in the PWB group, at least at the visits to the physiotherapy. The measurements further show that the FWB group had difficulties in performing FWB during the first week, probably because of postoperative pain. To increase loading in the FWB group intensive, supervised physiotherapy was given.

Both systems have their weaknesses. None has around-the-clock control of the patients. Physiotherapy programs for different weight bearing regimes achieve different loading of the hips in the different groups. Uncemented press-fit components seem to have good initial stability that withstands early rehabilitation well without leading to increased micromotion up to 5 years after THA.
Periprosthetic BMD

The CLS is designed for proximal press-fit implantation. Our findings in Study IV, with a restoration of the BMD in all Gruen zones except for zone seven, i.e. the medial proximal or calcar region, indicate that the fit of the stem is good. Nevertheless, there seems to be stress-shielding in the calcar region, i.e. by-passing of the load resulting in loss of BMD. This possibility is illustrated by the radiographic finding of calcar rounding in 76% of the patients in a 10-year follow-up of the CLS stem in 141 patients under the age of 55 years.

The pattern of BMD changes with different uncemented femoral stems in primary THA varies. Theoretically, it is mainly a matter of stem design, and more specifically, an effect of where the femoral stem is fixed and thereby where stress is created on the surrounding bone. For instance, distally fixed stems will lose bone proximally because of stress-shielding. This loss of bone proximally was illustrated in a comparison of ABG-I and ABG-II.

In several studies a BMD decrease occurred during the first 1-2 years in all zones. Often there is a successive catch up of BMD in the distal zones, but an ongoing bone loss occurs in the calcar region (zone one or seven, or both) depending on the type of stem. Bodén and Adolphson found progressive bone loss up to 20% from baseline in zones one and seven after 2 years in 20 patients with the Bi-metric stem, with less loss for FWB in zone one. This finding contrasts with our finding that there were no differences at any time point between the two weight bearing regimes. Moreover, whereas we observed restoration of BMD in all zones except zone seven (BMD loss of 22% at 5 years), Bodén and Adolphson found no restoration in zones one or seven. These differences might be the result of different stem designs. In addition, Alm et al. found that women with low systemic BMD showed a greater bone loss in the calcar region after uncemented THA than women with normal BMD.

The material of the stem and its mode of elasticity also influence the periprosthetic BMD. Titanium is more flexible than cobalt-chromium and will consequently transfer stress to the femur in a more biological way. Contrary to this, a stiffer stem resulted in less stress on the cement sheath in cemented THA.

Good preservation of the femoral bone stock should be the goal of THA since it would minimize the risk of aseptic loosening and facilitate the possible future revision. Revision THA is a difficult challenge for the orthopedic surgeon. In the case of severe stress-shielding the proximal bone stock might be compromised and present a suboptimal environment for proximally coated implants, such as the Bi-Metric. Distally anchored stems might also encounter problems with stability and subsidence. On the other hand, in a study of 170 patients with a mean follow-up of 13 years...
fully coated uncemented revision stems with diaphyseal fit showed good results in clinical scores and survival of the stem 130.

Implant stability and RSA

RSA is the gold standard for noninvasive assessment of implant stability and has been widely implemented for assessing stability of THA implants 99. Detection of early micromotion by RSA can predict future aseptic implant loosening 98, 114. A subsidence at two years of 1.2 mm or more of a cemented femoral stem increased the risk for revision by 50% 98.

RSA, which allows three-dimensional measurements, is the most accurate method in detecting micromotion 120. The accuracy in determining subsidence is 0.2 mm 115, 122, 185, which can be compared with 1.5 mm for EBRA 26. Digitized radiographs combined with software (UMA) had an accuracy of 2.5 mm in assessing subsidence and 1.8° in varus/valgus tilt as compared with RSA as the gold standard 54.

To our knowledge, only two other studies have addressed the question of postoperative weight bearing and femoral stem stability assessed with RSA 41, 166. Bottner et al. reported larger subsidence in the FWB at 6 weeks, but there was no difference at 6 months 41, whereas Thien et al. found no differences at 3 or 12 months 166. In Study IV we followed the patients for 5 years without any sign of differences in micromotion between the FWB and PWB groups. The only difference occurred at 3 months in anterior and posterior translation. However, the mean translation in both groups was small, approximately 0.1 mm. This value is well within the precision limits of the RSA method in this setting; hence, no true motion might have occurred.

However, the stability of acetabular cups has not been studied to the same extent as that of femoral stems. One reason for why acetabular cups have not been studied as much may be the difficulty in performing RSA examinations with an acceptable number of visualized and stable markers in metal backed cups and in the periprosthetic pelvic bone. New software tools will offer an improvement in cup measurements 17, 173.

We are aware of only one other RCT in which the effect of weight bearing on cup stability has been studied with RSA. Following 43 patients for 1 year, Thien et al. found no adverse effect of immediate weight bearing on the stability of an uncemented HA-coated press-fit cup (ABG) 166. The patients were similar in age to the patients in Study III, but both primary and secondary OAH were included. We found no differences in micromotion in our press-fit cups (Interop and Allofit) with a 5-year follow-up. A proximal movement of the cup was noted in both studies, approximately 0.15 mm in the Thien et al. study 166 and 0.45 mm in our study.
Body composition

THA is one of the most effective surgical procedures for postoperative outcome. The postoperative scores of QoL instruments, such as the SF-36 and the WOMAC, are improved in several studies \(^{51,119}\). The return to daily activities and physical exercise without being limited by pain could theoretically be of great benefit for the patients.

In normal aging the percentage of body fat increases in both men and women, although with higher values in women \(^{91,133}\). Physical exercise can diminish \(^{73}\) age-related fatty infiltration into muscle \(^{40}\). We could see no change in FM\% in the body or in the legs during the 5 years after THA. This failure to find a change in FM\% might reflect the return to daily physical activities or the rather young patient group, or even because of a limited number of patients.

We also found no change in weight during the 5 years after THA. This finding is in contrast with that of an annual weight loss of 1 kg in English men followed for 28 years \(^{42}\), but is supported by the finding of no weight change in Europeans older than 60 years that were followed for 4-5 years \(^{19}\). It could be speculated that the absence of pain would promote physical activity and result in weight loss, but again the study population might have been too small to detect any differences.

A study of 20 patients with unilateral OAH who received a cemented THA showed 25% less muscle mass and 6% less bone mass when assessed with QCT in the OAH leg as compared with the healthy leg preoperatively \(^{8}\). These changes were interpreted to illustrate the preoperative disuse of the OAH-affected leg. Another explanation is overuse of the healthy side as seen in chemically induced OA in dogs, where BMD even increased in the healthy knees \(^{153}\). OAH patients have reduced hip strength and gait performance compared with healthy controls \(^{94}\). These studies support our finding of a preoperative higher FM\% and lower LM\% in the OAH side compared with the healthy side.

For patients older than 50 years, an annual increase in TB FM\% and loss of TB LM\% has been found \(^{90}\). In addition, several reports have shown age-related loss of BMD at the FN \(^{87,90,147}\). Our findings of a decreased BMD in all ROIs of the contralateral hip 5 years after THA are in accord with these findings. However, we cannot see any change in FM\% or LM\% in TB or the legs after surgery. This lack of change might reflect the small study population. It might also reflect a return to activity that counteracts age-related body composition changes, but which is not possible to withstand the age-related changes in BMD.
Strengths and limitations

This thesis is based on five studies using the same study group. The studies were performed in a prospective RCT concerning the postoperative weight-bearing regime with a relatively long follow-up of 5 years. We can account for only three patients with a contralateral OAH requiring THA; these patients, however, were excluded since we wanted to study changes in unilateral OAH. We had a limited number of dropouts during the follow-up.

The same staff operated the same DXA machine throughout the study. Furthermore, the same trained nurse performed the RSA examinations during the entire study. Finally, the same physiotherapist performed the clinical follow-up, the F-scan, and the SF-36.

We used state of the art techniques in measuring implant stability, BMD, and body composition. We are not aware of any study that has investigated changes in body composition after THA.

The size of the study population was determined based on a power analysis for subsidence of the femoral stem. Twenty patients in each group were found to be sufficient to detect a significant difference in subsidence of 0.2 mm. This sample size might be too small to draw valid conclusions regarding changes in BMD and body composition. However, other studies on periprosthetic BMD have used study populations of our magnitude.

The fact that the change of cup design during the study was undesirable and out of our control might be considered a limitation, but also a strength to this study. We found no differences between the cups in terms of stability (although there might be lack of power) and thus we report results for press-fit titanium cups.

The compliance to the prescribed weight bearing in this study has been discussed. To separate the groups in terms of loading we also used different postoperative rehabilitation programs. The control of weight bearing performed at visits to the physiotherapist was done in a semi-blinded manner since the patients walked up and down the aisle several times without knowing when the measurements were done.
Conclusions

- OAH affected BMD of the proximal femur. BMD at the FN was higher and BMD at the TR and TH was lower than the healthy proximal femur.
- Correct positioning of the leg was found to be crucial to obtain correct densitometric values.
- The RSA baseline investigation for press-fit cups should be performed as soon as possible after the first postoperative day.
- FWB did not adversely affect the stability of the uncemented press-fit cups (i.e. the Interop and Allofit cups) over a 5-year follow-up.
- FWB did not adversely affect the periprosthetic BMD or the stability of the CLS femoral stem over 5 years.
- The periprosthetic BMD around the CLS stem showed recovery toward the postoperative baseline values in all Gruen zones, except in the calcar region where the BMD decreased continuously to -22% at 5 years.
- FWB had no effect on the change in the distribution of FM%, LM%, and BMC% after THA.
- FWB had no effect on the change in BMD in the contralateral hip or heels.
- A reduction in BMD in all ROIs of the contralateral hip as well as in TB BMD was observed 5 years after THA.
- Five years after THA there was a decrease in TB BMC%, but no change in TB LM% or FM%, which could have been expected.
Clinical implications

Better for the patient?
We have clearly shown that FWB has no adverse effect on stability on the press-fit CLS stem (Study IV) or on the press-fit titanium cups (Study III), i.e. the Interop and Allofit cups. Furthermore, there seems to be no change in periprosthetic BMD changes after THA.

    Faster rehabilitation and a quicker return to walking ability have been reported 93. We can speculate that FWB will lead to a faster return to physical activity and work.

Better RSA?
Concerning the press-fit cups used in this thesis, we have shown that there might be micromotion during the first postoperative week (Study II). The baseline examinations should preferably be performed as soon as possible after the first postoperative day in that this can provide a good and valid starting point for longitudinal measurements of micromotion.

Better for the orthopedic surgeon?
Postoperative rehabilitation after THA has for a long time relied on the clinical experience of the surgeons 187.

    We can now provide evidence from a RCT on the stability of press-fit cups (Study III) and of the uncemented press-fit CLS stem (Study IV). Moreover, the postoperative weight bearing regime does not affect the body composition or BMD (Study V).

    The orthopedic surgeons can now rely on this evidence when recommending full postoperative weight bearing after uncemented THA.

Målet med denna avhandling var att följa patienter som opererats med ocementerad höftprotes på grund av symptomgivande ensidig artros. Vi undersökte om den postoperativa belastningen påverkade stabiliteten hos protesdelarna, bentätheten eller kroppssammansättningen. Efter genomgången operation randomiserades patienterna till omedelbar full belastning kombinerat med intensiv sjukgymnastik eller till stegmarkering med 15 kg belastning under 3 månader. 46 patienter med en medelålder på 55 år inkluderades och följdes under 5 år med bentäthetsmätning (DXA) och radiosteoreometrisk analys (RSA). DXA mäter bentätheten per ytenhet och kan också bestämma fett och muskelmassa i undersökt kroppsdel. I RSA använder man sig av små kolor av tantal (atomnummer 73) för att analysera tredimensionell rörlighet mellan till exempel protesdelar och omkringliggande ben med stor precision (0,1-0,2 mm).

I den första studien jämfördes det artrosdrabbade benet med det friska. Vi fann en 4 % högre bentäthet i lårbenshalsen och en 8 % lägre bentäthet i trokantern och 5 % lägre räknat i hela höften. Dessa resultat kan förklara varför artrospatienter mer sällan drabbas av brott på lårbenshalsen utan ofta av pertrokatantåra frakturer.

I den andra studien undersökte vi stabiliteten hos de ocementerade ledskälarna under den första veckan efter operationen. Patienterna undersökes
med RSA redan inom en timme efter operationen med kvarvarande ryggedövning och sedan på nytt efter 1 dag och efter 5-7 dagar. Vi fann att det skedde minimala rörelser under den första veckan i medial och proximal riktning, det vill säga i belastningsriktningen. Startundersökningen för RSA av o cementerade ledskålar bör därför göras så snart som möjligt efter den första postoperativa dagen.

I den tredje studien undersökte vi om den postoperativa belastningen påverkade stabiliteten på 5 års sikt för ledskålarerna. Vi fann ingen skillnad i stabiliteten rörande ledskålarerna och övergick en rörelse på i snitt 0,05 mm i medial, 0,3 mm i proximal och 0,1 mm i anterior riktning.

I den fjärde studien undersökte vi om den postoperativa belastningen påverkar bentätheten kring protesstammen eller stabiliteten hos denna på 5 års sikt. Vi fann ingen skillnad vare sig i bentäthet eller i stabilitet mellan de olika belastningsgrupperna. Överlag visade alla zoner runt stammen en återhämtning av bentäthet, utom den mest proximala mediala zonen. Bentätheten i denna zon sjönk under hela uppföljningstiden och var vid 5 år 22 % lägre än från start. Vid 5 år hade stammarna i snitt sjunkit med 1,7 mm, roterat 3.0° bakåt och 0.4° i varus.

I den femte studien undersökte vi om belastningen påverkade fördelningen av fett-, muskel- och benmassa eller bentätheten i den friska höften eller hälarna. Vi fann ingen påverkan av belastning på dessa variabler efter 3 eller 12 månader. Vi följde därför alla patienter som en grupp och fann vid 5 år en minskning av benmineralinnehåll på 5 % i hela kroppen, 9 % i det opererade benet och 4 % i det friska benet. Däremot fann vi ingen förändring i fett- eller muskelmassa från före operationen till 5 år efter denna. Bentätheten sjönk med 3 % mätt för hela kroppen och med 2-3% i den friska höftens regioner. Bentätheten i hälarna visade ingen förändring under de 2 år som den fölljdes. Dessa fynd tolkar vi som om operationen innebär en sådan förbättring att det motverkar de åldersförändringar i fett- och muskelmassa som man tidigare funnit men att den möjliga ökade aktivitetsnivån inte är tillräcklig för att motverka bentäthetsförändringar.

Sammanfattningsvis så har inte omedelbar full belastning efter en cementerad höftprotesoperation några negativa effekter på stabilitet av implantaten, på bentäthet eller kroppssammansättning. Vidare borde omedelbar full belastning innebära en vinst i rehabiliteringstid, men det är inte undersökt i dessa studier.
Acknowledgements

I would like to express my sincere gratitude to everyone who made it possible for me to complete this thesis. In particular, I would like to thank:

**Hans Mallmin**, my supervisor, for introducing me to science, for practical and professional guidance, for always having some “spare” minutes, and for being a good friend always checking that the well-being of my family is prioritized.

**Sune Larsson**, my co-supervisor, for helping with quick and penetrating remarks and manuscript revisions.

**Jan Milbrink**, my co-supervisor, for believing in me, for support, and for still wanting me on “your team”.

**Per Mattsson**, my co-supervisor, for introducing me to and guiding me in the 3-D world of RSA.

**Håkan Ström**, for starting the BOS study and letting me be a part of it.

**Marja Gustafsson, Monica Gelotte, and Karin Huss** for invaluable help with DXA, RSA, and clinical follow-up.

**Lisa Wernroth**, for statistical guidance and expertise.

**Sonia Johansson**, for all practical help throughout the years,

**All colleagues at the Department of Orthopedics** for the friendly atmosphere and making our work so much fun, and especially **Olle Nilsson, Bengt Sandén, Hans-Olov Hellström, and Katarina Lönn** for providing time and financial support to perform and present my research at national and international congresses.

**Richard Marsell.** Your determination, achievements and commitment to your work have inspired me again and again.
All of my friends for sharing holidays, dinners, discussions, and time with the children. Also for keeping me in shape with numerous workouts on bike, skis, or with running shoes.

The Kalix gang: David, Jens, Johan, Jonas, Juha, Marcus, Mikael, Tobias F, Tobias L, and Urban with families for sharing good times and bad and for always being there. And for still hanging out.

My parents-in-law, Margareta and Jörgen, for relaxing times in the summer house and for helping out with the children.

My sister-in-law, Ulrika & Julien, for inspiration to finish this work and for showing us London.

My brother, Calle & Tina, and sister, Anna & Markus with kids for inviting us to amazing dinners far away from research. And for just being my brother and sister.

My parents, Lisa and Otto, for all your love, for making me curious about new things, not afraid of hard work, and for always supporting my family and me.

My beloved wife, Ninna. Thank you for your never-ending support, encouraging words in tough times, and for your interest in medicine (maybe orthopedics excluded), almost being the family doctor. Thank you for being so understanding at times when I spent more time with my laptop than with you. I love you!

My three wonderful and fantastic children for being a legitimate excuse for taking a break. Clara, for always laughing, being such a positive person, for asking about my “book”, and for giving me the opportunity to train a soccer team. Elsa, so intelligent: focused and determined when it comes to bringing to completion whatever you are doing, and yet the drama queen of the family. Max, my little package of power, for never being quite, and for making me play with LEGO. You make my life worth-while!

A special thank you to all participants of the BOS study.

The work with this thesis was supported by stipends from Norrlands Nation, namely Näslunds and Stenholms kirurgi, and from the Swedish Orthopaedic Association, namely Link Sweden’s hip and Sir John Charnley’s hip (Depuy). Zimmer sponsored the study financially. Financial support was also provided by the Orthopaedic Department by means of time for research (ALF). Thank you all!
References


97. Kährholm, J., Borsgren B., Lowenhielm G., and Snorraison F., Does early micromotion of femoral stem prostheses matter? 4-7-year stereoradiographic


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