A commentary by J. David Blaha, MD, is linked to the online version of this article at jbjs.org.

Volumetric Bone Mineral Density in Cementless Total Hip Arthroplasty in Postmenopausal Women

Effects on Primary Femoral Stem Stability and Clinical Recovery

Hannu T. Aro, MD, PhD, Klaus Engelke, PhD, Kimmo Mattila, MD, PhD, and Eliisa Löyttyniemi, MSc

Investigation performed at Turku University Hospital, Turku, Finland

Background: In cementless total hip arthroplasty, femoral stems should preferably not migrate at all postoperatively. This goal is difficult to achieve in postmenopausal women with impaired bone quality. Here, we explored the clinical importance of initial stem migration, measured by radiostereometric analysis (RSA), in women who underwent quantitative computed tomography (CT) of the involved hip preoperatively.

Methods: A prospective cohort of 65 postmenopausal women (mean age, 69 years) with hip osteoarthritis and Dorr type-A or B femoral anatomy underwent total hip arthroplasty with implantation of a tapered, single-wedge femoral stem. Volumetric bone mineral density (BMD) was measured using quantitative CT. Femoral stem translation and rotation were measured using model-based RSA within 3 days after the surgical procedure and were repeated at 3, 5, and 11 months. Postoperative recovery parameters included walking speed, walking activity, and patient-reported outcome measures. Subjects were categorized into 2 groups according to the magnitude of initial 5-month stem subsidence (<2 mm or ≥2 mm); RSA outliers (n = 7) were analyzed separately.

Results: Subjects with stem subsidence of ≥2 mm (mean, 3.09 mm [95% confidence interval (CI), 2.70 to 3.47 mm]) had lower intertrochanteric volumetric BMD (p = 0.008). Subjects with subsidence of <2 mm (mean, 0.80 mm [95% CI, 0.51 to 1.09 mm]) had faster improvement of patient-reported outcome measures and exhibited faster walking speed (p = 0.007) and greater walking activity (p = 0.010) at 11 months as well as better Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) scores (p = 0.002) and RAND 36-Item Health Survey mental component scores (p = 0.006) at 2 years. All cohort stems were osseointegrated at 2 years.

Conclusions: Femoral stem stability and resistance to subsidence were sensitive to adequate intertrochanteric volumetric BMD. Low intertrochanteric volumetric BMD was associated with greater stem migration. With initial migration, clinical recovery was slower and patient-reported outcome measures were less satisfactory.

Level of Evidence: Prognostic Level II. See Instructions for Authors for a complete description of levels of evidence.

In cementless total hip arthroplasty, the critical factors for osseointegration are adequate osseous contact, firm fixation (micromotion of <20 μm), and limited initial migration[1,2]. Initial stem migration, measured by radiostereometric analysis (RSA), refers to 3-dimensional implant translation and rotation, including proximal-distal translation (subsidence), during

Disclosure: This study was co-financed by the Academy of Finland and Turku University Hospital, Turku, Finland. The original trial was co-financed by Amgen, Inc. The funding sources had no involvement in the collection, analysis and interpretation of data, in the writing of the report, and in the decision to submit the article for publication. On the **Disclosure of Potential Conflicts of Interest** forms, *which are provided with the online version of the article*, one or more of the authors checked "yes" to indicate that the author had other relationships or activities that could be perceived to influence, or have the potential to influence, what was written in this work (http://links.lww.com/JBJS/G410).

TABLE I Patient Demographic and Preoperative Characteristics by Femoral Stem Subsidence Magnitude

	Subsidence <2 mm (N = 30)	Subsidence ≥2 mm (N = 28)	P Value*	Outliers (N = 7)	P Value†
Age‡ *(yr)*	67.1 (60 to 77)	70.4 (60 to 84)	0.021§	72.4 (65 to 78)	0.086
<75 yr#	29 (97%)	20 (71%)	0.011§	4 (57%)	0.009§
≥75 yr#	1 (3%)	8 (29%)		3 (43%)	
BMI** *(kg/m²)*	27.8 ± 4.2	28.2 ± 5.3	0.729	27.8 ± 3.6	0.941
Charnley classification#			0.410		0.809
Class A	10 (33%)	6 (21%)		2 (29%)	
Class B	4 (13%)	7 (25%)		2 (29%)	
Class C	16 (53%)	15 (54%)		3 (43%)	
ASA#††			0.096		0.612
Class I	0 (0%)	3 (11%)		0 (0%)	
Class II	19 (63%)	12 (43%)		5 (71%)	
Class III	11 (37%)	13 (46%)		2 (29%)	
History of low-energy fractures#			0.373		0.878
Yes	6 (20%)	9 (32%)		2 (29%)	
No	24 (80%)	19 (68%)		5 (71%)	
25-hydroxyvitamin D** *(nmol/L)*	93.8 ± 29.4	100.5 ± 27.7	0.377	85.9 ± 27.8	0.352
Areal BMD** *(g/cm²)*					
Total hip	0.95 ± 0.14	0.91 ± 0.14	0.286	0.82 ± 0.16	0.034§
Femoral neck	0.84 ± 0.12	0.84 ± 0.16	0.902	0.77 ± 0.13	0.130
Intertrochanteric	1.10 ± 0.18	1.03 ± 0.16	0.131	0.91 ± 0.19	0.035§
Lumbar spine areal	0.99 ± 0.15	1.02 ± 0.21	0.480	0.88 ± 0.08	0.057
WHO classification of areal BMD#‡‡			0.291		0.123
Normal BMD (T-score ≥ −1.0)	17 (57%)	13 (46%)		1 (14%)	
Osteopenia (−2.5 ≤ T-score < −1.0)	13 (43%)	13 (46%)		6 (86%)	
Osteoporosis (T-score < −2.5)	0 (0%)	2 (7%)		0 (0%)	
Femoral cortical thickness** *(mm)*					
Medial cortex	11.7 ± 2.6	12.6 ± 3.0	0.202	11.0 ± 3.8	0.380
Lateral cortex	6.9 ± 1.3	6.6 ± 1.4	0.394	6.7 ± 1.8	0.759
Canal flare index#			0.125		0.592
Stovepipe, <3.0	2 (7%)	3 (11%)		0 (0%)	
Normal, 3.0 to 4.7	24 (80%)	25 (89%)		6 (86%)	
Champagne flute, >4.7	4 (13%)	0 (0%)		1 (14%)	
Gluteus minimus and medius muscles**			0.610		0.190
Cross-sectional area *(mm²)*	4,560 ± 848	4,660 ± 630		4,212 ± 655	
Gait analysis**					
Walking speed *(m/s)*	0.90 ± 0.25	0.88 ± 0.28	0.754	1.10 ± 0.15	0.031§
Stride length *(m)*	1.02 ± 0.19	0.99 ± 0.23	0.577	1.11 ± 0.06	0.248
Cadence *(steps/min)*	102.5 ± 15.2	101.2 ± 15.8	0.760	115.8 ± 11.7	0.022§
Walking activity**§§ *(steps/day)*	3,120 ± 1,780	2,890 ± 2,180	0.673	3,700 ± 1,280	0.239
Denosumab#			0.610		0.214
Active drug	15 (50%)	16 (57%)		2 (29%)	
Placebo	15 (50%)	12 (43%)		5 (71%)	

*The statistical comparison of subjects with <2-mm or ≥2-mm stem subsidence was conducted using the independent-sample 2-tailed t test for continuous data and the 2-sided chi-square test or the Fisher exact test for the categorical variables. †The statistical comparison of outliers with non-outliers (subjects with a stem subsidence of <2 mm or ≥2 mm) was conducted using the independent-sample Mann-Whitney U test for continuous data and the 2-sided chi-square test or the Fisher exact test for the categorical variables. ‡The values are given as the mean, with the range in parentheses. §Significant. #The values are given as the number of patients, with the percentage in parentheses. **The values are given as the mean and the standard deviation. ††ASA = American Society of Anesthesiologists Physical Status classification. ‡‡Based on T-scores of the lumbar spine and the hips. §§Pedometer-measured activity during a 7-day preoperative period.

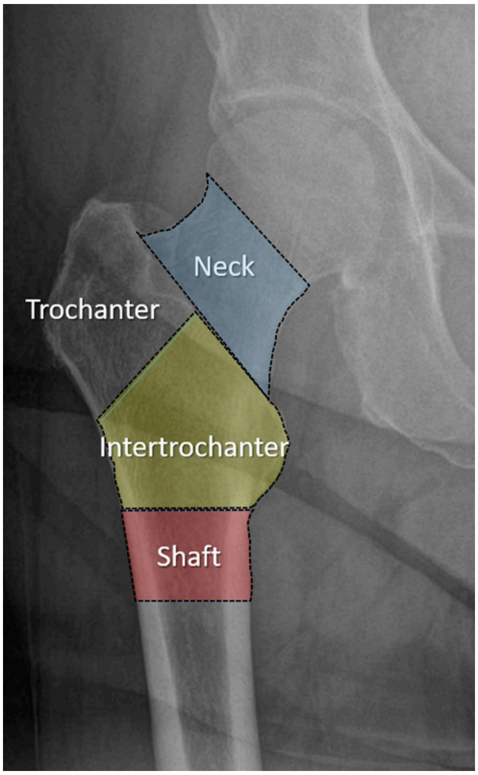

Fig. 1-A

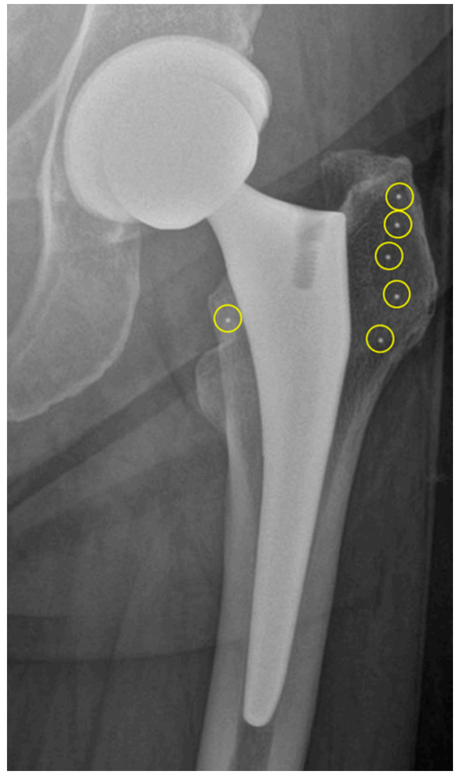
Fig. 1-B

Fig. 1-A Volumes of interest in preoperative quantitative CT analysis of volumetric BMD. **Fig. 1-B** Postoperative radiograph of an Accolade II stem with implanted RSA markers (yellow circles) in the trochanteric bone.

the settling period. Ideally, cementless femoral stems should not migrate at all[2]. Well-performing femoral stems have shown no or minimal (≤1.0 mm) subsidence during the first postoperative months[3-6]. Clinical subsidence, visible on postoperative radiographs, remains a source of postoperative morbidity[7] and even carries a risk of early revision[8]. Clinical subsidence has been associated with a lower cortical index and a lack of metaphyseal fit[9].

Good primary stem stability is difficult to achieve in postmenopausal women. Cementless stems rely on initial press-fit fixation against cortical bone[1], and, in postmenopausal women, cortical bone changes of the proximal part of the femur[10-12] pose natural difficulties in achieving primary axial and rotational stability. Postmenopausal women are prone to stem migration during the first 3 postoperative months[13-15]; such migration is resistant to antiresorptive treatment[14,15]. Despite initial migration, stems osseointegrate and are stable at 8 to 10 years postoperatively[15,16].

Although the initial migration measurable by RSA may not be detrimental for osseointegration, it may carry other untoward consequences. The purpose of the present analysis was to assess a possible relationship between the magnitude of initial stem migration and the speed of postoperative recovery in a cohort of postmenopausal women who underwent quantitative computed tomography (CT) of the proximal part of the femur prior to cementless total hip arthroplasty. We formulated 2 hypotheses concerning initial stem migration: (1) low volumetric bone mineral density (BMD) will be associated with greater migration, and (2) with lower volumetric BMD, clinical recovery will be slower and patient-reported outcome will be less satisfactory.

Materials and Methods

Study Design

A prior randomized, double-blinded, placebo-controlled trial[14] examined the effects of denosumab in postmenopausal women who underwent cementless total hip arthroplasty. Denosumab[17,18] prevented periprosthetic bone resorption but did not reduce the amount of initial stem migration[14].

Hip areal BMD measured by dual x-ray absorptiometry (DXA) is not sensitive in discriminating women at high risk for stem subsidence[19]. Quantitative CT of the proximal part of the femur allows cortical and cancellous volumetric BMD evaluation[20,21]. Here, we delineated preoperative volumetric BMD characteristics and postoperative recovery in patients who experienced initial stem subsidence of <2 mm or ≥2 mm in the denosumab trial. A subsidence threshold of 2 mm was adopted from the clinical literature[22]. The proportion of patients taking the drug rather than the placebo was similar in the groups with and without initial stem subsidence of ≥2 mm (Table I).

Patients

The cohort included 65 physically active postmenopausal women with Dorr type-A or B proximal femoral anatomy who

TABLE II Surgical Details

	Subsidence <2 mm	Subsidence ≥2 mm	P Value*	Outliers	P Value†
Size of the femoral stem‡	3 (1 to 5)	3 (2 to 6)	0.231	3 (2 to 4)	0.328
Offset of the femoral stem§			0.146		0.666
132° neck angle	11 (37%)	5 (18%)		1 (14%)	
127° neck angle	19 (63%)	23 (82%)		6 (86%)	
Size of the acetabular cup‡ *(mm)*	53 (50 to 56)	53 (50 to 54)	0.937	52 (50 to 54)	0.704
Stem-to-canal fill ratio#**					
Proximal stem *(%)*	97.9 ± 2.6	97.4 ± 2.2	0.431	98.3 ± 2.2	0.586
Middle stem *(%)*	86.5 ± 10.1	85.9 ± 6.8	0.767	82.0 ± 5.0	0.129
Distal stem *(%)*	85.8 ± 10.6	84.1 ± 7.6	0.508	81.6 ± 5.1	0.243
Femoral offset** *(mm)*					
Preoperative	37.6 ± 4.9	38.5 ± 4.7	0.494	37.9 ± 3.1	0.866
Postoperative	37.7 ± 4.4	38.0 ± 5.9	0.786	35.9 ± 4.2	0.228
Leg-length inequality†† *(mm)*					
Preoperative	0 (−6 to 6)	−2 (−6 to 2)	0.873	−3 (−15 to 17)	0.744
Postoperative	0 (−5 to 5)	−1 (−7 to 2)	0.281	−12 (−21 to 7)	0.074
Blood loss during surgery** *(mL)*	340 ± 120	370 ± 160	0.432	340 ± 190	0.477
Operative time** *(min)*	84 ± 10	80 ± 10	0.107	81 ± 6	0.958

*The statistical comparison of subjects with <2-mm or ≥2-mm stem subsidence was conducted using either the independent-sample 2-tailed t test or the Mann-Whitney U test for continuous data and the 2-sided Fisher exact test for the categorical variables. †The statistical comparison of outliers with non-outliers (subjects with a stem subsidence of <2 mm or ≥2 mm) was conducted using the independent-sample Mann-Whitney U test for continuous data and the 2-sided Fisher exact test for the categorical variables. ‡The values are given as the median, with the range in parentheses. §The values are given as the number of patients, with the percentage in parentheses. #The ratio of stem width to femoral canal width 10 mm above the lesser trochanter (proximal stem), 60 mm below the lesser trochanter (middle stem), and 25 mm above the distal tip of the stem (distal stem). **The values are given as the mean and the standard deviation. ††The values are given as the median, with the 95% CI in parentheses.

had primary hip osteoarthritis. The recruitment process involved strict inclusion and exclusion criteria[14]. The exclusion criteria included ever using bisphosphonates or use of other drugs that affect bone metabolism. Subjects with a Dorr type-C femur were excluded. Of the initially recruited 67 randomized subjects, 65 completed the 2-year follow-up and were evaluated in our study.

DXA and Bone Turnover Markers

Screening included hip, lumbar spine, and distal radial areal BMD evaluation via DXA imaging (Hologic Discovery DXA System; Hologic). Osteoporosis and osteopenia were defined on the basis of T-scores of the lumbar spine and the hips according to the World Health Organization (WHO) classification (Table I). Reflecting the exclusion of subjects with Dorr type-C femora, only 2 subjects had osteoporosis. The rate of bone turnover was evaluated via measurements of serum bone turnover marker levels (procollagen type-1 N-terminal propeptide [PINP] and C-terminal telopeptide of type 1 collagen [CTX])[14].

Quantitative CT

The proximal parts of the femora of patients were imaged via quantitative CT using a Somatom Sensation 64-slice CT scanner (Siemens AG Healthcare Sector) with a calibration phantom and were analyzed using MIAF (Medical Image Analysis Framework)-Femur software (Institute of Medical Physics, University of Erlangen)[21]. Volumetric cortical and trabecular BMD was analyzed in defined volumes of interest (femoral neck, intertrochanteric region, trochanter, subtrochanteric shaft) (Fig. 1-A). Ten subjects did not undergo quantitative CT evaluation.

Surgical Procedure and Postoperative Care

All subjects underwent cementless total hip arthroplasty using an anterolateral Hardinge approach and implantation of a tapered, single-wedge femoral stem (Accolade II; Stryker)[23], a 36-mm metallic head, and a cementless acetabular component with a polyethylene liner. The recommended broach-only technique[24] was employed to achieve adequate mediolateral cortical contact of the stem. Patients were mobilized postoperatively under the supervision of physiotherapists and unrestricted weight-bearing was allowed with the aid of crutches.

RSA

The femoral stem migration was measured by model-based RSA[25]. The accuracy of the method was verified in a phantom model[26]. As previously reported[14], computer-aided design surface models of each stem size, provided confidentially by the

TABLE III Preoperative Femoral Quantitative CT by Magnitude of Femoral Stem Subsidence

Variable	Subsidence <2 mm* (N = 27)	Subsidence ≥2 mm* (N = 22)	P Value†	Outliers* (N = 6)	P Value‡
Total hip					
Integral volumetric BMD *(mg/cm³)*	324.6 (304.0 to 345.2)	292.9 (270.9 to 315.0)	0.036§	268.5 (197.8 to 339.3)	0.116
Cortical volumetric BMD *(mg/cm³)*	709.2 (679.9 to 738.4)	676.5 (644.3 to 708.7)	0.127	613.6 (515.0 to 712.3)	0.063
Trabecular volumetric BMD *(mg/cm³)*	138.7 (122.5 to 154.9)	113.8 (97.4 to 130.3)	0.032§	107.1 (65.5 to 148.7)	0.347
Cortical bone thickness *(mm)*	2.00 (1.85 to 2.15)	2.07 (1.95 to 2.20)	0.447	1.98 (1.65 to 2.32)	0.518
Femoral neck					
Integral volumetric BMD *(mg/cm³)*	370.0 (344.5 to 395.5)	343.4 (314.1 to 372.8)	0.162	331.1 (281.6 to 380.6)	0.294
Cortical volumetric BMD *(mg/cm³)*	670.1 (638.5 to 701.8)	666.5 (632.7 to 698.3)	0.834	644.6 (594.4 to 694.8)	0.518
Trabecular volumetric BMD *(mg/cm³)*	188.3 (167.3 to 209.3)	157.0 (131.7 to 182.3)	0.053	146.5 (110.0 to 183.1)	0.282
Cortical bone thickness *(mm)*	1.94 (1.80 to 2.08)	1.99 (1.86 to 2.11)	0.635	1.98 (1.70 to 2.26)	0.782
Trochanter					
Integral volumetric BMD *(mg/cm³)*	265.9 (246.6 to 285.3)	242.9 (220.6 to 265.3)	0.113	232.9 (157.2 to 308.5)	0.361
Cortical volumetric BMD *(mg/cm³)*	585.2 (552.5 to 617.9)	545.3 (507.3 to 583.2)	0.105	507.2 (387.7 to 626.8)	0.144
Trabecular volumetric BMD *(mg/cm³)*	116.6 (100.2 to 132.9)	100.8 (81.3 to 120.4)	0.206	100.2 (54.4 to 146.0)	0.722
Cortical bone thickness *(mm)*	1.77 (1.63 to 1.92)	1.91 (1.78 to 2.03)	0.182	1.86 (1.50 to 2.22)	0.927
Intertrochanteric					
Integral volumetric BMD *(mg/cm³)*	362.5 (337.4 to 387.6)	314.9 (290.0 to 339.8)	0.008§	273.9 (194.5 to 353.4)	0.042
Cortical volumetric BMD *(mg/cm³)*	869.0 (834.5 to 903.5)	820.0 (780.8 to 859.2)	0.058	741.9 (635.3 to 848.5)	0.029
Trabecular volumetric BMD *(mg/cm³)*	133.8 (117.0 to 150.6)	104.7 (89.8 to 119.5)	0.012§	93.1 (53.1 to 133.1)	0.110
Cortical bone thickness *(mm)*	2.46 (2.25 to 2.68)	2.47 (2.30 to 2.63)	0.981	2.25 (1.83 to 2.67)	0.307
Shaft					
Integral volumetric BMD *(mg/cm³)*	670.1 (619.3 to 721.0)	609.7 (567.1 to 652.4)	0.074	486.3 (338.3 to 634.4)	0.009§
Cortical volumetric BMD *(mg/cm³)*	1,156.0 (1,120.0 to 1,191.9)	1,117.4 (1,082.0 to 1,152.8)	0.126	1,012.2 (851.1 to 1,173.3)	0.045§
Trabecular volumetric BMD *(mg/cm³)*	52.1 (33.9 to 70.5)	25.7 (9.5 to 41.8)	0.034§	39.8 (7.7 to 72.0)	0.803
Cortical bone thickness *(mm)*	3.85 (3.47 to 4.23)	3.82 (3.53 to 4.11)	0.905	3.02 (2.31 to 374)	0.018§

*The values are given as the mean, with the 95% CI in parentheses. †The statistical comparison of subjects with stem subsidence of <2 mm or ≥2 mm was conducted using the independent-sample 2-tailed t test. ‡The statistical comparison of outliers with non-outliers (subjects with a stem subsidence of <2 mm or ≥2 mm) was conducted using the independent-sample Mann-Whitney U test. §Significant.

implant manufacturer, were utilized. During the surgical procedure, multiple tantalum RSA markers were implanted into trochanteric bone (Fig. 1-B). The stability of the markers was assessed by calculating the mean error of rigid body fitting (upper limit, <0.35), and adequate distribution of the markers was assessed by calculating the mean error of the condition number (upper limit, <150). Baseline RSA imaging was performed within 3 days after the surgical procedure and was repeated after 3, 5, and 11 months. Time-related translations and rotations about the x, y, and z axes were measured using MBRSA software, version 3.34 (Medis Specials). Initial migration was defined as translation along the y axis (subsidence) and/or rotation around the y axis (rotation) at 5 months. Clinical precision, calculated for each axis based on double examinations[27], was 110 μm for the measurement of subsidence and 1.04° for the measurement of rotation.

Radiographic Assessments

A computerized method (Rhinoceros software, version 3.0SR5b; Robert McNeel & Associates) was used to evaluate the canal flare index[28], femoral offset[29], and stem-to-canal ratios[30]. The radiographic assessment of stem osseointegration was performed on the basis of the criteria of Engh et al.[31].

Functional Assessment

The objective assessment of functional recovery was based on the measurement of walking parameters[32] and walking activity[33]. Self-selected comfortable walking speed (m/s), stride length (m), and cadence (steps/min) were measured using a mobile inertial sensor gait analysis system (RehaWatch; HASOMED)[34] before the surgical procedure and were repeated at 3, 5, 11, and 24 months postoperatively. For the assessment of physical activity[35], total daily walking steps for periods of 7 days were recorded using digital pedometers before the surgical procedure and at 3, 5, and 11 months postoperatively.

Patient-Reported Outcome Measures

Clinical assessments included recordings of standard patient-reported outcome measures, including the Harris hip score (HHS), the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), the RAND

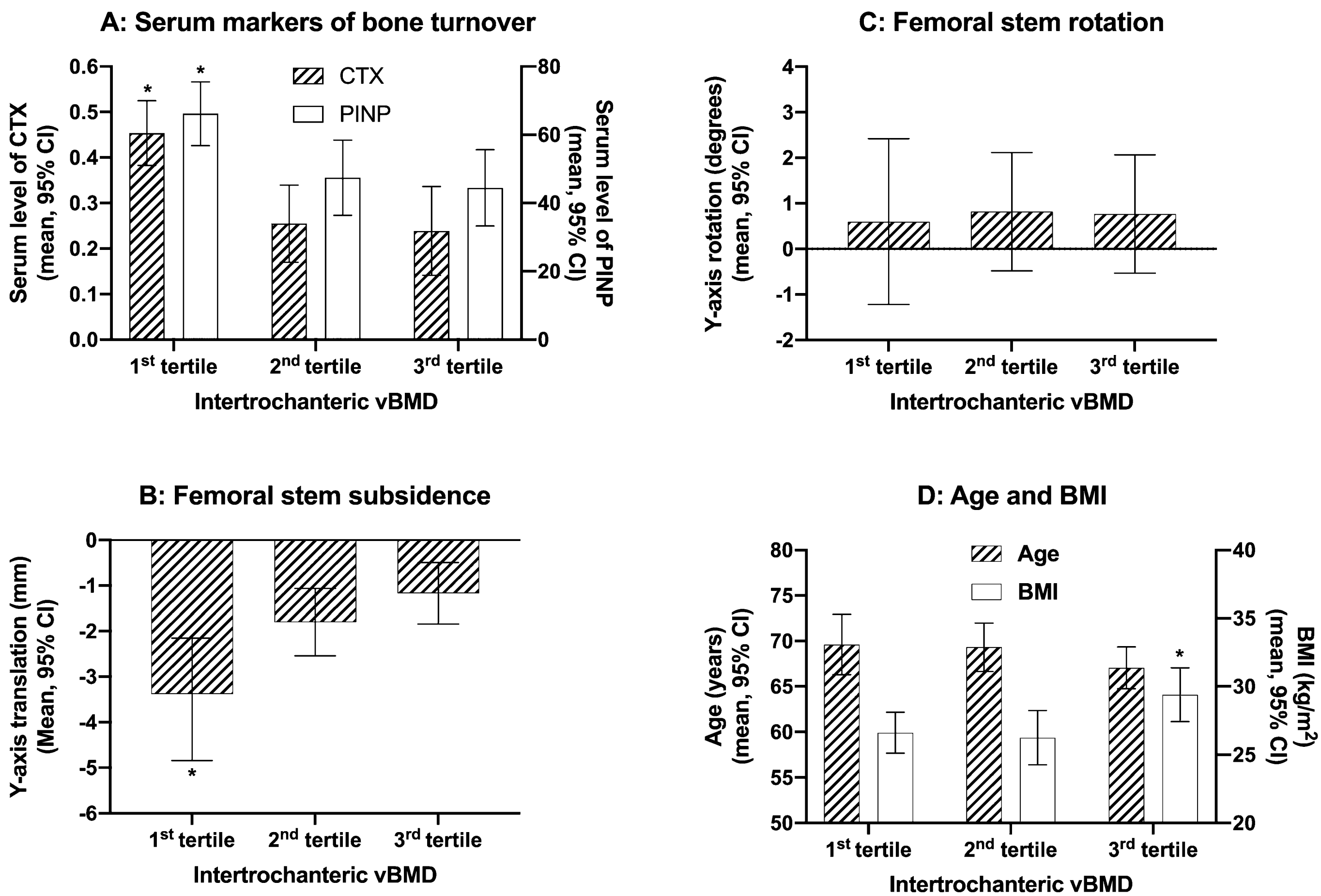

Fig. 2

Graphs showing mean serum markers of bone turnover (**Fig. 2-A**), RSA-measured femoral stem subsidence (**Figr. 2-B**), rotation (**Fig. 2-C**), and patient age and BMI (**Fig. 2-D**) among subjects categorized into 3 groups according to tertiles of intertrochanteric volumetric BMD (vBMD). The asterisks indicate significance ($p < 0.05$), and the error bars indicate the 95% CI.

36-Item Health Survey (RAND-36), and a Brief Pain Inventory (BPI) questionnaire.

Statistical Analysis

Analysis of prior trial data[14] was conducted according to the intention-to-treat principle without any exclusions or exploration of outliers. The comparison of subjects with subsidence of <2 mm or ≥2 mm was performed with and without RSA outliers (n = 7). The outliers[19] were identified by the applied statistical software, which defined the outliers as $X \geq Q3 + (1.5 \times$ interquartile range [IQR]) and $X \leq Q1 - (1.5 \times IQR)$, where X represents the migration (subsidence or rotation), Q1 represents the first quartile limit and Q3 represents the third quartile limit, and IQR represents the difference between Q1 and Q3 limits. The demographic and baseline characteristics of the 2 groups were compared using the independent-sample t test or Mann-Whitney U test for continuous variables and the 2-sided chi-square test or Fisher exact test for categorical variables. Differences in functional recovery and patient-reported outcome measures were analyzed using linear mixed-effects models for repeated measures. The diagnostic accuracy of volumetric BMD as measured by quantitative CT was tested using receiver operating characteristic (ROC) curves, which were created by plotting the true-positive rate (sensitivity) against the false-positive rate (1 − specificity). Statistics included the estimated area under the curve (AUC) and 95% confidence intervals (CIs). Subjects categorized according to the tertiles of intertrochanteric volumetric BMD values were compared using analysis of variance with the Tukey post hoc t test. A comparison of outliers and non-outliers was performed using the independent-sample Mann-Whitney U test and the 2-sided chi-square test or the Fisher exact test. Significance was set at $p < 0.05$. Analyses were performed using SAS version 9.4 (SAS Institute) and SPSS Statistics version 25.0 (IBM).

Results

Clinical Characteristics

In the comparison of the 2 groups, the mean age was higher in subjects with subsidence of ≥2 mm (Table I). The analysis

TABLE IV Initial Femoral Stem Migration by 5 Months Postoperatively

	Subsidence <2 mm* (N = 30)	Subsidence ≥2 mm* (N = 28)	Outliers* (N = 7)
Translation *(mm)*			
X axis	0.09 (−0.07 to 0.25)	0.18 (−0.16 to 0.53)	−1.25 (−2.03 to −0.48)
Y axis	−0.80 (−1.09 to −0.51)	−3.09 (−3.47 to −2.70)	−7.52 (−9.91 to −5.13)
Z axis	−0.39 (−0.60 to −0.17)	−0.66 (−0.90 to −0.41)	−0.33 (−1.50 to 0.85)
Rotation *(deg)*			
X axis	0.15 (−0.41 to 0.70)	−0.57 (−0.91 to −0.23)	−1.50 (−3.25 to 0.25)
Y axis	0.71 (−0.18 to 1.59)	1.23 (0.33 to 2.13)	−2.71 (−8.57 to 3.15)
Z axis	0.05 (−0.23 to 0.34)	0.28 (0.09 to 0.47)	0.45 (−0.82 to 1.73)

*The values are given as the mean, with the 95% CI in parentheses.

of surgery-related factors, including the measurement of stem-to-canal fill ratios, showed no significant intergroup differences (Table II). The 2 groups did not differ in hip areal BMDs as measured by DXA (Table I), but subjects with subsidence of ≥2 mm had significantly lower total hip integral volumetric BMD values ($p < 0.05$) and intertrochanteric integral volumetric BMD values ($p < 0.01$) (Table III).

Categorization of subjects according to tertiles of intertrochanteric volumetric BMD values, ranging from 259.2 mg/cm^3 (95% CI, 243.6 to 274.8 mg/cm^3) in the first tertile to 409.7 mg/cm^3 (95% CI, 390.7 to 428.8 mg/cm^3) in the third tertile, revealed an association between the rate of bone turnover, intertrochanteric volumetric BMD, and stem subsidence (Fig. 2). Subjects with the lowest (first tertile) intertrochanteric volumetric BMD were characterized by high levels of bone resorption (CTX) and bone formation (PINP) serum markers (Fig. 2-A) as well as a high magnitude of subsidence (Fig. 2-B) without a concomitant increase in stem rotation (Fig. 2-C).

Low intertrochanteric volumetric BMD values were common among patients ≥75 years of age, but were also noted in younger age groups (Fig. 2-D). There were lower body mass index (BMI) values for subjects in the first intertrochanteric volumetric BMD value tertile at a mean (and standard deviation) of 26.6 ± 3.0 kg/m^2 and for subjects in the second intertrochanteric volumetric BMD value tertile at 26.3 ± 4.2 kg/m^2 compared with subjects with the highest intertrochanteric volumetric BMD at 29.4 ± 4.0 kg/m^2 ($p = 0.027$).

RSA-Measured Stem Migration and Accuracy of Quantitative CT

Subsidence of <2 mm was characterized by y axis translation of 0.80 mm with marginal migrations in other directions (Table IV). Subjects with subsidence of ≥2 mm (mean, 3.09 mm) showed a concomitant y axis rotation of 1.23° (95% CI, 0.33° to 2.13°) into retroversion. The initial migration occurred predominantly during the first 3 postoperative months (see Appendix Supplementary Fig. 1). The evaluation of intertrochanteric volumetric BMD via ROC analysis revealed an AUC value of 0.708 (95% CI, 0.572 to 0.843; $p = 0.008$) for discriminating between subsidence of <2 mm and ≥2 mm. The corresponding AUC value was not significant (0.629 [95% CI, 0.493 to 0.765]; $p = 0.075$) for intertrochanteric areal BMD.

Walking Speed and Walking Activity

Subjects with subsidence of <2 mm were found to have faster postoperative improvement in walking speed and activity (Fig. 3). At 11 months, subjects with subsidence of <2 mm had greater walking speeds (1.24 m/s [95% CI, 1.16 to 1.32 m/s]) compared with subjects with subsidence of ≥2 mm (1.07 m/s [95% CI, 0.99 to 1.16 m/s]) ($p = 0.0074$).

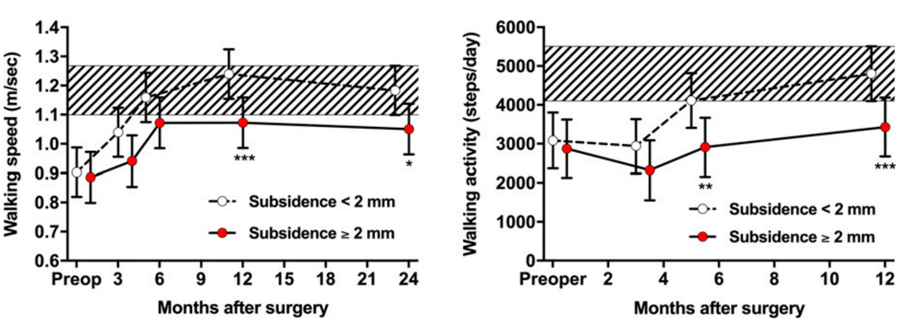

Fig. 3

Mean walking speed (left) and walking activity (right) preoperatively and as a function of time postoperatively. The cross-hatched zones represent the 95% CI values of subjects with stem subsidence of <2 mm at the latest postoperative visit. The asterisks indicate significance (*$p < 0.05$, **$p = 0.02$, and ***$p < 0.01$), and the error bars indicate the 95% CI.

TABLE V Clinical Scores of Patients by Magnitude of Femoral Stem Subsidence

Clinical Scores	Stem Subsidence <2 mm*	Stem Subsidence ≥2 mm*	P Value†
HHS *(points)*			
Preoperative	47.7 (42.7 to 52.6)	48.1 (43.0 to 53.2)	0.903
3 months	79.4 (74.5 to 84.4)	69.8 (64.6 to 75.0)	0.009‡
5 months	81.8 (76.9 to 86.8)	76.9 (71.7 to 82.0)	0.172
11 months	82.7 (77.8 to 87.7)	76.9 (71.8 to 82.0)	0.107
24 months	82.3 (77.4 to 87.2)	76.8 (71.7 to 81.9)	0.125
WOMAC *(points)*			
Preoperative	48.8 (43.9 to 53.7)	47.9 (42.6 to 53.2)	0.811
3 months	12.9 (8.0 to 17.9)	19.3 (13.9 to 24.7)	0.086
5 months	13.3 (8.4 to 18.2)	15.9 (10.7 to 21.1)	0.473
11 months	13.7 (8.7 to 18.6)	19.9 (14.7 to 25.0)	0.090
24 months	9.1 (4.2 to 14.1)	20.7 (15.6 to 25.8)	0.002‡
RAND-36 Physical Component *(points)*			
Preoperative	31.5 (23.3 to 39.6)	34.7 (26.4 to 43.1)	0.584
3 months	60.6 (52.5 to 69.6)	51.2 (42.7 to 59.7)	0.115
5 months	70.8 (62.7 to 78.9)	54.8 (46.3 to 63.3)	0.008‡
11 months	66.0 (58.0 to 74.1)	58.9 (50.5 to 67.4)	0.231
24 months	67.2 (59.1 to 75.3)	55.1 (46.8 to 63.5)	0.041‡
RAND-36 Mental Component *(points)*			
Preoperative	56.7 (49.6 to 63.7)	52.3 (45.1 to 59.2)	0.392
3 months	72.8 (65.8 to 79.8)	63.9 (56.6 to 71.2)	0.082
5 months	78.2 (71.2 to 85.2)	66.1 (58.7 to 73.5)	0.020‡
11 months	80.2 (73.2 to 87.2)	62.7 (55.4 to 70.0)	0.008‡
24 months	80.2 (73.2 to 87.2)	62.3 (55.1 to 69.6)	0.006‡

*The values represent the least squares means, with the 95% CI in parentheses. †The statistical comparison of subjects with <2 mm or ≥2 mm stem subsidence was performed using linear mixed-effects models for repeated measures. ‡Significant.

Subjects with subsidence of <2 mm also had greater walking activity (4,802 steps per day [95% CI, 4,099 to 5,505 steps per day]) compared with those with subsidence of ≥2 mm (3,429 steps per day [95% CI, 2,671 to 4,187 steps per day]) (p = 0.0096) at 11 months. Subsidence of ≥2 mm was not associated with any significant leg-length inequality (Table II).

Clinical Scores

Subjects with subsidence of <2 mm showed faster patient-reported outcome measure improvement postoperatively. The differences between the 2 groups were significant for the HHS at 3 months (p = 0.009) and for the RAND-36 physical component (p = 0.008) and mental component (p = 0.020) at 5 months (Table V). At 2 years, subjects with subsidence of <2 mm were noted to have lower (better) total WOMAC scores (p = 0.002) and higher RAND-36 mental component scores (p = 0.006) (Table V), lower interference of pain with activity (p = 0.001) (see Appendix Supplementary Table I), and a higher rate of minimum postoperative improvement in BPI pain severity (p = 0.013) (see Appendix Supplementary Table II). Two subjects had local pain in the involved hip, and both of them had subsidence of <2 mm. No single factor or a comorbidity was associated with any difference in continued pain.

Radiographic Osseointegration and Implant Survival

At 2 years, all cohort stems had high fixation scores (range, 3 to 10 points) and stability (range, 7 to 10 points) and were classified as stable and osseointegrated (Table VI). Stem subsidence was not associated with any failure of ultimate bonding. No periprosthetic fractures, deep infections, or hip dislocations occurred. No revision of any implant component was performed during the 3-year extension period of the trial.

Sensitivity Analysis

Comparisons of lower thresholds for stem subsidence (<1.0 mm, <1.5 mm, or <2.0 mm) showed not significant differences in terms of walking speed and patient-reported outcome measures (see Appendix Supplementary Fig. 2). Including only subjects <75 years of age (n = 53) did not affect differences among the 2 groups. Six patients who underwent contralateral total hip arthroplasty during the first 3 postoperative years did not affect statistical results.

TABLE VI Radiographic Evaluation of Femoral Stem Osseointegration at 2 Years Postoperatively

	Subsidence <2 mm	Subsidence ≥2 mm	P Value*	Outliers	P Value†
Fixation score‡ *(points)*	8.0 (6.7 to 9.3)	8.9 (7.9 to 10.0)	0.249	10.0 (10.0 to 10.0)	0.186
Stability score‡ *(points)*	8.3 (7.7 to 8.9)	8.4 (7.9 to 9.0)	0.739	9.5 (9.5 to 9.5)	0.047§
Total score‡ *(points)*	16.3 (14.9 to 17.7)	17.4 (16.3 to 18.4)	0.439	19.5 (19.5 to 19.5)	0.014§
Endosteal bone bridging#			0.212		1.000
Yes	21 (70%)	24 (86%)		6 (86%)	
No	9 (30%)	4 (14%)		1 (14%)	
Stable distal stem with pedestal formation#			0.151		1.000
Yes	24 (80%)	17 (61%)		5 (71%)	
No	6 (20%)	11 (39%)		2 (29%)	
Thin, radiodense lines surrounding the distal stem#			0.600		0.246
Yes	17 (57%)	18 (64%)		6 (86%)	
No	13 (43%)	10 (36%)		1 (14%)	
Distal cortical hypertrophy#			0.416		1.000
Yes	12 (40%)	8 (29%)		2 (29%)	
No	18 (60%)	20 (71%)		5 (71%)	

*The statistical comparison of subjects with a stem subsidence of <2 mm or ≥2 mm was conducted using the Mann-Whitney U test for continuous data and the 2-sided Fisher exact test for the categorical variables. †The statistical comparison of outliers with non-outliers (subjects with a stem subsidence of <2 mm or ≥2 mm) was conducted using the independent-sample Mann-Whitney U test for continuous data and the 2-sided Fisher exact test for the categorical variables. ‡The values are given as the mean, with the 95% CI in parentheses. §Significant. #The values are given as the number of patients, with the percentage in parentheses.

Outliers

The inclusion of outliers increased the significance of intergroup differences in walking speed, patient-reported outcome measures, and volumetric BMD values. Compared with non-outliers, outliers were older and had lower total hip and intertrochanteric areal BMD, quicker preoperative walking speed and better cadence (Table I), lower volumetric BMD values of the intertrochanteric and shaft regions, and thinner cortical bone of the shaft (Table III). Outliers had wide CIs of patient-reported outcome measures (see Appendix Supplementary Table III). Radiographic evaluation of osseointegration revealed that outliers had uniformly high fixation and stability scores (Table VI).

Discussion

According to our hypotheses, low volumetric density of intertrochanteric trabecular bone was associated with greater initial migration of the Accolade II stem. With lower volumetric BMD, clinical recovery was slower and patient-reported outcome was less satisfactory. Low volumetric BMD was associated with high serum levels of bone turnover markers (pathognomonic for postmenopausal bone loss).

Tapered, single-wedge stems (Type 1[1]) are designed to engage metaphyseal cortical bone in the medial-lateral plane only[23,24,30]. Taperloc (Zimmer Biomet), the first generation of this stem design, has shown minimal postoperative migration[4]. In postmenopausal women, cortical bone undergoes endosteal trabeculation[12] with concurrent loss of trochanteric trabecular bone[36], thus highlighting the observed relationship between low intertrochanteric trabecular volumetric BMD and subsidence. Concurrent changes of the endosteal surface of cortical bone were likely. Changes in cortical volumetric BMD reached significance in outliers with more severe bone loss and stem migration. Further clinical evidence of the critical role of cortical bone is illustrated by the recently described meticulous broaching technique that minimizes the risk of radiographic subsidence of the Accolade II stem[8].

Cementless stems differ in the means of obtaining cortical contact and initial fixation[1] and the stem design dictates sensitivity to subsidence. The use of tapered single-wedge stems requires adequate bone stock and unaltered femoral geometry[24]. Our RSA results confirmed the high primary stability of the Accolade II stem with fast clinical recovery in women with Dorr type-A or B femora and high intertrochanteric volumetric BMD. It is concerning that we were unable to define inadequate bone stock based on DXA-defined thresholds of osteoporosis and osteopenia. Hip DXA imaging is insensitive, likely due to osteoarthritic pathology[37]. However, proximal femoral quantitative CT, like imaging of the distal part of the radius[19], attained moderate accuracy (defined as an

AUC between 0.70 and 0.90) in distinguishing subjects at high risk for stem subsidence.

The implant manufacturer advises against use of the Accolade II stem in overweight patients[38]. However, current RSA results confirmed previously reported findings[22] with regard to the stem being resistant to BMI-related subsidence. Here, higher BMI was associated not only with higher intertrochanteric volumetric BMD but also with less stem subsidence.

Many prior RSA studies showed differences in migration of different femoral stem designs, but only a few were noted to exhibit concomitant differences in patient-reported outcome measures[3,39]. A prospective study of the Taperloc stem found no association between patient-reported outcome measures and stem subsidence[40]. As a new approach for RSA studies, we performed an objective assessment of the functional outcome. There are no clear explanations for the observed clinical consequences of the initial migration. Subsidence was only a few millimeters and was not associated with malrotation or any differences in the restoration of femoral offset and leg-length equality. Based on finite element models, stem micromotion is sensitive to local BMD[41]. We cannot exclude the possibility that permanent subsidence was associated with dynamic micromotion of the weight-bearing stem prior to stabilization.

As a limitation, this study had no control group. In a more definitive randomized trial, women with cemented femoral stems could serve as the negative control. Although our findings are relevant only for the investigated cementless stem design in postmenopausal women, it is likely that the functional consequences of initial subsidence are not implant-specific. Clinically, it is difficult to extrapolate the RSA-measured threshold of 2 mm to radiography in clinical practice. The accuracy of migration measurements is so low on clinical radiographs[42] that an appropriate clinical goal might be the absence of any measurable stem subsidence on radiographs.

The routine use of preoperative CT scans may not be practical for the guidance of treatment decision-making in postmenopausal women. However, patient selection based on any existing DXA scan and meticulous surgical technique may help to reduce the risk of subsidence.

Appendix

eA Supporting material provided by the authors is posted with the online version of this article as a data supplement at jbjs.org (http://links.lww.com/JBJS/G411). ■

Note: The authors thank Mia Vuopio, MSc, for performing gait analysis, and Sanaz Nazari-Farsani, MSc, for performing RSA measurements.

Hannu T. Aro, MD, PhD[1]
Klaus Engelke, PhD[2]
Kimmo Mattila, MD, PhD[3]
Eliisa Löyttyniemi, MSc[4]

[1]Department of Orthopaedic Surgery and Traumatology, Turku University Hospital and University of Turku, Turku, Finland

[2]Institute of Medical Physics, University of Erlangen-Nuremberg, Erlangen, Germany

[3]Department of Diagnostic Imaging, Turku University Hospital and University of Turku, Turku, Finland

[4]Unit of Biostatistics, Department of Clinical Medicine, University of Turku, Turku, Finland

Email address for H.T. Aro: hannu.aro@utu.fi

ORCID iD for H.T. Aro: 0000-0003-3118-9144
ORCID iD for K. Engelke: 0000-0001-9875-4123
ORCID iD for K. Mattila: 0000-0003-2969-4299
ORCID iD for E. Löyttyniemi: 0000-0002-7278-6511

References

1. Khanuja HS, Vakil JJ, Goddard MS, Mont MA. Cementless femoral fixation in total hip arthroplasty. J Bone Joint Surg Am. 2011 Mar 2;93(5):500-9.

2. Kärrholm J. Radiostereometric analysis of early implant migration - a valuable tool to ensure proper introduction of new implants. Acta Orthop. 2012 Dec;83(6):551-2. Epub 2012 Nov 5.

3. Søballe K, Toksvig-Larsen S, Gelineck J, Fruensgaard S, Hansen ES, Ryd L, Lucht U, Bünger C. Migration of hydroxyapatite coated femoral prostheses. A roentgen stereophotogrammetric study. J Bone Joint Surg Br. 1993 Sep;75(5):681-7.

4. Bøe BG, Röhrl SM, Heier T, Snorrason F, Nordsletten L. A prospective randomized study comparing electrochemically deposited hydroxyapatite and plasma-sprayed hydroxyapatite on titanium stems. Acta Orthop. 2011 Feb;82(1):13-9. Epub 2010 Dec 29.

5. Thien TM, Thanner J, Kärrholm J. Fixation and bone remodeling around a low-modulus stem seven-year follow-up of a randomized study with use of radiostereometry and dual-energy x-ray absorptiometer. J Arthroplasty. 2012 Jan;27(1): 134-142.e1. Epub 2011 May 5.

6. Kruijntjens DSMG, Koster L, Kaptein BL, Jutten LMC, Arts JJ, Ten Broeke RHM. Early stabilization of the uncemented Symax hip stem in a 2-year RSA study. Acta Orthop. 2020 Apr;91(2):159-64. Epub 2020 Jan 13.

7. Narayanan R, Elbuluk AM, Chen KK, Eftekhary N, Zuckerman JD, Deshmukh AJ. Does femoral morphology and stem alignment influence outcomes of cementless total hip arthroplasty with proximally coated double-tapered titanium stems? Hip Int. 2020 Jan 8;1120700019891702. Epub 2020 Jan 8.

8. Warth LC, Grant TW, Naveen NB, Deckard ER, Ziemba-Davis M, Meneghini RM. Inadequate metadiaphyseal fill of a modern taper-wedge stem increases subsidence and risk of aseptic loosening: technique and distal canal fill matter! J Arthroplasty. 2020 Jul;35(7):1868-76. Epub 2020 Feb 17.

9. Mulliken BD, Bourne RB, Rorabeck CH, Nayak N. A tapered titanium femoral stem inserted without cement in a total hip arthroplasty. Radiographic evaluation and stability. J Bone Joint Surg Am. 1996 Aug;78(8):1214-25.

10. Dorr LD, Faugere MC, Mackel AM, Gruen TA, Bognar B, Malluche HH. Structural and cellular assessment of bone quality of proximal femur. Bone. 1993 May-Jun; 14(3):231-42.

11. Szulc P, Seeman E, Duboeuf F, Sornay-Rendu E, Delmas PD. Bone fragility: failure of periosteal apposition to compensate for increased endocortical resorption in postmenopausal women. J Bone Miner Res. 2006 Dec;21(12):1856-63.

12. Zebaze RM, Ghasem-Zadeh A, Bohte A, Iuliano-Burns S, Mirams M, Price RI, Mackie EJ, Seeman E. Intracortical remodelling and porosity in the distal radius and post-mortem femurs of women: a cross-sectional study. Lancet. 2010 May 15; 375(9727):1729-36.

13. Aro HT, Alm JJ, Moritz N, Mäkinen TJ, Lankinen P. Low BMD affects initial stability and delays stem osseointegration in cementless total hip arthroplasty in women: a 2-year RSA study of 39 patients. Acta Orthop. 2012 Apr;83(2):107-14. Epub 2012 Apr 11.

14. Aro HT, Nazari-Farsani S, Vuopio M, Löyttyniemi E, Mattila K. Effect of denosumab on femoral periprosthetic BMD and early femoral stem subsidence in postmenopausal women undergoing cementless total hip arthroplasty. JBMR Plus. 2019 Aug 14;3(10):e10217.

15. Aro E, Moritz N, Mattila K, Aro HT. A long-lasting bisphosphonate partially protects periprosthetic bone, but does not enhance initial stability of uncemented femoral stems: a randomized placebo-controlled trial of women undergoing total hip arthroplasty. J Biomech. 2018 Jun 25;75:35-45. Epub 2018 May 3.

16. Aro E, Alm JJ, Moritz N, Mattila K, Aro HT. Good stability of a cementless, anatomically designed femoral stem in aging women: a 9-year RSA study of 32 patients. Acta Orthop. 2018 Oct;89(5):490-5. Epub 2018 Jul 10.

17. McClung MR, Lewiecki EM, Cohen SB, Bolognese MA, Woodson GC, Moffett AH, Peacock M, Miller PD, Lederman SN, Chesnut CH, Lain D, Kivitz AJ, Holloway DL, Zhang C, Peterson MC, Bekker PJ; AMG 162 Bone Loss Study Group. Denosumab in postmenopausal women with low bone mineral density. N Engl J Med. 2006 Feb 23; 354(8):821-31.

18. Zebaze R, Libanati C, McClung MR, Zanchetta JR, Kendler DL, Høiseth A, Wang A, Ghasem-Zadeh A, Seeman E. Denosumab reduces cortical porosity of the proximal femoral shaft in postmenopausal women with osteoporosis. J Bone Miner Res. 2016 Oct;31(10):1827-34. Epub 2016 May 19.

19. Nazari-Farsani S, Vuopio ME, Aro HT. Bone mineral density and cortical-bone thickness of the distal radius predict femoral stem subsidence in postmenopausal women. J Arthroplasty. 2020 Jul;35(7):1877-1884.e1. Epub 2020 Mar 5.

20. Genant HK, Libanati C, Engelke K, Zanchetta JR, Høiseth A, Yuen CK, Stonkus S, Bolognese MA, Franek E, Fuerst T, Radcliffe HS, McClung MR. Improvements in hip trabecular, subcortical, and cortical density and mass in postmenopausal women with osteoporosis treated with denosumab. Bone. 2013 Oct;56(2):482-8. Epub 2013 Jul 17.

21. Engelke K, Fuerst T, Dardzinski B, Kornak J, Ather S, Genant HK, de Papp A. Odanacatib treatment affects trabecular and cortical bone in the femur of postmenopausal women: results of a two-year placebo-controlled trial. J Bone Miner Res. 2015 Jan;30(1):30-8.

22. Grant TW, Lovro LR, Licini DJ, Warth LC, Ziemba-Davis M, Meneghini RM. Cementless tapered wedge femoral stems decrease subsidence in obese patients compared to traditional fit-and-fill stems. J Arthroplasty. 2017 Mar;32(3):891-7. Epub 2016 Sep 28.

23. Faizan A, Wuestemann T, Nevelos J, Bastian AC, Collopy D. Development and verification of a cementless novel tapered wedge stem for total hip arthroplasty. J Arthroplasty. 2015 Feb;30(2):235-40. Epub 2014 Oct 2.

24. Grayson C, Meneghini RM. Parallel-sided femoral stems. In: Lieberman JR, Berry DJ, editors. Advanced reconstruction hip 2. American Academy of Orthopaedic Surgeons and The Hip Society; 2017:119-125.

25. Kaptein BL, Valstar ER, Spoor CW, Stoel BC, Rozing PM. Model-based RSA of a femoral hip stem using surface and geometrical shape models. Clin Orthop Relat Res. 2006 Jul;448:92-7.

26. Nazari-Farsani S, Finnilä S, Moritz N, Mattila K, Alm JJ, Aro HT. Is model-based radiostereometric analysis suitable for clinical trials of a cementless tapered wedge femoral stem? Clin Orthop Relat Res. 2016 Oct;474(10):2246-53. Epub 2016 Jun 22.

27. Derbyshire B, Prescott RJ, Porter ML. Notes on the use and interpretation of radiostereometric analysis. Acta Orthop. 2009 Feb;80(1):124-30.

28. Noble PC, Box GG, Kamaric E, Fink MJ, Alexander JW, Tullos HS. The effect of aging on the shape of the proximal femur. Clin Orthop Relat Res. 1995 Jul;316: 31-44.

29. Mahmood SS, Mukka SS, Crnalic S, Wretenberg P, Sayed-Noor AS. Association between changes in global femoral offset after total hip arthroplasty and function, quality of life, and abductor muscle strength. A prospective cohort study of 222 patients. Acta Orthop. 2016 Feb;87(1):36-41. Epub 2015 Oct 16.

30. Issa K, Pivec R, Wuestemann T, Tatevossian T, Nevelos J, Mont MA. Radiographic fit and fill analysis of a new second-generation proximally coated cementless stem compared to its predicate design. J Arthroplasty. 2014 Jan;29(1):192-8. Epub 2013 May 21.

31. Engh CA, Massin P, Suthers KE. Roentgenographic assessment of the biologic fixation of porous-surfaced femoral components. Clin Orthop Relat Res. 1990 Aug; 257:107-28.

32. Foucher KC. Identifying clinically meaningful benchmarks for gait improvement after total hip arthroplasty. J Orthop Res. 2016 Jan;34(1):88-96. Epub 2015 Aug 6.

33. Schmalzried TP, Szuszczewicz ES, Northfield MR, Akizuki KH, Frankel RE, Belcher G, Amstutz HC. Quantitative assessment of walking activity after total hip or knee replacement. J Bone Joint Surg Am. 1998 Jan;80(1):54-9.

34. Schwesig R, Leuchte S, Fischer D, Ullmann R, Kluttig A. Inertial sensor based reference gait data for healthy subjects. Gait Posture. 2011 Apr;33(4):673-8. Epub 2011 Mar 31.

35. Schuna JM Jr, Johnson WD, Tudor-Locke C. Adult self-reported and objectively monitored physical activity and sedentary behavior: NHANES 2005-2006. Int J Behav Nutr Phys Act. 2013 Nov 11;10(1):126.

36. Moritz N, Alm JJ, Lankinen P, Mäkinen TJ, Mattila K, Aro HT. Quality of intertrochanteric cancellous bone as predictor of femoral stem RSA migration in cementless total hip arthroplasty. J Biomech. 2011 Jan 11;44(2):221-7. Epub 2010 Nov 11.

37. Nevitt MC, Lane NE, Scott JC, Hochberg MC, Pressman AR, Genant HK, Cummings SR; The Study of Osteoporotic Fractures Research Group. Radiographic osteoarthritis of the hip and bone mineral density. Arthritis Rheum. 1995 Jul;38(7):907-16.

38. Stryker. Surgical technique of Accolade II femoral hip system. 2012. Accessed 2021 Feb 11. https://www.strykermeded.com/media/1210/accolade-ii-surgical-technique.pdf

39. Kärrholm J, Malchau H, Snorrason F, Herberts P. Micromotion of femoral stems in total hip arthroplasty. A randomized study of cemented, hydroxyapatite-coated, and porous-coated stems with roentgen stereophotogrammetric analysis. J Bone Joint Surg Am. 1994 Nov;76(11):1692-705.

40. Nebergall AK, Rolfson O, Rubash HE, Malchau H, Troelsen A, Greene ME. Stable fixation of a cementless, proximally coated, double wedged, double tapered femoral stem in total hip arthroplasty: a 5-year radiostereometric analysis. J Arthroplasty. 2016 Jun;31(6):1267-74. Epub 2015 Dec 7.

41. Al-Dirini RMA, Martelli S, O'Rourke D, Huff D, Zhang J, Clement JG, Besier T, Taylor M. Virtual trial to evaluate the robustness of cementless femoral stems to patient and surgical variation. J Biomech. 2019 Jan 3;82:346-56. Epub 2018 Nov 15.

42. Malchau H, Kärrholm J, Wang YX, Herberts P. Accuracy of migration analysis in hip arthroplasty. Digitized and conventional radiography, compared to radiostereometry in 51 patients. Acta Orthop Scand. 1995 Oct;66(5):418-24.