Clin Orthop Relat Res (2016) 474:1788–1797
DOI 10.1007/s11999-016-4787-2

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A Publication of The Association of Bone and Joint Surgeons®

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CLINICAL RESEARCH

Does Degenerative Lumbar Spine Disease Influence Femoroacetabular Flexion in Patients Undergoing Total Hip Arthroplasty?

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Received: 1 December 2015 / Accepted: 8 March 2016 / Published online: 28 March 2016

Abstract
Background Sitting pelvic tilt dictates the proximity of the rim of the acetabulum to the proximal femur and, therefore, the risk of impingement in patients undergoing total hip arthroplasty (THA). Sitting position is achieved through a combination of lumbar spine segmental motions and/or femoroacetabular articular motion in the lumbar-pelvic-femoral complex. Multilevel degenerative disc disease (DDD) may limit spine flexion and therefore increase femoroacetabular flexion in patients having THAs, but this has not been well characterized. Therefore, we measured standing and sitting lumbar-pelvic-femoral alignment in patients with radiographic signs of DDD and in patients with no radiographic signs of spine arthrosis.

Questions/purposes We asked: (1) Is there a difference in standing and sitting lumbar-pelvic-femoral alignment before surgery among patients undergoing THA who have no radiographic signs of spine arthrosis compared with those with preexisting lumbar DDD? (2) Do patients with lumbar DDD experience less spine flexion moving from a standing to a sitting position and therefore compensate with more femoroacetabular flexion compared with patients who have no radiographic signs of arthrosis?
Methods Three hundred twenty-five patients undergoing primary THA had preoperative low-dose EOS spine-to-ankle lateral radiographs in standing and sitting positions. Eighty-three patients were excluded from this study for scoliosis (39 patients), spondylolysis (15 patients), not having five lumbar vertebrae (7 patients), surgical or disease fusion (11 patients), or poor image quality attributable to high BMI (11 patients). In the remaining 242 of 325 patients (75%), two observers categorized the lumbar spine as either without radiographic arthrosis or having DDD based on defined radiographic criteria. Sacral slope, lumbar lordosis, and proximal femur angles were measured, and these angles were used to calculate lumbar spine flexion and femoroacetabular flexion in standing and sitting positions. Patients were aligned in a standardized sitting position so that their femurs were parallel to the floor to achieve approximately 90° of apparent hip flexion.
Results After controlling for age, sex, and BMI, we found patients with DDD spines had a mean of 5° more posterior pelvic tilt (95% CI, −2° to −8° lower sacral slope angles; $p < 0.01$) and 7° less lumbar lordosis (95% CI, −10° to −3°; $p < 0.01$) in the standing position compared with patients without radiographic arthrosis. However, in the sitting position, patients with DDD spines had 4° less posterior pelvic tilt (95% CI, 1°–7° higher sacral slope angles; $p = 0.02$). From standing to sitting position, patients with DDD

One of the authors (CIE) is partially supported by a Ruth L. Kirschstein National Research Service Award from the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the National Institutes of Health under Award Number AR007281. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.
All ICMJE Conflict of Interest Forms for authors and *Clinical Orthopaedics and Related Research*® editors and board members are on file with the publication and can be viewed on request.

Each author certifies that his or her institution approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.

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spines experienced 10° less spine flexion (95% CI, −14° to −7°; $p < 0.01$) and 10° more femoroacetabular flexion (95% CI, 6° to 14°; $p < 0.01$).

Conclusions Most patients undergoing THA sit in a similar range of pelvic tilt, with a small mean difference in pelvic tilt between patients with DDD spines and those without radiographic arthrosis. However, in general, the mechanism by which patients with DDD of the lumbar spine achieve sitting differs from those without spine arthrosis with less spine flexion and more femoroacetabular flexion.

Clinical Relevance When planning THA, it may be important to consider which patients sit with less posterior pelvic tilt and those who rotate their pelvises forward to achieve a sitting position, as both mechanisms will limit or reduce the functional anteversion of the acetabular component in a patient with a THA. Our study provides some additional perspective on normal relationships between pelvic tilt and femoroacetabular flexion, but further research might better characterize this relationship in outliers and the possible implications for posterior instability after THA.

Introduction

Instability is a troublesome problem in total hip arthroplasty (THA) with a reported frequency after primary THA from 0.1% to 9% [7, 13, 14]. The etiology of hip instability is multifactorial and often has been associated with such surgical variables as operative approach, implant choice and position, and soft tissue repair [6, 34]. However, more recently a topic of considerable discussion is dynamic sagittal pelvic tilt and its role in deciding the optimal position of the acetabular component to avoid instability [21, 30]. Variability in pelvic tilt can change acetabular component orientation after THA, and hip replacement surgeons have investigated pelvic tilt in sitting posture [11, 19, 20], because posterior dislocations often occur when a patient is rising from a chair. Sitting pelvic tilt dictates the proximity of the rim of the acetabulum to the proximal femur and, therefore, the risk of impingement. Although some studies have described pelvic tilt during postural changes [11, 41], few have considered pelvic tilt as a function of the hip-spine relationship [23, 24], because it is difficult to view the entire lumbar spine (L1-S1) and hips on a conventional lateral radiograph.

The pelvis has been described as an intercalary bone in the lumbar-pelvic-femoral complex, or a "pelvic vertebra" [17, 22], such that pelvic tilt is dependent on spinal and femoral alignment. As a patient sits with 90° of apparent hip flexion (brings his or her femurs approximately 90° to the vertical plane), there will be motion through the lumbar spine segments and/or the femoroacetabular articulation in the lumbar-pelvic-femoral complex. It has been shown that there is limited change in pelvic tilt from standing to sitting position in patients with spine stiffness or surgical fusion [19, 22, 23]. Therefore, these patients with stiff spines need to compensate for limited lumbar spine flexion by flexing more through the hip and potentially increasing the risk of impingement of the prosthetic femoral neck on the edge of the acetabular cup or bone and therefore the risk of prosthetic dislocation.

The relative amount of lumbar spine flexion and femoroacetabular flexion during 90° of apparent hip flexion in patients undergoing THA has not been quantified. Patients with THAs often present with concurrent hip and spine arthritis, because these patients are most commonly 65 to 85 years old [3], an age group that is also at greater risk of lumbar degenerative disc disease (DDD) [37]. Because lumbar DDD can contribute to spine stiffness, and therefore pelvic tilt, we wished to quantify lumbar spine flexion and femoroacetabular flexion in two groups of potential patients with THAs: those with DDD and those without DDD. We hypothesized that as these patients go from a standing to a sitting position, patients with lumbar DDD will have limited spine flexion and therefore greater femoroacetabular flexion. Using a new low-dose radiation imaging system that can capture standing and sitting lateral radiographs of the entire lumbar-pelvic-femoral complex, we measured lumbar lordosis (L1-S1), pelvic tilt (measured as the sacral slope angle between the endplate of the sacrum and the horizontal plane), and proximal femur angles (angle between the anterior cortex of a femur and the vertical plane) to elucidate the preoperative relationship between spine flexion and femoroacetabular flexion during 90° of apparent hip flexion in patients undergoing THA.

We asked: (1) Is there a difference in standing and sitting lumbar-pelvic-femoral alignment before surgery among patients undergoing THA who have no radiographic signs of spine arthrosis compared with those with preexisting lumbar spine DDD? (2) Do patients with lumbar DDD experience less spine flexion moving from a standing to a sitting position and therefore compensate with more femoroacetabular flexion compared with patients who have no radiographic signs of arthrosis?

Patients and Methods

From February to December 2014, 325 patients undergoing primary THA were recruited to participate in this institutional review board-approved, cross-sectional study. In addition to conventional radiographs, spine-to-ankle radiographs using a low-dose radiation imaging system (EOS Imaging System; EOS Imaging Inc, Paris, France) were taken preoperatively of all patients with osteoarthritis undergoing THA who met the inclusion criteria: adults older than 18 years with no prior lower extremity joint replacement surgery. Seventy-two of the 325 patients (22%) with preexisting spinal conditions that would interfere with the desired comparisons between patients without radiographic arthrosis and patients with lumbar spondylosis were excluded (Fig. 1). Specifically, 39 patients with scoliosis, which was defined as an abnormal lateral curvature of the spine greater than 10° to the right or left in the coronal plane, 15 patients with spondylolysis (fracture of the pars interarticularis), and 7 patients who did not have five lumbar vertebrae (having four or six instead) were excluded, because these conditions can change the center of rotational axis of the lumbar spine [39]. Eleven patients who had spine ankylosis (with complete bridging osteophytes, ankylosing spondylitis, or diffuse idiopathic skeletal hyperostosis) or had surgical fusion as a treatment for their disc disease were excluded because spine fusion limits lumbar mobility [22]. Eleven additional patients (3%) with a BMI greater than 40 kg/m^2 were excluded because of poor EOS image quality. Therefore, preoperative spine-to-ankle radiographs of 242 of 325 (75%) patients (110 females) were analyzed to answer our research questions.

Biplanar Imaging and Spine Parameters

All patients underwent standing and sitting biplanar frontal and lateral plane two-dimensional radiographs from the thoracolumbar junction (T12-L1) to the ankles using the EOS imaging system. The introduction of this newer imaging technology has made it easier to quantify the hip-spine relationship in patients undergoing THA by capturing the entire lumbar-pelvic-femoral complex of patients in standing and sitting positions without image stitching or vertical distortion [10, 32]. Patients were asked to stand first and then sit in a consistent position on an adjustable stool with both feet resting flat on the floor and legs spread apart. The proximal femur angle was measured between a vertical line and the line defined by the anterior cortex of the most visible femur on standing and sitting images (Fig. 2). Patients were aligned consistently when seated on the stool so that their femurs were aligned approximately parallel to the floor (to achieve 90° of apparent hip flexion); the mean sitting proximal femur angle relative to vertical for all patients in this study was 87° ± 5°.

For each patient, three alignment parameters were measured digitally by two observers (CIE, BTB) from the lateral preoperative radiographs (Sectra PACS™ imaging system; Philips Medical Systems, Sectra Imtec AB, Linkoping, Sweden) of standing and sitting postures: proximal femur angles (described previously), sacral slope, and total segmental lumbar lordosis (Fig. 2). "Pelvic tilt" can be measured on lateral views using various anatomic landmarks, including the anterior pelvic plane, the femoral head axis (for pelvic incidence), or the endplate of the sacrum [19, 21]. For the purpose of this study, we used sacral slope angle (the angle between the endplate of the sacrum and the horizontal plane) as a surrogate for pelvic

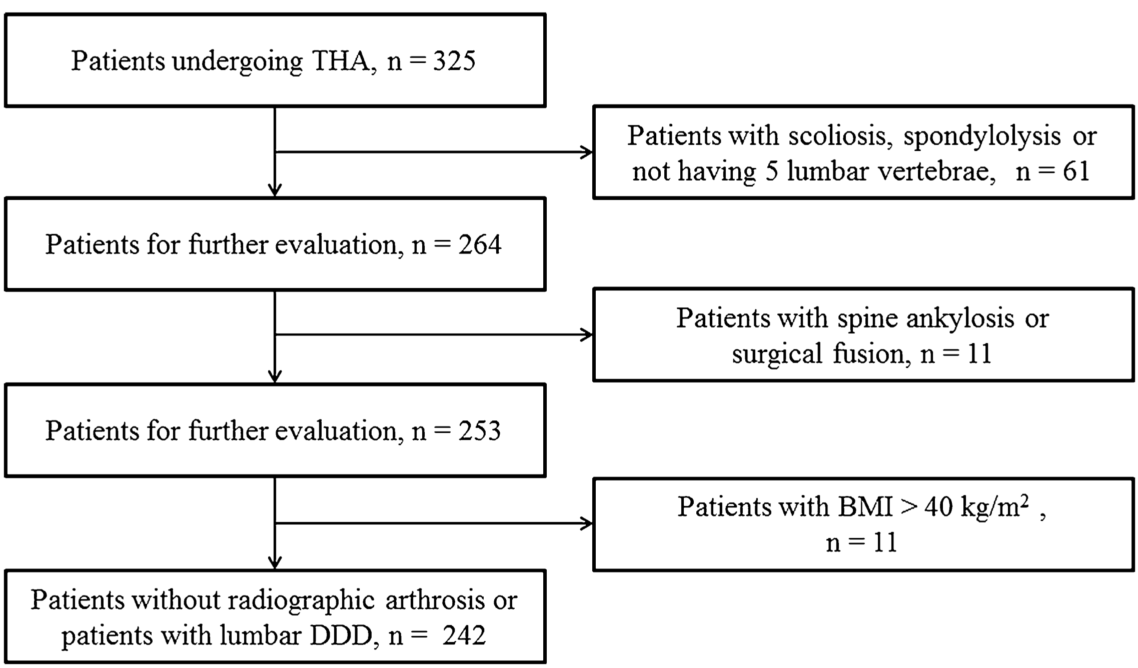

Fig. 1 A flow diagram shows the method for selecting patients without radiographic arthrosis or patients with lumbar DDD. DDD = degenerative disc disease.

tilt in standing and sitting positions [19]. A patient whose pelvis is aligned with a high sacral slope has anterior pelvic tilt (a forward-tilting pelvis), whereas a patient with a low sacral slope has posterior pelvic tilt (a backward-tilting pelvis). A pelvis will roll backward (more posterior tilt) when sacral slope decreases from standing to sitting position and will roll forward (more anterior tilt) when sacral slope increases. The two observers also measured the lumbar lordosis angle between the tangent lines along the vertebral body superior endplates of L1 and S1 (Fig. 2) [15].

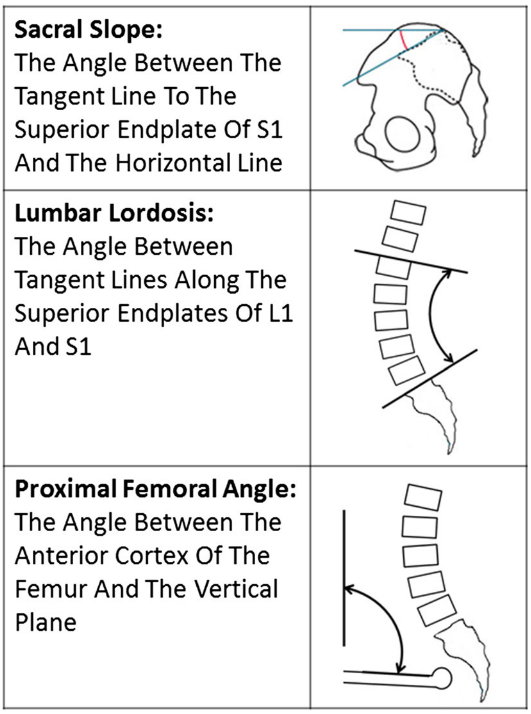

Fig. 2 The pelvic, lumbar, and femoral angles used to measure pelvic alignment in 242 patients undergoing THA in standing and sitting positions are shown.

Spine flexion was calculated as the change in lumbar lordosis angle (L1-S1) between standing and sitting positions (Fig. 3). Femoroacetabular flexion was calculated by adding the change in position of the proximal femur and the change in position of the pelvis (using the sacral slope angle), always subtracting sitting position values from standing position values:

$$\Delta \text{ proximal femur angle } + \Delta \text{ sacral slope angle} = \text{femoroacetabular flexion}$$

According to the equation above, Patient 1 (Fig. 3) experienced 39° femoroacetabular flexion, and Patient 2 (Fig. 3) experienced 74° femoroacetabular flexion.

Defining Lumbar Spine Disorders

Patients were categorized as having no radiographic arthrosis or as having multilevel DDD. A nine-point classification system was developed and used by two independent observers, a spine surgeon (HJK) and a musculoskeletal radiologist (TTM), to differentiate a disc without radiographic arthrosis from a degenerative disc based on facet arthrosis, disc height narrowing, and endplate proliferative changes (Table 1). Patients were considered to have no radiographic arthrosis if they had no or single-level

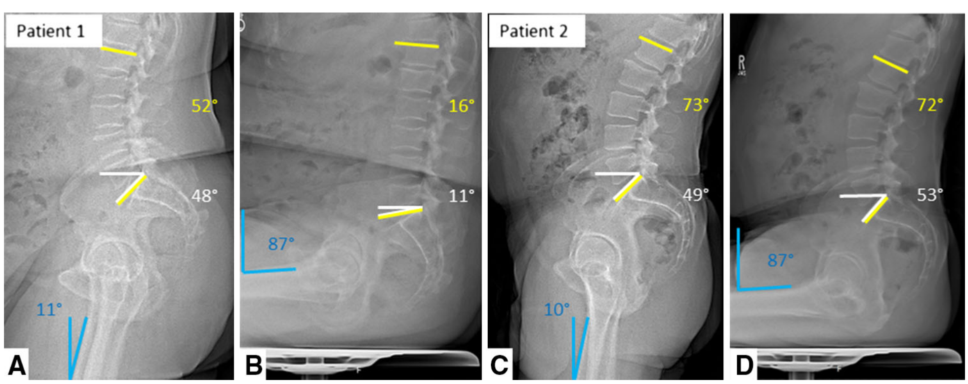

Fig. 3A–D (**A**) Standing lateral and (**B**) sitting lateral two-dimensional radiographs of the spine and pelvis of Patient 1, a 60-year-old man without spine arthrosis undergoing THA, who has sagittal rotation of the pelvis in standing and sitting positions are shown. Patient 1 (**A**) stands and (**B**) sits with 48° and 11° of sacral slope, respectively. Therefore, the patient's pelvis is more retroverted (rotated backward 37°) in a sitting position. In contrast, (**C**) standing lateral and (**D**) sitting lateral two-dimensional radiographs of the spine and pelvis of Patient 2, a 57-year-old man with a DDD spine, show an increase in sacral slope angles from 49° in (**C**) standing to 53° sacral slope in (**D**) sitting. In contrast to Patient 1, Patient 2 has a pelvis that is more anteverted (rotated forward 4°) in a sitting position. Patient 1 experienced 35° of spine flexion (52° minus 16°) and 39° of femoroacetabular flexion (87°–11° + 11°–48°). Patient 2 experienced less spine flexion (1°) compared with Patient 1 and therefore more femoroacetabular flexion (74°). DDD = degenerative disc disease.

DDD, whereas patients with multilevel DDD had two or more degenerative discs. The interobserver agreement between the spine surgeon and radiologist and the intrarater reliability of the spine surgeon for classifying DDD were assessed by calculating the weighted kappa statistic and 95% CI [1]. From the 242 patients included in this study, 148 (61%) were classified as having no or single-level DDD and 94 (39%) as having lumbar spines with multilevel DDD. The interobserver kappa coefficient for classifying patients with DDD was 0.80 (95% CI, 0.64–0.97) between the two observers; the intraobserver kappa coefficient was 0.92 (95% CI, 0.82–1.00), which is considered "good agreement" for inter- and intraobserver variability [1].

Table 1. Scoring criteria for each degenerative disc

Points	Criteria
Facet arthrosis	
0	None
1	Mild
2	Moderate
3	Severe
Disc height narrowing	
0	None
1	Mild narrowing (25%–50%)
2	Moderate narrowing (50%–75%)
3	Severe narrowing (more than 75%)
Endplate proliferative changes	
0	None
1	Mild
2	Moderate
3	Severe
Total	
0–5	Disc without arthrosis
6–9	Diseased disc

Degenerative disc disease was characterized as two or more diseased discs using this grading scheme.

Description of Study Population

Patients were a mean age of 58 ± 11 years with a mean BMI of 28 ± 6 kg/m^2. The patients without spine arthrosis were younger at 54 years than the patients with DDD at 64 years old ($p < 0.01$) (Table 2). No association was found between sex and lumbar DDD. Females had lower standing proximal femur angles ($p < 0.01$), higher sitting lumbar lordosis angles ($p = 0.04$), and lower sitting proximal femur angles ($p < 0.01$) than males (Table 3). For every one-unit increase in BMI, the sitting lumbar lordosis parameter decreased by 0.4° (± 0.2°) and the sitting sacral slope decreased by 0.4° (± 0.1°), showing a negative relationship between BMI and these parameters. Females had less spine flexion ($p = 0.01$) and less change in sacral slope ($p = 0.04$) than males.

Statistical Methods

At least 93 patients in each group (without arthrosis or with DDD spines) were required to achieve 80% power to detect a difference of 5° in sacral slope angle from standing to sitting between the two groups with an estimated group mean of 25° and with a significance level of 0.05 using a

Table 2. Differences in lumbar-pelvic-femoral alignment between patients with no radiographic signs of spine arthrosis (control) and patients with lumbar DDD

Parameters	Control (n = 148) Mean ± SD	DDD (n = 94) Mean ± SD	p value	Total (n = 242) Mean ± SD
Female, number (%)	65 (44%)	45 (48%)	0.55	110 (46%)
BMI (kg/m^2)	29 ± 6	28 ± 5	0.21	28 ± 6
Age (years)	54 ± 11	64 ± 10	< 0.01	58 ± 11
Standing lumbar lordosis	55 ± 11	48 ± 13	< 0.01	52 ± 12
Standing sacral slope	41 ± 10	36 ± 9	< 0.01	39 ± 10
Standing femur angle	8 ± 5	9 ± 5	0.04	8 ± 5
Sitting lumbar lordosis	25 ± 13	29 ± 16	0.03	27 ± 14
Sitting sacral slope	16 ± 12	20 ± 11	0.03	18 ± 12
Sitting femur angle	87 ± 5	88 ± 6	0.04	87 ± 5
Spine flexion	30 ± 12	19 ± 10	< 0.01	25 ± 13
Femoroacetabular flexion	54 ± 16	63 ± 12	< 0.01	58 ± 15
Change in sacral slope from standing to sitting	25 ± 12	16 ± 10	< 0.01	22 ± 12

DDD = degenerative disc disease.

two-sided two-sample t-test. Multiple linear regression analysis was performed in comparing the alignment parameters between patients without radiographic arthrosis and patients with DDD lumbar spines adjusting for patient's age, sex, and BMI. Descriptive statistics were displayed as means (and 95% CIs) for continuous variables. All tests were two-sided with a significance level of 0.05. All statistical analyses were performed using SAS® Version 9.3 (SAS Institute Inc, Cary, NC, USA).

Results

After controlling for age, sex, and BMI, we found that patients with DDD spines had 5° more posterior pelvic tilt (95% CI, −2° to −8° lower sacral slope angles; $p < 0.01$) and 7° less lumbar lordosis angles (95% CI, −10° to −3°; $p < 0.01$) when standing than patients without arthrosis (Table 3). However, in a sitting position, patients with DDD spines had a mean of 4° less posterior pelvic tilt (95% CI, 1°–7° higher sacral slope angles; $p = 0.02$). Great variability existed in sacral slope in standing (range, 13°–74°) and sitting (range, −9° to 55°) positions (Fig. 4). Eight patients (five without spine arthrosis, three with DDD spines) sat with anterior pelvic tilt (forward-tilting pelvises with high sacral slopes ≥ 40°). There was a strong positive correlation between sacral slope and lumbar lordosis in standing ($R^2 = 0.65$; $p < 0.01$) and in sitting ($R^2 = 0.75$; $p < 0.01$).

From standing to sitting position, patients with DDD spines had a mean of 10° less spine flexion ($p < 0.01$) and therefore a mean of 10° more femoroacetabular flexion ($p < 0.01$). Because patients with DDD had less spine flexion, they had a mean of 9° less change in sacral slope ($p < 0.01$) than patients without spine arthrosis. In all patients, spine flexion ranged from −3° to 57° and femoroacetabular flexion ranged from 15° to 95° (Fig. 5). A strong negative correlation was found between spine flexion and femoroacetabular flexion ($R^2 = 0.70$; $p < 0.01$). Seven patients (3%) sat with more anterior pelvic tilt from standing to sitting position (pelvises rolled forward so the sacral slope angle was higher in sitting than in standing (Fig. 3, Patient 2).

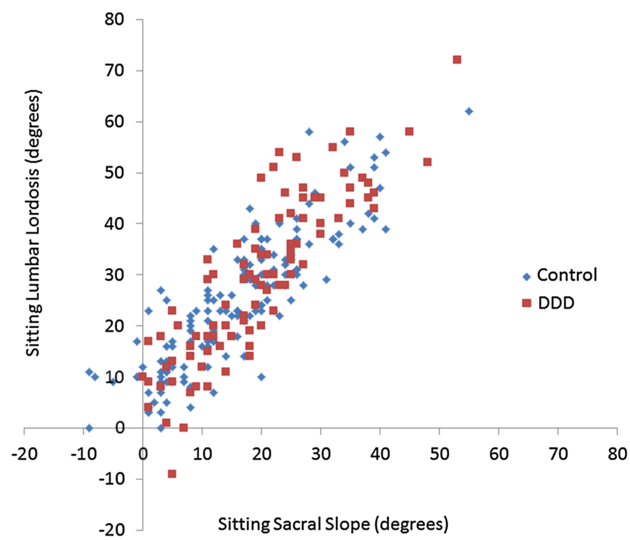

Fig. 4 A scatterplot shows the sitting sacral slope and sitting lumbar lordosis angles in control patients without spine arthrosis and in lumbar spine DDD patients. There was a positive linear correlation ($R^2 = 0.75$) between sacral slope and lumbar lordosis. DDD = degenerative disc disease.

Table 3. Differences in alignment and flexion parameters

Variable	Mean	95% CI	p value	Mean	95% CI	p value	Mean	95% CI	p value
	Standing lumbar lordosis			Standing sacral slope			Standing proximal femur angle		
Control versus DDD	−6.7	−10 to −3.4	< 0.01	−4.8	−7.5 to −2.1	< 0.01	0.3	−0.9 to 1.5	–
Female versus male	0.1	−2.9 to 3	–	−0.9	−3.3 to 1.5	–	−2.4	−3.5 to −1.2	< 0.01
Age	−0.1	−0.2 to 0.1	–	−0.1	−0.2 to 0	–	0.1	0.1 to 0.2	< 0.01
BMI	−0.1	−0.4 to 0.1	–	−0.1	−0.4 to 0.1	–	0.2	0.1 to 0.3	< 0.01
	Sitting lumbar lordosis			Sitting sacral slope			Sitting proximal femur angle		
Control versus DDD	3.7	−0.3 to 7.7	–	4.0	0.7 to 7.2	0.02	1.3	0 to 2.7	–
Female versus male	3.8	0.2 to 7.4	0.04	2.1	−0.8 to 5.0	–	−3.9	−5.1 to −2.7	< 0.01
Age	0.0	−0.2 to 0.2	–	−0.1	−0.2 to 0	–	0.0	−0.1 to 0.1	–
BMI	−0.4	−0.7 to 0	0.02	−0.4	−0.7 to −0.2	< 0.01	−0.2	−0.3 to −0.1	< 0.01
	Spine flexion			Femoroacetabular flexion			Change in sacral slope		
Control versus DDD	−10.4	−13.6 to −7.2	< 0.01	9.8	5.7 to 13.9	< 0.01	−8.7	−12 to −5.5	< 0.01
Female versus male	−3.8	−6.7 to −0.9	0.01	1.5	−2.2 to 5.2	–	−3.0	−5.9 to −0.2	0.04
Age	0.0	−0.2 to 0.1	–	−0.1	−0.3 to 0	–	0.0	−0.1 to 0.1	–
BMI	0.2	0 to 0.5	–	−0.6	−0.9 to −0.3	< 0.01	0.3	0 to 0.5	0.04

DDD = degenerative disc disease.

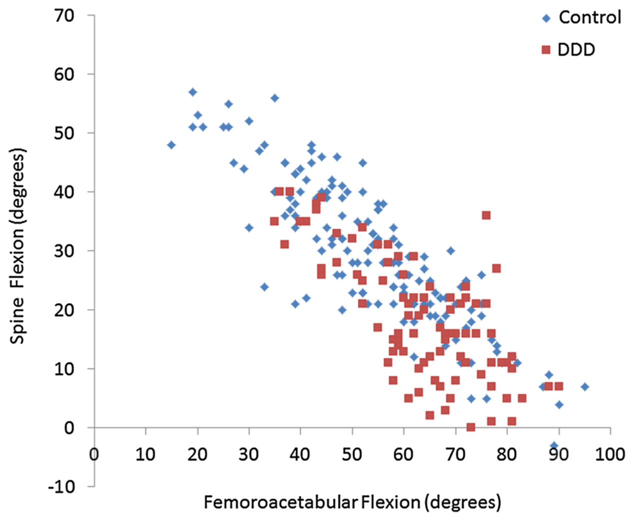

Fig. 5 A scatterplot shows femoroacetabular flexion and spine flexion angles in control patients without spine arthrosis and in lumbar spine DDD patients. Patients with DDD spines had less spine flexion ($p < 0.01$) and more femoroacetabular flexion ($p < 0.01$) compared with patients without spine arthrosis. There was a negative linear correlation ($R^2 = 0.70$) between femoroacetabular flexion and spine flexion. DDD = degenerative disc disease.

Discussion

Degenerative changes of end-stage arthritis in the hip and spine can significantly alter body kinematics and therefore lumbar-pelvic-femoral alignment [24, 36, 42]. There is evidence that lumbar-pelvic-femoral mobility affects the risk of dislocation after THA, with a case report of late posterior hip dislocation after lumbar spinopelvic fusion [33]. The patient's inability to accommodate postural changes through the lumbar spine after spine surgery, with limited change in pelvic tilt during functional activities, may explain the reported dislocation event. Pelvic tilt affects the functional orientation of acetabular components in patients undergoing THA, such that increasing posterior pelvic tilt increases functional acetabular inclination and anteversion, while decreasing pelvic tilt will result in the loss of functional inclination and anteversion [31]. Previous studies have shown that preoperative pelvic tilt from standing to sitting position can be used to reliably predict postoperative THA cup orientation with standing and sitting lateral radiographs [19, 23]. However, it remains unclear whether patients at risk of dislocation can be identified preoperatively based on lumbar-pelvis-femoral mobility, and whether patient-specific plans for THA implant position can reduce the incidence of dislocation and therefore improve patient outcomes. This study quantified the relative contribution of spine flexion and femoroacetabular flexion during 90° of apparent hip flexion in patients with concurrent hip and spine arthritis. We found that most patients, regardless of whether they have DDD, have lumbar-pelvic-femoral alignment that is similar in the sitting position, but patients with DDD require greater femoroacetabular flexion to achieve the sitting position, as they have more limited spine flexion. This study provides baseline information regarding lumbar-pelvic-femoral alignment in a large series of patients before undergoing THA, and ultimately may be used to consider whether certain outliers undergoing THA are at higher risk of prosthetic dislocation.

This study has limitations. First, static imaging in standing and sitting may not fully represent the patient's pelvic orientation during the dynamic motion of sitting down on a stool. During activities of daily living, sacral slope can go from very high in a supine position with the legs in extension to null or negative sacral slope when in a crouching position [24]. Second, we do not know how much pelvic tilt is clinically relevant or whether the presented preoperative information is representative of what happens postoperatively; however, we are following these patients prospectively for complications including dislocation and analyzing postoperative imaging for comparison. Third, we did not image the entire spine; however, we found strong correlations using lumbar images alone. Fourth, the accuracy of measuring sacral slope angles is dependent on the radiographic definition of the anterior part of the sacrum [27]. We did not evaluate the accuracy of methods for measuring pelvic, lumbar, and femoral angles. The accuracy of the measurements is disputed in the literature, since accuracy is dependent on the ability to identify landmarks in the presence of degenerative diseases of the spine [18, 27]. However, excellent intra- and interobserver reliability for measuring sacral slope and lumbar lordosis angles on lateral radiographs has been reported [9]. Finally, the images we acquired were dependent on how patients were positioned in the imaging system. We believed it better to position patients with their femurs aligned approximately parallel to the floor to assume 90° of apparent hip flexion to measure spine and femoroacetabular flexion across patients. This may not replicate how patients sit comfortably during their daily activities. However, previous studies used the same method [22, 24].

Previous studies have measured pelvic tilt in patients undergoing THA during sitting and standing positions, usually reporting values similar to ours with mean standing sacral slope angles between 35° and 40°, and mean sitting sacral slope angles between 14° and 24° [19, 22, 26]. Our study is the first, to our knowledge, to stratify patients undergoing THA into those with or without lumbar DDD, and we found that most patients with DDD had flattened backs (mean 7° less lumbar lordosis) and more posterior pelvic tilt (mean 5° more sacral slope) in standing.

Decreasing values in lumbar lordosis and sacral slope angles in patients with DDD are consistent with the spine literature, where these sagittal parameters are used to evaluate individual sagittal balance [4, 5, 28]. Interestingly, similar to a previous study evaluating sagittal balance during standing in patients undergoing THA [24], some patients with DDD in our study had such excessive posterior pelvic tilt and lack of lumbar lordosis that they required knee flexion to adapt, because hip extension was insufficient. In the sitting position, we found a statistically significant difference suggesting the opposite was true when comparing sitting pelvic tilt in patients with and without DDD, such that patients with DDD sat with less posterior pelvic tilt and with more lumbar lordosis, since they flexed their spines less. However, this was only a 4° difference in pelvic tilt between patients with and without DDD in the sitting position (mean sacral slope of 16° versus 20°, respectively). This small difference in pelvic tilt between groups is comparable to the expected error in the measurement technique [18], confirming that patients with lumbar DDD are not predisposed to excessive pelvic tilt when sitting. Most patients, regardless of whether they have DDD, sit within a similar range of pelvic tilt (Fig. 4). Rather, it might be more important to consider the outliers, which include 3% (eight patients) who sat with anterior pelvic tilt (forward-tilting pelvises with high sacral slopes $\geq$ 40°). It has been suggested that patients who sit with forward-tilting pelvises may benefit from increased acetabular cup anteversion to avoid instability [19]. In our study, patients who sat with anterior pelvic tilt included those without radiographic arthrosis as well as those with DDD, discrediting the notion that patients with DDD are more prone to abnormal pelvic motions in sitting and suggesting there is no need for optimized surgical plans for adjusting the THA implant position for patients with DDD. The rare occurrence of anterior pelvic tilt in the sitting position also might explain why the overall rate of hip dislocation is low [3]. Increased age has been shown to be a significant risk factor for DDD [37, 40], and our study patients with DDD were found to be older (Table 2). Females sat with more lumbar lordosis compared with males (Table 3), which explains why they had less spine flexion from a standing to a sitting position. This may be attributed to differences in socially acceptable sitting positions for men and women such that men sit in more open positions with their legs farther apart, whereas women sit with their arms and legs relatively close together [44]. Greater BMI also was found to contribute to a flatter back and more retroverted pelvis in sitting, which would be needed to accommodate a greater body mass to achieve sitting position. In the literature the effect of BMI on sagittal spinopelvic alignment is unclear, with some reports finding an association and others not [2, 8, 16, 38]. To our knowledge, our study is the first to find a relationship between BMI and sitting sacral slope.

Although we found a small difference in sitting pelvic tilt between patients with and without DDD, we found that patients with DDD of the lumbar spine flex approximately 10° less through their spine and 10° more through their hips (greater femoroacetabular flexion) than patients without spine arthrosis to achieve a sitting position. These differences are greater than those found when comparing just standing or sitting parameters between groups. A patient who cannot flex through his or her lumbar spine will not experience a change in pelvic tilt from standing to sitting position [19, 22]. This may have consequences in a patient with a THA, since there will be no change in the functional anteversion of the acetabular component [29, 45]. An increase in functional anteversion of the acetabular component is thought to be protective against posterior dislocation in the sitting position, because it provides more posterior coverage of the prosthetic head [19] and reduces the likelihood of anterior impingement of the prosthetic femoral neck on the edge of the acetabular cup or bone [12]. Our study patients experienced a mean increase in posterior pelvic tilt of 22° from standing to sitting position, which is similar to values reported in previous studies [19, 25, 35], and this increase in posterior pelvic tilt would increase the functional anteversion of the acetabular component by approximately 15° [29, 31]. It might be important to consider the outliers, which include 3% of patients (with and without DDD) who actually rotated their pelvises forward (more anterior tilting pelvises) from standing to sitting position. This mechanism would reduce the functional anteversion of the acetabular component, which could predispose impingement of the anterior aspect of the pelvis on the bone or neck of the femoral component during sitting and thus increase the risk of posterior prosthetic dislocation (Fig. 3, Patient 2). Standing lumbar lordosis is an indicator of the potential a patient has to compensate through the spine as they move to a sitting position. In general, patients with DDD stand with limited lumbar lordosis and more posterior-tilting pelvises [4], and thus they have less potential for further change in pelvic tilt when moving to a sitting position. Because these patients have less flexible spines that may not accommodate a sitting posture through the lumbosacral spine, they require greater femoroacetabular flexion to achieve 90° of apparent hip flexion.

The hip-spine relationship plays an important role in the functional range of motion of hips after THA [22, 24]. Therefore, we quantified the relationship between spine flexion and femoroacetabular flexion during 90° of apparent hip flexion in a large cohort of patients before undergoing THA. Consistent imaging techniques accounting for femoral alignment are important, as the femur has been shown to play a fundamental role in the hip-spine relationship and the degree of hip flexion influences pelvic tilt and lumbar lordosis [23, 35]. We found a strong positive correlation between sacral slope and lumbar lordosis in patients undergoing THA (Fig. 4), which also has been reported in asymptomatic subjects and patients with spinal stenosis [9, 43], and we found a negative correlation between spine flexion and femoroacetabular flexion (Fig. 5), because we asked patients to achieve 90° of apparent hip flexion in the sitting position regardless of whether they flexed through their spine or their hips. To answer the research questions, we used EOS imaging to capture lumbar-pelvic-femoral alignment in patients undergoing THA, but EOS imaging currently is available only at select centers. As an alternative, surgeons performing THAs might be able to use conventional standing and sitting lateral spinopelvic radiographs to measure sacral slope angles and femoroacetabular flexion to deduce whether a patient is flexing through his or her lumbar spine. Pelvic tilt in standing and sitting positions varied on a patient-specific level. When planning THA, it may be important to consider pelvic tilt in a sitting position and femoroacetabular flexion through the hips to achieve a sitting position, because both will contribute to the risk of anterior impingement and posterior dislocation in a sitting position. Considering these dynamic relationships when planning THA seems prudent, and further research will better quantify what changes are of clinical importance and whether an outlier group that is at greater risk for postoperative dislocation can be identified preoperatively.

Acknowledgments We thank Joseph Lipman MS (Department of Biomechanics, Hospital for Special Surgery) for valuable discussions during the preparation of this article and Lily Yuo-yu Lee MS (Healthcare Research Institute, Hospital for Special Surgery) for statistical assistance.

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