Implications of Spinopelvic Mobility on Total Hip Arthroplasty: Review of Current Literature

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Abstract

Understanding the impact of pathologic spinopelvic mobility on total hip arthroplasty instability requires an appreciation of the dynamic interplay between and the spine, hip and pelvis. This complex interdependent relationship changes with position, pathology and surgical intervention. Spinal pathology may prevent normal dynamic motion leading to spinopelvic stiffness and abnormal pelvic position. Patients at high risk for pathologic spinopelvic motion and subsequent total hip arthroplasty (THA) dislocation should be assessed with a functional imaging series with lateral standing, sitting and AP standing radiographs. Common patterns of stiffness and imbalance as well as proposed surgical treatment algorithms are presented and discussed in this review.

Keywords

Total hip arthroplasty, dislocation, spinopelvic mobility, flatback, adult spinal deformity, acetabular anteversion, pelvic tilt

Abbreviations

AI = Anteinclination
APPt = Anterior plate pelvic tilt
CSI = Combined Sagittal Index
DAA = Direct Anterior Approach
LSZ = Lewinnek Safe Zones
PFA = Pelvic Femoral Angle
PI = Pelvic Incidence
PT = Pelvic Tilt
sPT = spinopelvic tilt
SS = Sacral slope
THA = Total hip arthroplasty

Introduction

The spine, hip and pelvis have a dynamic and interdependent relationship that changes with position, pathology and surgical interventions. Normal motion requires adequate spinopelvic mobility and proper posture.[1-5] However spine disease can decrease motion, through degenerative disease or surgical arthrodesis, and cause abnormal spinopelvic posture due to compensatory pelvic rotation to maintain sagittal balance with an energy efficient posture.[6] The lack of proper spinopelvic motion and coordination may jeopardize the functional position of the acetabulum. As a result, there has been a recent increase in interest to characterize spinopelvic motion abnormalities and elucidate their impact on total hip arthroplasty (THA) outcomes.[7-12] This is particularly relevant in the modern era of advanced medical interventions that prolong expected lifespan. The prevalence of concomitant degenerative hip and spine disease continues to increase with more patients undergoing both lumbar spine fusions (LSF) and THAs. A review of Medicare data found a 293% increase in patients with LSFs undergoing THA over a period of 12 years.[13] The prevalence of degenerative lumbar spine disease in patients undergoing primary THA for hip osteoarthritis was approximately 40%.[8,14]

The effect of spine disease on THA arthroplasty has largely focused on dislocation risk. Postsurgical hip instability has altogether been shown to be 2%-4% in large multicenter studies.[15-18] However, contemporary studies focusing on THA in patients with degenerative spines disease or long segment LSFs has shown a dislocation risk of 8%-18%.[13,17,19-24] Perfetti, et al, noted a seven times higher rate of dislocation with a prior spine fusion[25] and several authors have demonstrated a positive association with the number of levels fused[19,22,26] and degree of spinal imbalance.[27,28] Malkani found that LSFs performed within five years prior to THA to be an independent risk factor for THA dislocation and corroborates previously published data.[13,22,25,26] THA patients with concomitant spinal sagittal imbalance that have not yet been treated with a LSF are also at risk for posterior impingement, dislocation and superior edge loading. Furthermore, standing posterior pelvic tilt has been shown to progressively worsen with increasing age and therefore further increases these risks.[6,29,30] There is potentially a new set of risks in these patients if corrective spine surgery is performed post THA due to readjustment of posterior pelvic tilt, functional acetabular anteversion, and spinal stiffness.[6,31,32]

The impact of spinopelvic imbalance is particularly profound in THA late dislocations. Heckmann, et al, reported that 90% of their late dislocations (defined as >1 year) had spinopelvic imbalance.[33] However, not all patients with spinopelvic abnormalities will dislocate, as shown by Yukizawa, et al, in their 10 year follow up study on THA patients which found 62% had abnormal spinopelvic motion.[34] One should also consider that loss of spinopelvic balance and mobility is often progressive. The prevalence of spinal stiffness in patients undergoing primary THA was found to increase from 20% to 60% after 10 years,[8,34] often with progressive loss of sagittal balance and increasing pelvic tilt.[29,35] Consequently, the risk of hip instability in elderly patients with non-instrumented spine disease continues to increase with age and progression of disease.

To appropriately address these issues, surgeons must understand the dynamic interplay between the spine, pelvis and hip. Lazennec et al. pioneered the study of the hip and spine relationship in 2004 and has introduced the idea of a "functional" acetabular component position in the sagittal plane.[3] Several authors have continued to champion this investigation including Lawrence Dorr.[7,8,33,36,37] In this review we will examine the current literature, define the commonly used nomenclature, describe normal and pathologic spinopelvic motion, propose means to identify high risk patients with options presented to work them up, and provide surgical interventions to consider.

Nomenclature

One of the challenges to understanding the spine, pelvis, and hip interplay has been the use of non-standardized and uncommon nomenclature. However this may change with the formation of the "Hip-Spine Workgroup."[12] Ike, et al, provided an excellent list of many of the common terms that are used in the literature and defined them.[7] The authors of this review have chosen additional terms that are used and often not fully understood. We provided a list of these terms and their definitions in Table 1. To further complicate the issue, some of the same terminology is defined differently in the spine versus arthroplasty literature.

The term pelvic tilt (PT) used in arthroplasty literature for hip navigation is the rotation of the pelvis in the sagittal plane as measured by the angle formed between the coronal plane and the anterior pelvic plane (APP) which is defined by a line from the anterior superior iliac spine (ASIS) to pubic symphysis. Therefore, we will hereon refer to this term as anterior pelvic plane tilt (APPt). APPt can be either anterior or posterior because it is referenced from the coronal plane (neutral APPt). Posterior APPt occurs when the pelvis tilts backwards such that the S1 endplate becomes more horizontal which can also be thought of as the long axis of the sacrum itself becoming more vertical. Posterior APPt refers to the same motion as pelvic retroversion.

Table 1. Additional Commonly Used Terms

Term	Definition
Combined sagittal index (CSI)	Angle of the acetabular cup in the sagittal plane that is the sum of the ante-inclination and the pelvic-femoral angle.
Hypermobility	Normal variation of spinopelvic motion defined as excessive dynamic motion when transitioning from standing to sitting. Defined as > 30 degrees ΔSS
Pelvic retroversion	Posterior rotation of the pelvic in the sagittal plane, equivalent to posterior anterior plane pelvic tilt.
Anterior Plane Pelvic Tilt (APPt):	Term for pelvic tilt used in arthroplasty literature referring to the rotation of the pelvis in the sagittal plane as measured by the angle formed between the coronal plane and a line from the anterior superior iliac spine (ASIS) to pubic symphysis.
Spinopelvic Tilt (sPT):	Term for pelvic tilt used in spine literature referring to the position of the sacrum relative to the femoral heads, as defined by the angle between the vertical axis and a line from the femoral head to the midpoint of the S1 endplate.
Unbalanced Spine	Pelvic incidence to Lumbar Lordosis mismatch greater than 10 degrees

This is particularly confusing for arthroplasty surgeons which typically refer to retroversion in relation to the acetabular cup which is the opposite motion. For example, with posterior pelvic tilt, or pelvic retroversion, the functional position of the acetabular cup becomes more anteverted.

To further add to the confusion, the term pelvic tilt is used in the spine literature as a spinopelvic parameter referring to the position of the sacrum relative to the femoral heads, as defined by the angle between the vertical axis and a line from the femoral head to the midpoint of the S1 endplate. As a result, some authors use the term spinopelvic tilt (sPT) to distinguish between the two definitions of pelvic tilt, but this is not standard. Spinopelvic tilt is also a function of sacral slope (SS) because the sum of sPT and SS is equal to pelvic incidence (PI),[38] which is essentially a constant value that is defined anatomically, but differs for each individual patient. Spinopelvic tilt is inversely related to SS, therefore an increase in sPT corresponds to a decrease in SS and this motion is equivalent to a posterior APPt, as used by arthroplasty surgeons.

When considering dynamic spinopelvic motion that changes with position, static versus functional position also needs to be understood. Arthroplasty surgeons focus on placing components into the ideal Lewinnek Safe Zones (LSZ) in the static intraoperative supine or lateral position. There is a lack of consideration for the dynamic postural changes that take place when the patient is standing or sitting. Focus should be placed on the "functional" position of the components that takes into account the functional motion of the pelvis. It should also be noted that abnormal static pelvic tilt will distort perceived component position on AP pelvis imaging. The original LSZ was determined with the use of a jig that positioned the patient such that the APP was parallel to the floor.[39] However, with any pathologic pelvic tilt in the supine or lateral position intraoperatively, radiographic measurements of anteversion and inclination are inaccurate. For each 1^o of posterior APPt, functional acetabular anteversion will increase by 0.7^o-0.8^o.[9,24,40] The change in functional acetabular inclination is less significant and nonlinear, depending on the degree of PT.[10] There have been efforts to identify landmarks on AP pelvis imaging to quantify the degree of pelvic tilt, including the symphysis to sacrococcygeal joint distance,[41] or the obturator foramen width to height ratio.[42] In general, greater posterior APPt will appear more as an outlet view whereas greater anterior APPt will appear more as an inlet view on conventional AP pelvic imaging. This projection consideration excludes component placement with the use of computer navigation technology because it references the APP at 0^o.

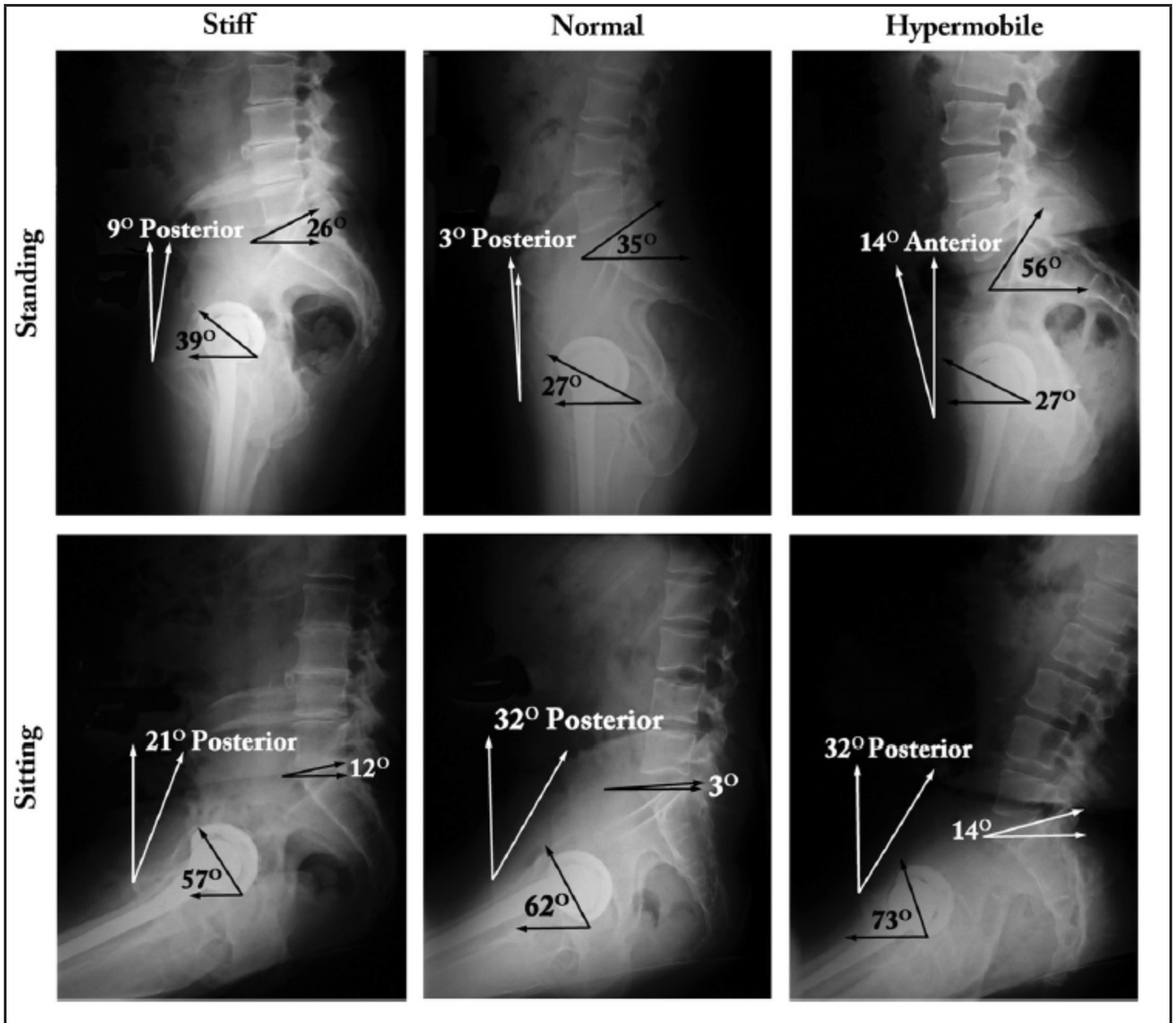

Figure 1. Lateral standing (top row) and sitting (bottom row) spinopelvic radiographs showing the three classes of pelvic stiffness. Pelvic tilt (white arrows), sacral tilt (black arrows at L5-S1), and ante-inclination (black arrows measuring the cup angle) measured 9° posterior, 26°, and 39°, respectively, on the standing radiographs and 21° posterior, 12°, and 57° on the sitting radiographs of the patient with a stiff pelvis; 3° posterior, 35°, and 27° on the standing radiographs and 32° posterior, 3°, and 62° on the sitting radiographs of the patient with a normal range of pelvic tilt; and 14° anterior, 56°, and 27° on the standing radiographs and 32° posterior, 14°, and 73° on the sitting radiographs of the patients with a hypermobile pelvis." Permission from *Kanawade, V., L.D. Dorr, and Z. Wan, Predictability of Acetabular Component Angular Change with Postural Shift from Standing to Sitting Position. J Bone Joint Surg Am, 2014. 96(12): p. 978-986.*

Normal Spinopelvic Motion

Pelvic tilt is key to understanding spinopelvic kinematics (Figure 1). Normal standing posture consists of slight anterior APPt with a mean sacral slope of 40° and adequate physiologic lumbar lordosis (LL) to achieve sagittal balance. The functional acetabular position covers the femoral heads under the central weight bearing dome and allows slight hip extension for ambulation. As one transitions from standing to sitting, the pelvis tilts posteriorly approximately 20° in order to increase functional acetabular anteversion 15 to 20° to accommodate hip flexion without anterior impingement and subsequent posterior dislocation. With 20° of posterior APPt, the hip needs to only flex 55° to 70° to achieve proper sitting posture.

In terms of spinopelvic kinematics, when the pelvis tilts posteriorly by a mean of 20°, the sacral slope decreases by the same value of 20^0.[3,33,38] As the SS decreases, the lumbar spine flexes which decreases LL in order to maintain sagittal balance, bringing the trunk and head forward. As the pelvis tilts posteriorly, the acetabular anteversion increases 0.8° for every 1° of posterior APPt.[9] However, a more accurate parameter to use is the sagittal parameter of anteinclination (AI) which combines changes in both acetabular anteversion and inclination.[9]

When transitioning from standing to supine, the pelvis tilts as well, but anteriorly and to a much lesser degree compared to sitting.[3,43] The mean pelvic arc of motion has been reported to be <5°,[7] but many authors report significantly larger changes and have strongly recommended the use of standing AP pelvis radiographs to be used as a reference for component positioning.[10,12,44]

Abnormal Spinopelvic Motion

As evident in normal spinopelvic kinematics, APPt, SS, and AI are significant functional parameters that compose the dynamic nature of spinopelvic motion. Abnormal motion occurs due to spinal pathology leading to either sagittal imbalance, stiffness, or both.

Spinal sagittal imbalance occurs as the aging spine becomes progressive more kyphotic due to degenerative disease.[45,46] In order to regain sagittal balance above the pelvis and maintain an energy efficient and pain-free erect posture,[45] compensatory mechanisms are employed which include obligatory posterior APPt. The limit of posterior APPt is dependent on individual PI and hip extension reserve.[47] With posterior APPt while standing, the acetabulum is functionally anteverted so there is a risk for posterior impingement and subsequent anterior dislocation with hip extension.

The other factor to consider is flexibility of the spine (Figure 1). Spine mobility can be limited by degenerative spine disease[48] or iatrogenic postsurgical long segment lumbosacral fusions, typically ≥ 3 levels. The normal spine can accommodate a mean posterior APPt of 20° (ΔAPPt or ΔSS of 20°) when transitioning from standing to sitting.[3,38] Spinal stiffness is defined as ΔSS less than 10°.[8] Consequently, patients with spinal stiffness cannot increase their functional acetabular anteversion to accommodate hip flexion when transitioning from standing to sitting and therefore risk anterior impingement with subsequent posterior dislocation. It is important to note though that stiffness is not always present in patients with spinal pathology such as sagittal imbalance.

Classifications

The challenge presented to the total arthroplasty surgeon is how to optimally position acetabular components to minimize risk for dislocation as well as surface wear and liner fracture.

Several authors have created classification schemes for patients to aid in creating a treatment algorithm to address the issue. Stefl, et al, [8] described 5 patterns of spinopelvic mobility: fixed anterior tilt ("stuck standing"), fixed posterior tilt ("stuck sitting"), kyphotic, fused, and hypermobile. Stuck standing is a stiff spine that maintains anterior tilt with a SS $>30°$ in both sitting and standing (Figure 2). Stuck sitting is a stiff spine that maintains posterior tilt with a SS $<30°$ in both sitting and standing (Figure 3). Kyphotic is a pattern defined by a sitting SS of <5, but mobility is undefined. Fused spines have ΔSS $<5°$ and hypermobile spines have ΔSS $>30°$ when transitioning from standing to sitting.

Phan, et al,[11] described 4 combinations patterns of spinal flexibility and balance (balanced defined as sPT $<25°$; PI–LL mismatch $<10°$): Flexible and balanced, rigid and balanced, flexible and unbalanced, and rigid and unbalanced. Flexible and balanced patients have normal spinopelvic mobility. Rigid and balanced are stiff, in a position akin to "stuck standing," and are therefore at risk for posterior dislocation upon sitting. Flexible and unbalanced include patients with degenerative, postlaminectomy or neuromuscular kyphosis. The posterior tilt of the pelvis while standing places them at risk of posterior impingement and subsequent anterior dislocation. Rigid and unbalanced patients are stiff, in a position akin to "stuck sitting", and therefore at risk for anterior dislocation when standing. These patients include iatrogenic flat back fusions and ankylosing spondylitis patients.

Luthringer, et al,[12] proposed 4 categories (1A, 1B, 2A, 2B) very similar to Phan, et al, PI-LL mismatch $>10°$ was termed flatback deformity and stiffness was defined as ΔSS $<10°$ from standing to sitting. 1A had normal alignment and mobility, 1B have normal alignment with stiffness, 2A have flatback deformity with normal mobility, and 2B have flatback deformity with stiffness.

These classifications can be useful as general categories, but the degree of stiffness and sagittal imbalance should be determined on a case by case basis. Additionally, as patients age or undergo surgical procedures, they may transition from one category to another.[29] Spine disease is progressive and loss of spinopelvic mobility and sagittal balance may be responsible for late dislocations. In contrast, release of hip flexion contractures after THA may actually increase spinopelvic mobility because flexion contractures prevent the pelvis from tilting posteriorly during ambulation.[49] Sariali, et al, found a post-THA mean increase in ΔSS of 5° and 3° with standing and sitting, respectively.[50] Stefl, et al, noted that 54% of patients undergoing THA had normal spinopelvic mobility preoperative, and that this increased to 80% after THA, which the authors attribute to release of hip flexion contractures.[8]

Work Up

Proper preoperative work up of a patient with suspected spinopelvic abnormalities that may influence functional THA component positioning should include proper imaging and a thorough history and physical exam.[8,9,46] Three views of the pelvis should be obtained to including lateral standing and sitting (90° trunk-thigh angle) and AP standing. Standing AP pelvis much more accurately represents functional pelvis position than supine radiographs.[12] It is also recommended to center the AP radiograph slightly more cephalad than standard practice

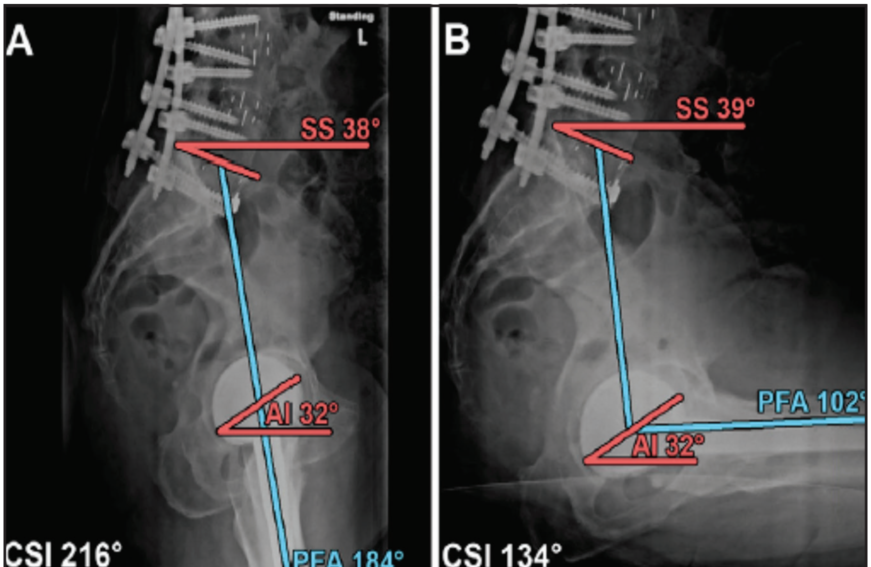

Figure 2. Standing lateral radiograph showing a surgical fusion in lordosis indicated by a sacral slope (SS) of 38°. Figure 2B Sitting lateral radiograph showing a fused spine with a sacral slope of 39°, which means that the pelvis is fixed in anterior tilt; an acetabular cup that does not open, with a cup ante-inclination (AI) of 32° in both positions; and a femur in relative hyperflexion, indicated by a pelvic-femoral angle (PFA) of 102°, to compensate for a pelvis that does not tilt posteriorly during sitting. The sitting combined sagittal index (CSI) is low (134°: 32° + 102°), which is predictive of anterior impingement." Permission from Heckmann N, et al. Late Dislocation Following Total Hip Arthroplasty: Spinopelvic Imbalance as a Causative Factor. *J Bone Joint Surg Am.* 2018;100(21):1845-1853.

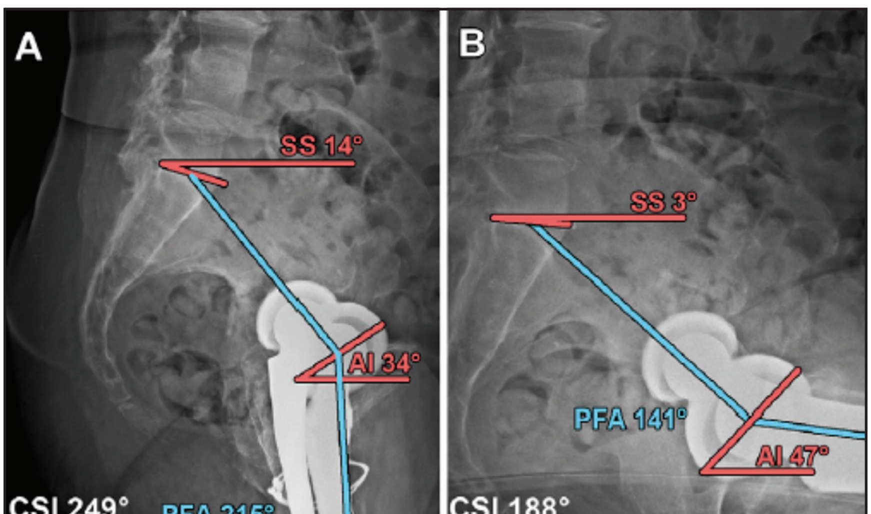

Figure 3. Standing lateral radiograph showing loss of lumbar lordosis and a posterior position of the pelvis as indicated by a sacral slope (SS) of 14°. The femur is in hyper-extension relative to the pelvis as indicated by a pelvic-femoral angle (PFA) of 215°. A standing combined sagittal index (CSI) of 249° (34° + 215°) is predictive of posterior impingement. Figure 3B Sitting lateral radiograph showing relative kyphosis of the spine indicated by a sacral slope of 3°. The sitting combined sagittal index is 188° (47° + 141°), which is within the normal range." Permission from Heckmann N, et al, Late Dislocation Following Total Hip Arthroplasty: Spinopelvic Imbalance as a Causative Factor. *J Bone Joint Surg Am*. 2018;100(21):1845-1853.

in order to capture more of the lumbar spine which may reveal evidence of prior surgery or other pathologic spine disease. Lateral views should include the L1 vertebrae to evaluate lumbar spine mobility or at least the L3 vertebrae because most of the lumbar motion occurs between L3 to L5.[7,12]

With the standing and sitting lateral radiographs, one can measure multiple parameters including, Pelvic Femoral Angle (PFA), SS, AI, PI, as well as the change in dynamic parameters. The two most important measurements to determine pathologic pelvic tilt and spinal stiffness are standing APPt and ΔAPPt (or ΔSS) when transitioning from standing to sitting. Standing posterior or anterior APPt can be measured in reference to the coronal plane of the body (neutral APPt) and serve as a surrogate for spinal imbalance.[12] ΔSS (or ΔAPPt) from standing to sitting will determine stiffness ($\Delta SS < 10^o$).

Other useful measurements to obtain from the lateral standing XR include PI, LL and PI-LL mismatch. PI can be precisely measured or simply estimated from the location of the femoral heads relative to S1, where femoral heads that are anterior to S1 or directly below S1 correspond to high and low PI, respectively. Spine surgeons commonly use standing lateral lumbopelvic radiographs to determine sagittal balance by measuring LL and PI. PI and standing LL should be within 10^o of one another and a mismatch greater than 10^o is considered unbalanced and has been shown to correlate with dislocation risk.[27] The deformity is also known as flatback because LL is approaching 0^o.

Combined Sagittal Index (CSI) is a newly described parameter for sagittal functional hip motion introduced by Heckmann, et al, that may predict impingement in late THA dislocations in patients with spinopelvic abnormality.[33] It is made up of the sum of AI and PFA. In a cohort of 20 patients, the authors demonstrated a correlation between late dislocation and abnormal CSI. Increased standing CSI was predictive for posterior impingement in 8 of 9 patients that dislocated anteriorly, whereas decreased sitting CSI was predictive for anterior impingement in 10 of 11 patients that dislocated posteriorly. Following this, Tezuka, et al, proposed a functional sagittal safe zone defined by CSI and challenged the notion that cups placed within the Lewinnek coronal safe zone are also in the ideal sagittal position, or normal functional hip zone.[36] The authors demonstrated that 14% of hips within the LSZ were not within the normal functional sagittal safe zone. The poor concordance of LSZ coronal and functional sagittal safe zone persisted even when the LSZ was narrowed to 37^o-46^o of inclination and 12^o-22^o of anteversion.[51,52] The authors further describe the 3 factors from most to least predictive of abnormal CSI and thus risk for dislocation was increased PFA, stiffness ($\Delta SS < 11^o$) and low PI. The mechanism of impingement is thought to be due to increased femoral motion (high PFA), particularly in the setting of decreased pelvic motion (stiffness and low PI).

Screening all patients for loss of spinopelvic mobility and sagittal imbalance may be ideal but is certainly not practical for a high-volume arthroplasty surgeon. Back pain is very prevalent, particularly in elderly patients with degenerative disease. Therefore screening should be reserved for high risk patients that may benefit from more extensive work up including those with spinal pathology including history of spine surgery particularly long segment lumbosacral fusion, evidence of severe degenerative spinal disease, and kyphotic standing posture, or those with hip pathology including history of hip dislocation, revision THA, and hip flexion contractures.

Treatment

Most patients undergoing THA will have normal spinopelvic motion,[8] (ΔSS 20^o-40^o from standing to sitting) and will not have clinically significant sagittal imbalance (standing $PT \pm 10^o$).[10] Futhermore, Stefl, et al, demonstrated that 16% of patients with preoperative spinopelvic abnormality regained normal spinopelvic motion post THA, presumably due to release of hip flexion contractures. As a result, for most patients, placement of the acetabular component in the standard coronal plane LSZ, has demonstrated great results for so many years. Even THA in patients with minor spinopelvic abnormalities have historically stayed safe from dislocation because surgeons tend to target narrow acetabular inclination and anteversion angles of 30^o-45^o and 15^o-20^o, respectively.[7] It should be recognized though that there is a spectrum of instability including impingement pain without frank dislocation. For the high-risk patients with pathologic spinopelvic mobility, several authors have described classification schemes and provided potential solutions.

Phan, et al, proposed adjusting acetabular anteversion according to 4 patterns of flexibility and sagittal balance.[11] In a flexible and balanced spine, standard LSZ anteversion was recommended. In a rigid and balanced spine, there is a loss of dynamic motion so a more anteverted and narrow range of 15-25^o of anteversion was recommended. For the flexible and unbalanced spine as well as a rigid and unbalanced spine, the patient may first undergo spinal realignment procedure which would place them into the rigid and balanced pattern. However, if THA is performed first, the authors recommend decreasing cup anteversion for a kyphotic deformity to prevent posterior impingement while standing.

Luthringer, et al,[12] proposed conceptually similar recommendations to Phan, et al, but specific to each patient's standing AP pelvis in order to account for standing pelvic tilt (referred to as functional pelvic plane) and therefore provide a functional acetabular position (Figure 4). For 1A (normal alignment and mobility), standard anteversion was recommended. For 1B (normal alignment with stiffness), 30^o of anteversion on the standing AP pelvis is recommended to avoid anterior impingement upon

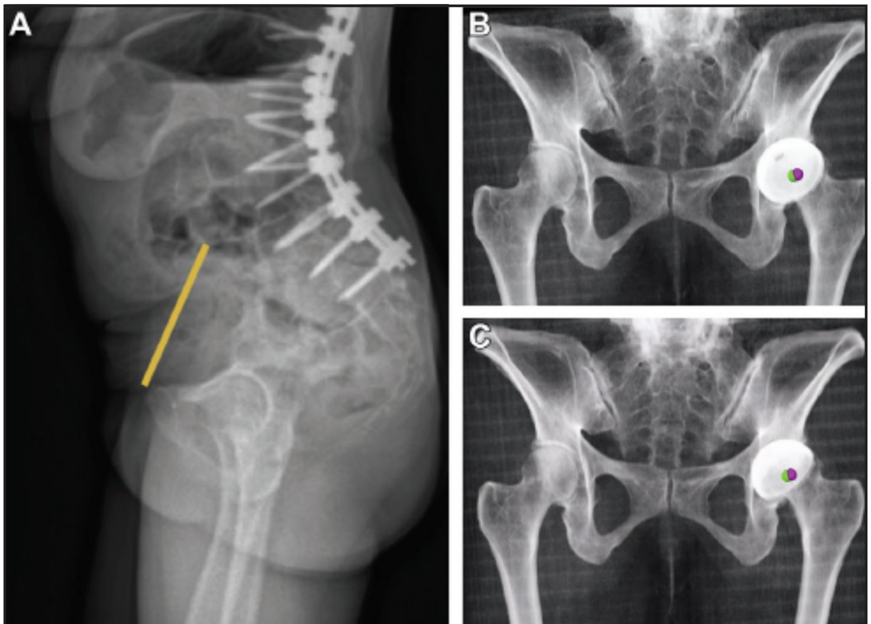

Figure 4. (A) Preoperative standing lateral image of a patient with severe posterior pelvic tilt (APP, yellow). (B) Templated cup position of 40º of inclination and 20º of anteversion relative to the APP (or traditional bony landmarks intraoperatively) leads to functional cup position of 45º of inclination and 38º of anteversion when the patient stands. (C) After accommodating for the patient's posterior pelvic tilt in the functional (standing) position, placement of the cup in 35º of inclination and 2º of anteversion relative to the APP will lead to a cup position of 40º of functional inclination and 20º of functional anteversion relative to the coronal plane when standing." Permission from Luthringer TA, Vigdorchik JM. A Preoperative Workup of a "Hip-Spine" Total Hip Arthroplasty Patient: A Simplified Approach to a Complex Problem. *J Arthroplasty.* 2019.

sitting. For 2A (flatback deformity with normal mobility), 25º-30º of anteversion on standing AP pelvis is recommended. For 2B (flatback deformity with stiffness), 30º of anteversion on the standing AP pelvis is recommended, but the authors note that there is a very narrow safe zone between inadequate anteversion causing anterior impingement when seated and excessive anteversion causing posterior impingement when standing, and therefore recommended dual mobility articulation.

Stefl, et al, proposed adjusting both anteversion and inclination according to 5 patterns of flexibility. Hypermobile is a variant of normal but with a tendency to become excessively anteverted when transitioning from standing to sitting so the authors recommend decreasing inclination and anteversion within a more narrow range of 35º-40º and 15º-20º, respectively. A stiff pelvis fixed in either anterior or posterior tilt is unable to functionally antevert its acetabulum upon sitting, therefore the authors recommend increasing inclination, anteversion, and combined anteversion within a more narrow range of 45º–50º (50º reserved for elderly patients), 20º-25º, and 35º-40º respectively. Kyphotic pattern (sitting SS < 5) will have a very vertical position of their acetabulum when seated. The recommendation for hypermobile kyphotic pattern is to decrease inclination, anteversion, and combined anteversion within a narrower range of 35º-40º, 15º-20º, and 25º-35º, respectively. Stiff and kyphotic patients, similar to the rigid and unbalanced pattern by Phan, et al, present a particular challenge because they require increased functional acetabular anteversion to avoid anterior impingement while sitting, but that places them at risk for dropout dislocation while standing. Therefore, the authors recommend a dual mobility articulation component. The authors also characterized the severity of the sagittal imbalance as either pathologic, dangerous or inconsequential. Pathologic imbalance could not be overcome with an ideal acetabular component placement; dangerous imbalance could be managed with precise acetabular component placement; and inconsequential imbalance was clinically insignificant that it did not require specific acetabular component position.

Sultan, et al,[19] performed an analysis of 14 studies on outcomes of THA before and after spine surgery to address whether to perform THA before or after spinal deformity correction in patients with concomitant pathology. The authors propose initial evaluation of any hip flexion contractures, which if present, should be addressed with initial THA then reevaluation of spinal pathology. If hip flexion contractures are not present, the decision to address the hip or spine first depends on severity of symptoms. The authors then defer the positioning of components according to recommendations by Phan, et al.

The contribution of pathologic spinopelvic motion on THA dislocations is certainly not insignificant, particularly in late dislocations and revisions in elderly patient. However, acute primary THA dislocations are typically not due to spinopelvic abnormalities,[33,53] rather, they are attributed to decreased leg length or offset, component malposition, or abductor insufficiency. The same may be said for late dislocations. This discrepancy though may partly be due to the fact that most arthroplasty surgeons simply do not evaluate the spine and attribute instability and wear problems on familiar and common complications. For revisions and late dislocations, Heckmann, et al, recommend evaluating for bony impingement at extremes of motion with preoperative imaging.[33] If present, consideration should be made to increase offset or partially remove or even distally advance the greater trochanter.

In some cases, spinopelvic limitations preclude the use of standard components. Tezuka, et al, identified the 3 strongest factors predictive for dislocation, namely stiff pelvic motion, low PI, and excessive femoral flexion (PFA).[36] The authors suggest there is no component "safe zone" for these patients and recommended placement of dual mobility articulation. Further studies would need to be performed to further characterize the range of pathologic stiffness, PI and PFA to narrow down the indications for dual mobility articulation. Vigdorchik and colleagues have presented preliminary data supporting the use of a new risk assessment score to identify patients at high-risk for dislocation and have found promising results with the use of dual mobility constructs leading to a 6-fold decrease in the rate of dislocations in this cohort.[54]

Discussion

Spinopelvic mobility can be confusing. Most arthroplasty surgeons focus on the acetabular component positioning according to the static position of the pelvis. However, the functional position should be used instead. This will account for the dynamic interplay between the spine, pelvis, and hip.

THA positioning according to LSZ will be adequate for most people. Patients at high risk should be identified and screened more carefully.

Taken altogether, in order to avoid impingement, the position of the anticipated position should take into consideration:

Spinopelvic Stiffness

This will determine the dynamic change in the functional position of acetabulum when transitioning from standing to sitting. Stiffness can be either biologic due to degenerative spine disease or iatrogenic due to multilevel lumbosacral fusion. Stiffness prevents normal dynamic posterior pelvic tilt upon sitting and most commonly therefore increases the risk of anterior impingement.

Sagittal Balance

Position of the pelvis while standing. Compensation for a kyphotic spine is posterior pelvic tilt when standing which creates a functionally anteverted cup and thus increases the risk of posterior impingement.

Pelvic Incidence

PI will determine the degree of femoral flexion required to sit. The lower the PI, the less the pelvis will tilt so greater femoral flexion is required and thus higher risk for bony impingement and dislocation.[36]

Many dislocations will still occur despite adequate component positioning. It is difficult to predict postoperative positioning. For example, patients with hip osteoarthritis may have hip flexion contractures, which when released by THA, may allow for increased spinopelvic mobility. Furthermore, standing PT has been shown to worsen over time as patients become increasing kyphotic leading to late dislocations. The mathematical relationship between APPt and AA, inclination, AI, and SS may help elucidate the ideal position.[9,10,32,40] Further studies on a functional sagittal safe zone, potentially with the use of CSI parameters, may be more applicable than the coronal LSZ.

Lateral standing and sitting radiographs should be obtained in patients that may be a risk. Late dislocation and revisions need to incorporate routine work up for spinopelvic abnormalities as a potential cause for failure. Hips that fall outside the normal range of CSI may be particularly risk.

Options for treatment are to modify acetabular component positioning accordingly or utilize a dual mobility articulation. Ultimately, a compromise must be reached between attaining adequate hip stability while minimizing superior edge loading, polyethylene wear, liner fracture, and inadequate implant-bone contact for osteointegration. Significant and symptomatic spine disease would warrant spine surgery first, whereas symptomatic hip pathology and or flexion contracture may benefit from a THA first.

It should be noted that the cause of acute as well as late dislocations are certainly multifactorial with a significant soft tissue component including attenuation of the hip capsule due to the surgical approach or subsequent wear debris, imbalance and weakness of surrounding musculature, particularly the abductors, and improper positioning of implants. It is the stance of the senior author, who exclusively performs THA via the direct anterior approach (DAA), that less soft tissue disruption may mitigate the dislocation risk, which would be particularly important in those with pathologic spinopelvic motion. The DAA also allows for placement of components within a narrow range with the aid of fluoroscopy. A practical and simple modification that can be instituted by surgeons utilizing intraoperative imaging is to match their intraoperative supine AP pelvis with the preoperative standing AP pelvis by tilting the bed up or down. By referencing off a tilted pelvis and placing the components in 40^{o} inclination and 20^{o} anteversion, the surgeon should match the functional position of the patient's pelvis while standing. This adjustment, however, does not account for any dynamic motion limitations due to spinal stiffness.

Conclusion

The dynamic interplay between the spine, pelvis and hip is complex with significant implications on total hip arthroplasty outcomes in cases of pathologic spinopelvic motion. As our appreciation and understanding progresses, we hope to be able to more accurately identify high risk patients, effectively and expeditiously characterize their individual anatomy, and ultimately identify the ideal component position to maximize stability and minimize wear. Currently for primary THA, we recommend the screening for high risk patients to include a history of spinal pathology including spine surgery with long segment lumbosacral fusion, evidence of severe degenerative spinal disease, and kyphotic standing posture, or those with hip pathology including history of hip dislocation, revision THA, and hip flexion contractures. A functional spinopelvic imaging series should be obtained for these patients which includes three views of the pelvis: lateral standing and sitting (90^{o} trunk-thigh angle) and AP standing. Evaluation should begin with identification of the deformity type (stuck standing, stuck sitting or kyphotic) and the degree of stiffness. Our recommendations for management are in line with the classification scheme and treatment algorithm proposed by Luthringer, et al.[12] Use of the DAA with minimal soft tissue disruption may also mitigate instability risk.

Ideal component composition continues to be elusive. Reconsideration of component "safe zones" has begun to stray away from the coronal plane values proposed by Lewinnek. A new focus has been placed on sagittal plane safe zones and with the introduction of the combined sagittal index it may provide more appropriate and accurate safe zones. Future studies are needed to identify and narrow down this proposed sagittal safe zone. However, some cases of pathologic motion are so severe that dual mobility articulation implants may be required, particularly in the revision setting.

Conflict of Interest

None of the authors identify a conflict of interest.

Disclosure Statement

Dr. Harpstrite reports personal fees from DePuy, A Johnson & Johnson Company, personal fees from Orthopedic Development Corporation, and personal fees from Smith & Nephew, outside the submitted work.

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References

1. Philippot R, Wegrzyn J, Farizon F, Fessy MH. Pelvic balance in sagittal and Lewinnek reference planes in the standing, supine and sitting positions. *Orthop Traumatol Surg Res.* 2009;95(1):70-76.
2. Lazennec JY, Riwan A, Gravez F, et al. Hip spine relationships: application to total hip arthroplasty. *Hip Int.* 2007;17 Suppl 5:S91-104.
3. Lazennec JY, Boyer P, Gorin M, Catonné Y, Rousseau MA. Acetabular anteversion with CT in supine, simulated standing, and sitting positions in a THA patient population. *Clin Orthop Relat Res.* 2011;469(4):1103-1109.
4. Lazennec JY, Brusson A, Rousseau MA. Hip-spine relations and sagittal balance clinical consequences. *Eur Spine J.* 2011;20 Suppl 5:686-698.
5. Lazennec JY, Brusson A, Rousseau MA. Lumbar-pelvic-femoral balance on sitting and standing lateral radiographs. *Orthop Traumatol Surg Res.* 2013;99(1 Suppl):S87-103.
6. Barrey C, Roussouly P, Le Huec JC, D'Acunzi G, Perrin G. Compensatory mechanisms contributing to keep the sagittal balance of the spine. *Eur Spine J.* 2013;22 Suppl 6:S834-841.
7. Ike H, Dorr LD, Trasolini N, Stefl M, McKnight B, Heckmann N. Spine-Pelvis-Hip Relationship in the Functioning of a Total Hip Replacement. *J Bone Joint Surg Am.* 2018;100(18):1606-1615.
8. Stefl M, Lundergan W, Heckmann N, et al. Spinopelvic mobility and acetabular component position for total hip arthroplasty. *Bone Joint J.* 2017;99-B(1 Supple A):37-45.
9. Kanawade V, Dorr LD, Wan Z. Predictability of Acetabular Component Angular Change with Postural Shift from Standing to Sitting Position. *J Bone Joint Surg Am.* 2014;96(12):978-986.
10. Maratt JD, Esposito CI, McLawhorn AS, Jerabek SA, Padgett DE, Mayman DJ. Pelvic tilt in patients undergoing total hip arthroplasty: when does it matter? *J Arthroplasty.* 2015;30(3):387-391.
11. Phan D, Bederman SS, Schwarzkopf R. The influence of sagittal spinal deformity on anteversion of the acetabular component in total hip arthroplasty. *Bone Joint J.* 2015;97-B(8):1017-1023.
12. Luthringer TA, Vigdorchik JM. A Preoperative Workup of a "Hip-Spine" Total Hip Arthroplasty Patient: A Simplified Approach to a Complex Problem. *J Arthroplasty.* 2019.
13. Malkani AL, Garber AT, Ong KL, et al. Total Hip Arthroplasty in Patients With Previous Lumbar Fusion Surgery: Are There More Dislocations and Revisions? *J Arthroplasty.* 2018;33(4):1189-1193.
14. Esposito CI, Miller TT, Kim HJ, et al. Does Degenerative Lumbar Spine Disease Influence Femoroacetabular Flexion in Patients Undergoing Total Hip Arthroplasty? *Clin Orthop Relat Res.* 2016;474(8):1788-1797.
15. Patel PD, Potts A, Froimson MI. The dislocating hip arthroplasty: prevention and treatment. *J Arthroplasty.* 2007;22(4 Suppl 1):86-90.
16. Esposito CI, Gladnick BP, Lee YY, et al. Cup position alone does not predict risk of dislocation after hip arthroplasty. *J Arthroplasty.* 2015;30(1):109-113.
17. Abdel MP, von Roth P, Jennings MT, Hanssen AD, Pagnano MW. What Safe Zone? The Vast Majority of Dislocated THAs Are Within the Lewinnek Safe Zone for Acetabular Component Position. *Clin Orthop Relat Res.* 2016;474(2):386-391.
18. Delaunay C, Hamadouche M, Girard J, Duhamel A, Group S. What are the causes for failures of primary hip arthroplasties in France? *Clin Orthop Relat Res.* 2013;471(12):3863-3869.
19. Sultan AA, Khlopas A, Piuzzi NS, Chughtai M, Sodhi N, Mont MA. The Impact of Spino-Pelvic Alignment on Total Hip Arthroplasty Outcomes: A Critical Analysis of Current Evidence. *J Arthroplasty.* 2018;33(5):1606-1616.
20. Gausden EB, Parhar HS, Popper JE, Sculco PK, Rush BNM. Risk Factors for Early Dislocation Following Primary Elective Total Hip Arthroplasty. *J Arthroplasty.* 2018;33(5):1567-1571.e1562.

21. An VVG, Phan K, Sivakumar BS, Mobbs RJ, Bruce WJ. Prior Lumbar Spinal Fusion is Associated With an Increased Risk of Dislocation and Revision in Total Hip Arthroplasty: A Meta-Analysis. *J Arthroplasty.* 2018;33(1):297-300.
22. Buckland AJ, Puvanesarajah V, Vigdorchik J, et al. Dislocation of a primary total hip arthroplasty is more common in patients with a lumbar spinal fusion. *Bone Joint J.* 2017;99-B(5):585-591.
23. Bedard NA, Martin CT, Slaven SE, Pugely AJ, Mendoza-Lattes SA, Callaghan JJ. Abnormally High Dislocation Rates of Total Hip Arthroplasty After Spinal Deformity Surgery. *J Arthroplasty.* 2016;31(12):2884-2885.
24. Eneqvist T, Nemes S, Brisby H, Fritzell P, Garellick G, Rolfson O. Lumbar surgery prior to total hip arthroplasty is associated with worse patient-reported outcomes. *Bone Joint J.* 2017;99-B(6):759-765.
25. Perfetti DC, Schwarzkopf R, Buckland AJ, Paulino CB, Vigdorchik JM. Prosthetic Dislocation and Revision After Primary Total Hip Arthroplasty in Lumbar Fusion Patients: A Propensity Score Matched-Pair Analysis. *J Arthroplasty.* 2017;32(5):1635-1640.e1631.
26. Sing DC, Barry JJ, Aguilar TU, et al. Prior Lumbar Spinal Arthrodesis Increases Risk of Prosthetic-Related Complication in Total Hip Arthroplasty. *J Arthroplasty.* 2016;31(9 Suppl):227-232.e221.
27. DelSole EM, Vigdorchik JM, Schwarzkopf R, Errico TJ, Buckland AJ. Total Hip Arthroplasty in the Spinal Deformity Population: Does Degree of Sagittal Deformity Affect Rates of Safe Zone Placement, Instability, or Revision? *J Arthroplasty.* 2017;32(6):1910-1917.
28. Nam D, Riegler V, Clohisy JC, Nunley RM, Barrack RL. The Impact of Total Hip Arthroplasty on Pelvic Motion and Functional Component Position is Highly Variable. *J Arthroplasty.* 2017;32(4):1200-1205.
29. Tamura S, Nishihara S, Takao M, Sakai T, Miki H, Sugano N. Does Pelvic Sagittal Inclination in the Supine and Standing Positions Change Over 10 Years of Follow-Up After Total Hip Arthroplasty? *J Arthroplasty.* 2017;32(3):877-882.
30. Miki H, Kyo T, Kuroda Y, Nakahara I, Sugano N. Risk of edge-loading and prosthesis impingement due to posterior pelvic tilting after total hip arthroplasty. *Clin Biomech (Bristol, Avon).* 2014;29(6):607-613.
31. Hu J, Qian BP, Qiu Y, et al. Can acetabular orientation be restored by lumbar pedicle subtraction osteotomy in ankylosing spondylitis patients with thoracolumbar kyphosis? *Eur Spine J.* 2017;26(7):1826-1832.
32. Buckland AJ, Vigdorchik J, Schwab FJ, et al. Acetabular Anteversion Changes Due to Spinal Deformity Correction: Bridging the Gap Between Hip and Spine Surgeons. *J Bone Joint Surg Am.* 2015;97(23):1913-1920.
33. Heckmann N, McKnight B, Stefl M, Trasolini NA, Ike H, Dorr LD. Late Dislocation Following Total Hip Arthroplasty: Spinopelvic Imbalance as a Causative Factor. *J Bone Joint Surg Am.* 2018;100(21):1845-1853.
34. Yukizawa Y, Dorr LD, Ward JA, Wan Z. Posterior Mini-Incision With Primary Total Hip Arthroplasty: A Nine to Ten Year Follow Up Study. *J Arthroplasty.* 2016;31(1):168-171.
35. Okanoue Y, Ikeuchi M, Takaya S, Izumi M, Aso K, Kawakami T. Chronological changes in functional cup position at 10 years after total hip arthroplasty. *Hip Int.* 2017;27(5):477-482.
36. Tezuka T, Heckmann ND, Bodner RJ, Dorr LD. Functional Safe Zone Is Superior to the Lewinnek Safe Zone for Total Hip Arthroplasty: Why the Lewinnek Safe Zone Is Not Always Predictive of Stability. *J Arthroplasty.* 2019;34(1):3-8.
37. Lum ZC, Coury JG, Cohen JL, Dorr LD. The Current Knowledge on Spinopelvic Mobility. *J Arthroplasty.* 2018;33(1):291-296.
38. Legaye J, Duval-Beaupère G, Hecquet J, Marty C. Pelvic incidence: a fundamental pelvic parameter for three-dimensional regulation of spinal sagittal curves. *Eur Spine J.* 1998;7(2):99-103.
39. Lewinnek GE, Lewis JL, Tarr R, Compere CL, Zimmerman JR. Dislocations after total hip-replacement arthroplasties. *J Bone Joint Surg Am.* 1978;60(2):217-220.
40. Lembeck B, Mueller O, Reize P, Wuelker N. Pelvic tilt makes acetabular cup navigation inaccurate. *Acta Orthop.* 2005;76(4):517-523.
41. Tannast M, Murphy SB, Langlotz F, Anderson SE, Siebenrock KA. Estimation of pelvic tilt on anteroposterior X-rays--a comparison of six parameters. *Skeletal Radiol.* 2006;35(3):149-155.
42. Tang WM, Chiu KY, Kwan MF, Ng TP. Sagittal pelvic mal-rotation and positioning of the acetabular component in total hip arthroplasty: Three-dimensional computer model analysis. *J Orthop Res.* 2007;25(6):766-771.
43. Eddine TA, Migaud H, Chantelot C, Cotten A, Fontaine C, Duquennoy A. Variations of pelvic anteversion in the lying and standing positions: analysis of 24 control subjects and implications for CT measurement of position of a prosthetic cup. *Surg Radiol Anat.* 2001;23(2):105-110.
44. Uemura K, Takao M, Otake Y, et al. Change in Pelvic Sagittal Inclination From Supine to Standing Position Before Hip Arthroplasty. *J Arthroplasty.* 2017;32(8):2568-2573.
45. Schwab F, Patel A, Ungar B, Farcy JP, Lafage V. Adult spinal deformity-postoperative standing imbalance: how much can you tolerate? An overview of key parameters in assessing alignment and planning corrective surgery. *Spine (Phila Pa 1976).* 2010;35(25):2224-2231.
46. Schwab FJ, Blondel B, Bess S, et al. Radiographical spinopelvic parameters and disability in the setting of adult spinal deformity: a prospective multicenter analysis. *Spine (Phila Pa 1976).* 2013;38(13):E803-812.
47. Hovorka I, Rousseau P, Bronsard N, et al. [Extension reserve of the hip in relation to the spine: Comparative study of two radiographic methods]. *Rev Chir Orthop Reparatrice Appar Mot.* 2008;94(8):771-776.
48. Kyo T, Nakahara I, Miki H. Factors predicting change in pelvic posterior tilt after THA. *Orthopedics.* 2013;36(6):e753-759.
49. Weng WJ, Wang WJ, Wu MD, Xu ZH, Xu LL, Qiu Y. Characteristics of sagittal spine-pelvis-leg alignment in patients with severe hip osteoarthritis. *Eur Spine J.* 2015;24(6):1228-1236.
50. Sariali E, Lazennec JY, Khiami F, Gorin M, Catonne Y. Modification of pelvic orientation after total hip replacement in primary osteoarthritis. *Hip Int.* 2009;19(3):257-263.
51. Elkins JM, Callaghan JJ, Brown TD. The 2014 Frank Stinchfield Award: The 'landing zone' for wear and stability in total hip arthroplasty is smaller than we thought: a computational analysis. *Clin Orthop Relat Res.* 2015;473(2):441-452.
52. Murphy WS, Yun HH, Hayden B, Kowal JH, Murphy SB. The Safe Zone Range for Cup Anteversion Is Narrower Than for Inclination in THA. *Clin Orthop Relat Res.* 2018;476(2):325-335.
53. Dorr LD, Wan Z. Causes of and treatment protocol for instability of total hip replacement. *Clin Orthop Relat Res.* 1998(355):144-151.
54. Vigdorchik JM EA, Carroll KM, Mayman DJ, Iorio R, Buckland A, et al. A new risk-assessment score and treatment algorithm for patients at high-risk of dislocation following total hip arthroplasty. In. 2018 ed. New Orleans: American Academy of Orthopaedic Surgeons 2018 Annual Meeting; 2018.