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Spinopelvic challenges in primary total hip arthroplasty

George Grammatopoulos[1], Moritz Innmann[2], Philippe Phan[1], Russell Bodner[3] and Geert Meermans[4]

[1]The Ottawa Hospital, Ottawa, Ontario, Canada
[2]Heidelberg University Hospital, Heidelberg, Germany
[3]Midwest Orthopedic Institute, Sycamore, United States of America
[4]Bravis Hospital, Roosendaal, The Netherlands

Correspondence should be addressed to G Meermans
Email
geertmeermans@hotmail.com

- There is no universal safe zone for cup orientation. Patients with spinal arthrodesis or a degenerative lumbar spine are at increased risk of dislocation and have a narrower zone of optimal cup placement.
- The relative contributions of the hip (femur and acetabulum) and of the spine (lumbar spine) in body motion must be considered together. The pelvis links the two and influences both acetabular orientation (i.e. hip flexion/extension) and sagittal balance/lumbar lordosis (i.e. spine flexion/extension).
- Examination of the spino-pelvic motion can be done through clinical examination and standard radiographs or stereographic imaging. A single, lateral, standing spinopelvic radiograph would be able to provide the most relevant information required for screening and pre-operative planning.
- A significant variability in static and dynamic spinopelvic characteristics exists amongst healthy volunteers without known spinal or hip pathology.
- The stiff, arthritic, hip leads to greater changes in pelvic tilt (changes are almost doubled), with associated obligatory change in lumbar lordosis to maintain upright posture (lumbar lordosis is reduced to counterbalance for the reduction in sacral slope). Following total hip arthroplasty and restoration of hip flexion, spinopelvic characteristics tend to change/normalize (to age-matched healthy volunteers).
- The static spinopelvic parameters that are directly associated with increased risk of dislocation are lumbo-pelvic mismatch (pelvic incidence – lumbar lordosis angle > 10°), high pelvic tilt (>19°), and low sacral slope when standing. A high combined sagittal index (CSI) when standing (>245°) is associated with increased risk of anterior instability, whilst low CSI when standing (<205°) is associated with increased risk of posterior instability.
- Aiming to achieve an optimum CSI when standing within 205–245° (with narrower target for those with spinal disease) whilst ensuring the coronal targets of cup orientation targets are achieved (inclination/version of 40/20 ±10°) is our preferred method.

Keywords

- hip–spine
- total hip arthroplasty
- cup orientation
- instability
- spinopelvic mobility
- pelvic tilt

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Introduction

Appropriate component orientation is important for success following hip arthroplasty (1). The significance of appropriate acetabular component (cup) orientation was further highlighted with the use of the third-generation metal-on-metal hip resurfacing implants (2, 3, 4). It was noted that patients with suboptimal cup orientations (e.g. high inclination) had high metal ions (surrogate measures of *in vivo* wear) and were more likely to develop soft-tissue reactions about the hip (2, 3, 4). However, not all patients with suboptimal cup orientation would exhibit high wear and similarly patients with 'optimal' orientation might have higher metal ions than expected, illustrating that optimal component orientation may be different for each patient and likely multifactorial (3, 5, 6, 7). The effect of cup orientation in total hip arthroplasty (THA) outcome was further studied in the setting of instability. Numerous authors, in the recent years, have challenged the validity of the Lewinnek zone as a universally 'safe' zone for component orientation in THA as a significant proportion of unstable hips have cup orientations, when

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supine, within the radiographic inclination/anteversion boundaries described by Lewinnek or others (8, 9, 10, 11, 12). Furthermore, a large number or patients with cup orientations outside these boundaries do not exhibit hip instability (8, 9, 10). The interaction between the hip and spine and the assessment of the sagittal plane has gained interest as changes in posture lead to alteration in the position of the pelvis and thus influence cup orientation (13, 14). Cup orientation affects joint mechanics, influencing impingement-risk (15) and thus wear, pain, and instability (16, 17).

The overarching aim of this review is to highlight the relevance of the spinopelvic complex in hip arthroplasty; in doing so, it aims to provide guidance on how to assess it, diagnose the presence of abnormality, and incorporate it into the daily routine of the hip arthroplasty surgeon.

Importance of hip–spine relationship

The relevance of considering the function of the spine in arthroplasty patients has been highlighted in recent years (18, 19, 20, 21, 22, 23, 24). The increased prevalence of concomitant hip and spine pathology and the heightened interest regarding hip–spine syndrome further contributed to the study of the hip–spine relationship (25). Observational studies have illustrated that THA in the setting of prior lumbar arthrodesis is associated with inferior outcome (increased complication and revision rates) for a multitude of reasons (18, 19, 20, 21, 22, 26, 27). The complication with the greatest risk following THA in the presence of spinal arthrodesis is that of instability/dislocation (18, 19, 20, 21, 22). Patients are at increased risk of THA dislocation in the presence of spinal arthrodesis or a degenerative lumbar spine (biological arthrodesis). Furthermore, the risk of instability is dependent on number of levels fused (or degenerate) and whether the fusion extends into the sacrum or pelvis (19, 28). There is contradicting evidence on whether the spine or hip should be addressed first in observational cohort studies; some advocate that the THA should be performed first, followed by delayed fusion (29, 30), whilst others have reported on increased risk of complications if the THA is performed first (31). A prolonged delay in undertaking the THA, due to delays associated with spinal treatment, is likely to lead to worse hip function pre-operatively and thus a likely worse function post-THA, which should be considered in the decision-making (20). Furthermore, possible alleviation of any fixed flexion deformities and an improvement in the hip's range of movement are likely to alleviate demand on the lumbar spine and might reduce spinal pain and potential delay need for surgery. Shared decision-making between patients and surgeons (spinal and arthroplasty) is of importance to improve outcomes. Spinal surgeons should be cognizant that a change in the sagittal profile/balance will change the functional component orientation of the pelvis/acetabulum and may lead to instability (13, 14). Furthermore, the longer the arthrodesis, the stiffer the spinal complex and the greater the demand on the hip, for any given task. This leads to a greater risk of impingement and subsequent instability.

Terminology – spinopelvic parameters

To better characterize the spinal, pelvic and femoral morphology, it is of importance to describe the terms commonly used. Table 1 and Fig. 1 provide detailed descriptions and illustrations of the angles commonly measured. The nomenclature used has not been standardized – particularly for pelvic tilt (PT) – which commonly differs between spine and hip surgeons.

Pelvic incidence (PI) is a morphological parameter, characterizing the sagittal profile of the pelvis, which relates the hip (bicoxofemoral) axis to the slope of the sacral end plate (32, 33, 34). This value is constant following maturation of the skeleton and does not change with different postures or the occurrence of hip or spine degeneration. The PI value denotes the sacral angle and position and thus has an influence on the optimal lumbar

Table 1 Descriptions, abbreviations, and measurements for radiographic spinopelvic parameters.

Spinopelvic parameter	Radiographic measurement
Anterior pelvic plane angle (APPt)	The anterior pelvic plane tilt is defined as the angle between the plane created by the bilateral anterior superior iliac spine to the pubic symphysis and the coronal vertical plane (47).
Ante-inclination (AI)	Ante-inclination is the angle between a line tangent to the anterior and posterior edges of the acetabular cup and a horizontal line parallel to the margin of the radiograph (48).
Lumbar lordosis angle (LL)	The lumbar lordosis angle is defined by the angle between the upper plane of the L1 lumbar vertebrae and the upper plane of the S1 sacral vertebrae.
Spinopelvic pelvic tilt (sPT or PT)	Spinopelvic tilt or pelvic tilt is defined as the angle between a line drawn from the midpoint of the bicoxofemoral axis to the midpoint of the sacral plate and the vertical (47).
Pelvic incidence (PI)	Pelvic incidence is defined as the angle between a line perpendicular to the sacral plate at its midpoint and a line connecting the same point to the center of the bicoxofemoral axis (34).
Pelvic femoral angle (PFA)	The pelvic femoral angle is the angle subtended by a line connecting the midpoint of the S1 end plate and the center of the bicoxofemoral axis and line from the center of the bicoxofemoral axis projected distally toward the center of the knee, typically along the anterior shaft of the proximal femur.
Sacral slope (SS)	The sacral slope is defined as the angle between the superior plate of S1 and a horizontal line (34).

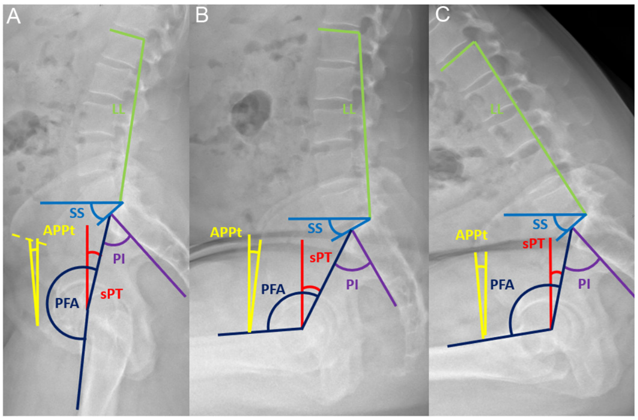

Figure 1
The measurements for radiographic spinopelvic parameters in the (A) standing, (B) upright seated, and (C) deep-flexed-seated position for normal spinopelvic mobility in an asymptomatic volunteer.

lordosis (measured as the Cobb angle between first sacral and first lumbar end plates). The difference between PI and lumbar lordosis angle (LL) (PI – LL) dictates whether appropriate lumbar lordosis for a given PI value is present (32, 33, 34).

Hip surgeons refer to PT from the anterior pelvic plane tilt (APPt) (11, 35). The APPt is defined as the angle between the vertical (when standing) or horizontal (when supine) and a line correcting the midpoint of the two anterior superior iliac spines (ASIS) to the pubic symphysis. It is commonly thought that the APPt when standing is close to 0° to be sagittally balanced and in optimal sagittal position; however, this has not been shown to be the case as wide variability exists (35, 36). The APPt is of value as it is recorded and accounted for in many of the navigation software used in hip arthroplasty to aid component placement (36). Spine surgeons refer to PT as the angle between the vertical (when standing) or horizontal (when supine) and a line connecting the center of the sacral end plate (S1) to the center of the bicoxofemoral axis (midpoint between the femoral heads). This angle has also been termed as spinopelvic tilt (sPT or PT) in the hip literature. The sPT is the angle that best characterizes the sagittal balance between the hip and spine as it reflects the relative position of the femoral heads (appendicular skeleton) to the spine (axial skeleton) and is thus the angle providing most physiological information regarding body weight transfer (37). An additional parameter that is commonly used is sacral slope (38, 39). This is the angle between the horizontal (when standing) and vertical (when supine) and the sacral end plate. The algebraic sum of sPT and sacral slope (SS) is the PI.

Several important parameters regarding tilt and its measurement/description are worth noting:

- The angular values of APPt and the sPT are not numerically the same, and the deviation of the two values will be dependent on the inherent morphology of the pelvis (PI) (36).
- The APPt, sPT, and SS can all be measured in different functional positions from radiographs and CT scans – they can thus be used to measure/quantify pelvic motion/mobility that takes place. The values derived quantifying pelvic mobility would be the same.
- The pelvis can rotate anteriorly or posteriorly. An anterior pelvic rotation implies that the ASISs rotate anteriorly relatively to the pubis, with an accompanying reduction in sPT and increase in SS. A posterior pelvic rotation describes the opposite movement. A large variability in terminology exists in the literature to describe pelvic movement (pelvic retroversion/anteversion, pelvic flexion/extension, and positive/negative tilt), which can lead to confusion, and for the purpose of this review, anterior and posterior tilt will be the terms used (40).

The sagittal position of the femur relative to the spine is measured with the pelvic femoral angle (PFA) (41, 42). The PFA is a measure of hip flexion/extension as it considers the relative position of the hip joint center relative the sacrum and femur. An additional parameter of value is the ante-inclination (AI) value, describing the acetabular opening in the sagittal plane relative to the horizontal. The AI value for any given acetabulum is dependent on the degree of PT present; the greater the posterior PT, the greater the AI present and the greater the degree of available, impingement-free, flexion (43, 44, 45). The sum of PFA and AI is the combined sagittal index (CSI), characterizing the sagittal characteristics of the hip joint, considering both the acetabular and femoral orientations (44).

Measurement of these angles from radiographs in different postures allows the determination of the degree of lumbar spine flexion (change in lumbar lordosis angle), pelvic mobility (change in APPt or SPT or SS), and hip flexion (change in PFA). Thus, one can determine the relative contribution of the hip to the overall sagittal movement (hip and spine flexion) by calculating the relative hip–spine user index ($HUI = \Delta PFA / (\Delta PFA + \Delta LL) \times 100$) (46).

Evaluation: clinical and radiographic

Patient evaluation should be multifaceted and include pertinent points in the history and examination in addition to the detailed radiographic evaluation. Relevant points in the history should include but not be limited to the presence of previous spinal surgery (arthrodesis or not), back pain, history of inflammatory arthropathies, previous spinal/pelvic trauma (including spondylolisthesis) and presence of neurological symptoms.

The clinical examination should include a detailed examination of the hip, including assessment for the presence of true or apparent leg-length discrepancy (LLD), muscle contractures, and rotation profile asymmetry. Gait assessment provides valuable information of sagittal characteristics. In addition, spinal assessment should be performed to further determine the spinal contribution to the findings, for example, the presence of scoliosis is likely to lead to asymmetry in pelvic rotation and obliquity (contributing to LLD and rotational differences), whilst the presence of kyphosis is likely to lead to a flatback deformity. Spinal assessment can include the Schober's test, testing spinal mobility, although its value in predicting spinopelvic characteristics is limited (49).

Radiographic evaluation can take place with routine, easily available radiographs of the pelvis and spinopelvic complex. These radiographs can either be flat-plate radiographs or stereoradiographs (EOS Imaging, Paris, France) (43, 44, 45). Care should be taken with rotation and centering of the flat-plate beam, when supine and/or standing AP pelvic radiographs are obtained, as the two-dimensional pelvic appearance is sensitive to the x-ray beam center position. It is our recommendation that the beam center is positioned vertically, halfway between the ASIS and the pubis, in line with previous descriptions (50), and that the beam is not adjusted to a sacro-pubic distance within 3–4 mm (51) as this would not reflect native anatomy and variance in tilt. Radiographs obtained with EOS are not sensitive to such errors – however, the use of EOS does not allow for supine radiographs, and the small, confined, space of the EOS enclosure might be too small to obtain radiographs in different postures (e.g. standing with leg on chair and deep-flexed seated) in people with certain body habitus (tall or large width).

Several radiographs have been described for the study of the hip–spine interaction in the sagittal plane. These include standing radiographs, including the femur, pelvis, and various contributions of the lumbar spine as per differing recommendations and flexed positions in different postures (relaxed, deep flexed, and leg on a chair) (35, 40, 46, 49). Which radiographs are to be obtained depend on how much the sagittal plane is to be studied and whether the information obtained is to identify patients at risk and be used for pre-operative cup orientation planning. The authors of this article obtain the following four radiographs routinely: (i) AP pelvic radiograph (supine); (ii) AP pelvic radiograph (standing); (iii) lateral standing spinopelvic view; and (iv) lateral deep-flexed spinopelvic view (52; Table 2). The rationale for why to obtain these four radiographs is to be described below, along with what information can be obtained from the relaxed-seated radiograph if to be used.

Supine and standing AP pelvic radiographs

The supine AP pelvic radiograph has traditionally been the gold standard for the arthroplasty surgeon to pre-operatively plan, especially when two-dimensional software is used (1, 53). The difference between supine and standing radiographs aids to identify patients with:

- Aberrant change in PT – the pelvis adopts more of a pelvic inlet (reduction in sPT) or outlet (increase in sPT) view. The change can be quantified by measuring the sacro-femoral-pubic angle and its difference between the two radiographs (54).
- Pelvic obliquity – the cranio-caudal position of each pelvic crest and hip joint center (or hemi-pelvis) allow for the determination of the presence of any scoliosis, muscle contracture (adductor or abductor), and LLD. Further assessment of the LLD as to its origin (spinal or lower-limb origin) would be required.
- Pelvic rotation – the relative symmetry of the obturator foramina and the iliac wings best assesses for this. The presence of rotational asymmetry raises the possibility of muscular contractures or scoliosis, leading to different functional orientations of each hemipelvis and acetabulum.

Standing spinopelvic radiograph

The standing spinopelvic radiograph should include the first lumbar vertebra proximally and the proximal femoral shaft distally. Occasionally, the distance between cassette and beam would have to be adjusted to capture the whole field of interest. Pertinent points of this assessment include the following:

- Presence of spinal pathology – radiographs are screened for the presence of arthrodesis (of note to consider levels and if sacrum involved), degenerative disk disease, and spondylolisthesis
- LL angle – a standing LL angle <45° has been associated with the presence of spinal stiffness and a degenerate spine (55).
- Presence of a lumbo-pelvic mismatch – a PI – LL value of greater than 10° is an important screening tool to identify the presence of a flatback deformity, although this threshold value is dependent on the individual's PI value (56).
- Assessment of sagittal balance – an sPT value greater than 19° should alert for the presence of abnormal sagittal characteristics (42, 46).

Table 2 Spinopelvic parameters between standing, 'relaxed-seated', and 'deep-flexed' seated positions in patients who underwent total hip arthroplasty and controls. Data are presented as mean± S.D.

	Controls	Pre-THA patients	*P* value†	Δ Pre- vs post-THA	Post-THA patients	*P* value‡	*P* value§
LL (°)							
Standing	56.6 ± 12.1	55.6 ± 12.2	0.680	0.4 ± 6.7	56.0 ± 10.5	0.651	0.820
Relaxed seated	38.9 ± 11.4	32.9 ± 15.1	0.044	7.8 ± 13.1	40.7 ± 13.3	<0.001	0.503
Deep seated	11.9 ± 13.1	12.7 ± 12.7	0.766	4.2 ± 8.3	16.9 ± 10.4	0.001	0.045
SS (°)							
Standing	40.1 ± 8.4	43.2 ± 8.9	0.086	−3.2 ± 7.3	40.0 ± 6.2	0.004	0.944
Relaxed seated	26.4 ± 9.8	21.4 ± 11.4	0.032	4.4 ± 11.7	25.8 ± 9.3	0.013	0.755
Deep seated	46.9 ± 18.6	36.1 ± 11.2	0.001	6.8 ± 14.7	42.8 ± 11.9	0.003	0.211
PT (°)							
Standing	13.9 ± 8.2	13.7 ± 9.6	0.903	1.6 ± 4.9	15.3 ± 10.5	0.028	0.478
Relaxed seated	26.6 ± 10.2	35.7 ± 14.4	0.001	−5.8 ± 12.1	30.2 ± 11.4	0.002	0.131
Deep seated	6.8 ± 15.9	20.9 ± 15.6	<0.001	−7.4 ± 16.9	13.5 ± 15.0	0.004	0.041
PFA (°)							
Standing	184.8 ± 10.1	182.7 ± 11.8	0.356	1.1 ± 8.3	183.9 ± 12.6	0.348	0.685
Relaxed seated	115.7 ± 10.6	127.9 ± 15.6	<0.001	−9.8 ± 16.8	118.1 ± 13.7	<0.001	0.342
Deep seated	98.5 ± 14.1	114.2 ± 18.5	<0.001	−12.7 ± 19.4	101.5 ± 15.7	<0.001	0.331
PI standing (°)	54.2 ± 11.3	57.0 ± 12.6	0.260	−1.7 ± 6.3	55.3 ± 12.4	0.065	0.663
PI-LL (°)							
Standing	−2.3 ± 11.6	1.4 ± 12.6	0.135	−2.2 ± 5.9	−0.7 ± 14.5	0.016	0.555
Mismatch > 10° (*n* (%))	6 (12.8%)	10 (21.3%)	0.272 ††	–	9 (19.1%)	0.797††	0.398††

†Independent samples *t*-test comparing values pre-operative group with control group values; ‡paired samples *t*-test comparing pre-operative values with post-operative values; §independent samples *t*-test comparing post-operative values with control group values; ††Chi-square test.

Deep-flexed-seated spinopelvic radiograph

The deep-flexed-seated position provides an assessment of the hip in a position of 'danger' for anterior impingement and resultant posterior edge loading or instability – the most common direction of instability post-THA (35). The flexed torso provides a significant lever arm, leading to lumbar flexion and anterior PT (52). This movement and assessment, therefore, provide information on whether spinal stiffness is present or not. This is of significant relevance for the study of the hip–spine interaction. The deep-flexed-seated radiograph has superior sensitivity-, specificity, and negative and positive predictive values in identifying spinal stiffness and thus the presence of abnormal spinopelvic characteristics relative to the relaxed-seated radiographs, and it should thus be the radiograph of choice if quasi-static radiographs are to be used (57). Furthermore, radiographic measurements of the spinopelvic complex (with standing and deep seated radiographs) have been shown to correlate with axial- and coronal- plane kinematics during daily tasks as assessed in a motion analysis laboratory (58).

Relaxed-seated spinopelvic radiograph

The relaxed-seated, spinopelvic radiograph has been reported as a valuable tool to assess for spinopelvic mobility (39, 40, 41, 42, 59). The change in sacral slope between the standing and relaxed-seated postures has been advocated by many authors as a surrogate measure of spinopelvic mobility. A change in sPT between 10° and 30 is considered normal, whilst a pelvis with less than 10° of change in tilt is considered stiff and one with greater than 30° of change is considered hypermobile. However, the change in SS measures the change in PT but provides no direct measure of spinal stiffness (57). Only 15% of 'stiff' hips as measured by the relaxed seated would truly exhibit spinal stiffness as per deep-seated assessments. Thus, the relaxed-seated assessment is likely to lead to overestimation of hips at risk (57). Furthermore, about ≈20% of hips with osteoarthritis pre-THA would have features of spinopelvic hypermobility, due to the arthritic hip, lacking movement and tilting the pelvis posteriorly when adopting a relaxed-seated position as a compensatory manoeuver (42, 46, 49). Such compensation manoeuver is no longer necessary in most patients post-THA (see section on Spinopelvic parameters in normal and pathological states) (60, 61). It is for these reasons, that the authors suggest the deep-seated assessment for quasi-static assessment, if seated radiographs are to be used in clinical or academic practice.

There is little doubt that these radiographs are cumbersome and lead to increased radiation exposure, radiographer time, and cost. To improve efficiencies, it is our opinion that performing a single, lateral, standing spinopelvic radiograph would be able to provide the most relevant information required for screening and pre-operative planning, and reducing patient and health system burdens. Furthermore, for surgeons only interested in screening to identify patients at risk, in patients below the age of 55 years and without the presence of known spinal history, the chances of having adverse spinal features are very small, and thus, lateral spinopelvic radiographs are not necessary (55).

Spinopelvic parameters in normal and pathological states

'Normal'

A significant variability in static and dynamic spinopelvic characteristics exists amongst healthy volunteers without known spinal or hip pathology (62). Akin to the shoulder, where the scapula-thoracic and gleno-humeral movements must be considered separately as part of the abduction arc, the relative contributions of the hip (femur and acetabulum) and of the spine (lumbar spine and sacrum) must be considered in conjunction. The pelvis is the important link, creating the important middle cogwheel (43, 44). Hip flexion can occur in four different ways (Fig. 2) (46). The hip (femoroacetabular joint) on average contributes to approximately two-third of the whole sagittal movement, whilst the lumbar spine contributes the remaining one-third (46, 62). When moving from a supine to a standing position, the sPT slightly increases, increasing acetabular anteversion (35, 46). When moving from standing to a relaxed-seated position, the sPT once again increases (further increasing anteversion), allowing for the hip to flex. How much the pelvis posteriorly tilts is dependent on how much femoroacetabular flexion is possible; the lesser the impingement-free flexion possible, the greater pelvic roll back (PT increase) required to adopt a relaxed-seated position. The change in tilt might also be dependent on spinal characteristics (63), but this has not been validated to date. Whatever change takes place in the pelvis is accompanied by a change in the lumbar spine, i.e. the change in sacral slope dictates change in lumbar lordosis as part of the kinetic chain (35, 46). When transitioning to a flexed-seated position, the body tries to achieve maximal sagittal flexion. In doing so, the spine flexes, leading to an associated movement of the pelvis, reducing sPT (anterior tilt of pelvis) and anteversion. During this movement, maximum femoroacetabular flexion takes place and the hip is at risk of anterior impingement. How much flexion takes place is dependent on spinal and hip flexibility.

The static and dynamic spinopelvic parameters, in the absence of hip or spinal disease, are sensitive to age, race, inherent variance in femoral, acetabular, pelvic, and spinal anatomy, and underlying pathology amongst other factors (64). With age, standing lumbar lordosis reduces, and the rate of reduction is likely dependent on the lumbar lordosis that one starts with, which is itself dependent on one's PI (62). The PI varies amongst races and is lowest amongst Asians. As we age, the rate of relative loss of spinal mobility is greater (9% per decade) than the rate of loss of hip mobility (4%), and we thus place relatively increased demands on our hip – we become relative hip users (62). Males and females do not seem to have significantly different standing spinopelvic characteristics or spinal mobility. However, sex-dependent differences exist in hip mobility. Men exhibit less hip flexion and relatively lower

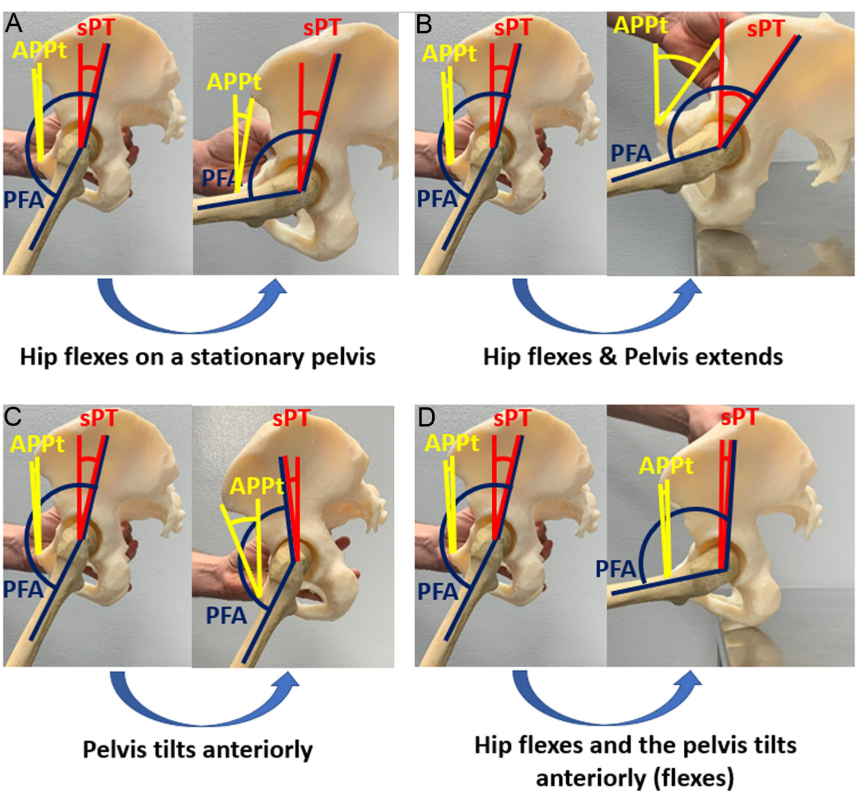

Figure 2
Four different scenarios for hip flexion and pelvic tilt in the sagittal plane when moving from a standing to a relaxed-seated position. (A) Femur flexes on a stationary pelvis; (B) femur flexes and the pelvis tilts posteriorly (extends); (C) pelvis tilts anteriorly (flexes) on a stationary femur; and (D) femur and pelvis flex.

hip use, presumably due to the increased prevalence of cam morphology and reduced femoral version (62). Body mass index exhibits a negative correlation with hip and spinal flexion, presumably due to increased abdominal girth and soft-tissue impingement with flexion, which in turn restricts the degree of flexion (62).

'Pathology'

In the presence of hip arthritis, a similarly wide variability in all spinopelvic characteristics exists. There are no clinically significant differences in static, standing, and spinopelvic characteristics between 'normal' and patients with hip arthritis. However, some note-worthy differences between normal and arthritic patients exist. In the presence of hip arthritis, the possible femoroacetabular flexion is significantly reduced. The reduced available femoroacetabular flexion leads to a compensatory increased sPT when adopting a relaxed-seated position, with associated compensatory changes in the spine. PT changes are almost doubled in the presence of hip arthritis (20° vs 13°), and lumbar lordosis is reduced to counterbalance the reduction in sacral slope change (linked segments). When adopting a flexed-seated position, the overall sagittal arc is reduced due to the reduced femoroacetabular flexion (60) (Fig. 3).

Most of the work to date has been performed in the presence of hip arthritis, with varying degrees of spinal pathology. Little data exist on functional compensatory patterns present amongst spinal patients without the presence of hip disease. This would enable further uncoupling of the associated compensatory mechanisms and provide further insight into the hip–spine relationship.

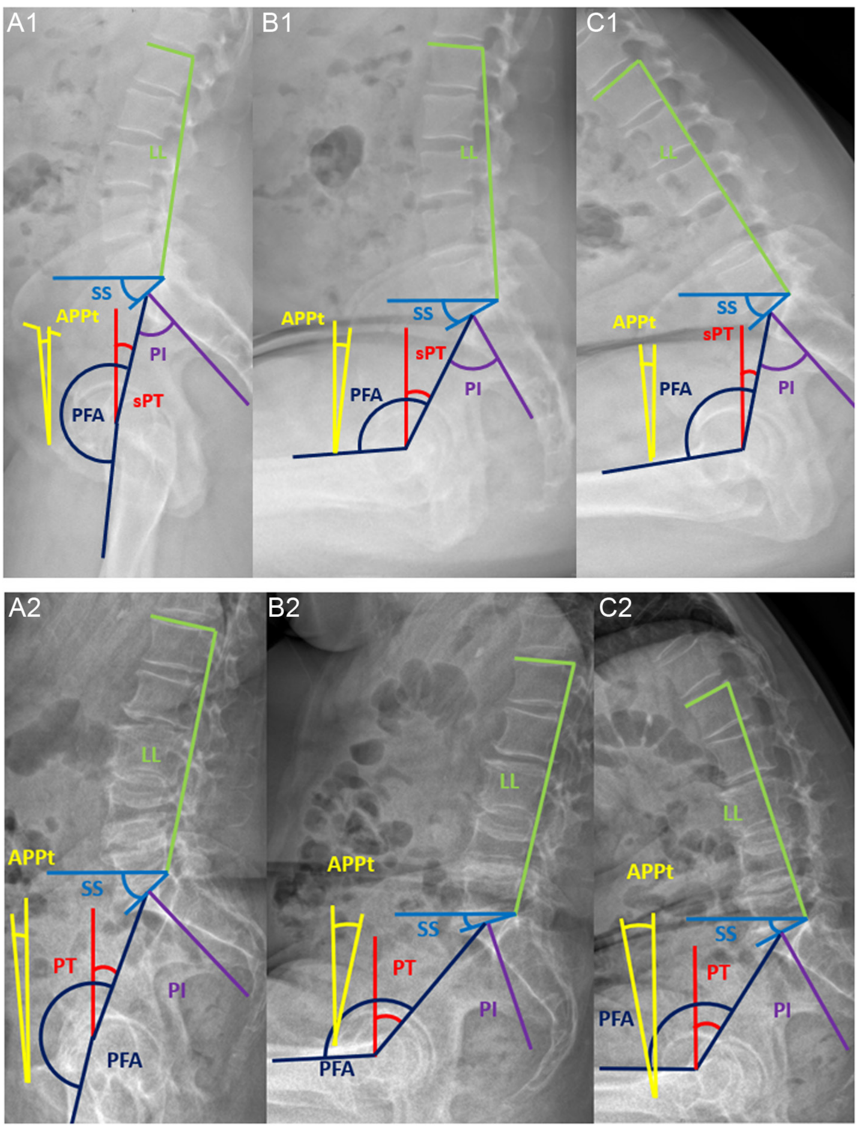

Figure 3
Measurements for radiographic spinopelvic parameters in the (A) standing, (B) upright seated, and (C) deep-flexed-seated position for pathological spinopelvic mobility in a volunteer without hip osteoarthritis (A1–C1) and a hip osteoarthritis patient pre-THA (A2–C2).

Post-THA

Following THA and restoration of increased hip flexion, spinopelvic characteristics change. It has been shown that spinopelvic hypermobility (increase in PT) when transitioning from standing to relaxed seated, resolves in most cases. This is presumably due to restoration of hip flexion (45, 60, 61). Furthermore, when adopting a flexed-seated position, the spine is no longer required to perform most of the action, and thus the lumbar spine flexion seen is reduced. The spinopelvic characteristics following THA are restored to what would be expected of age-, gender-, and body mass index-matched asymptomatic volunteers (60) (Figs. 3 and 4).

Spinopelvic parameters associated with outcome post-THA

Several studies have reported on spinopelvic characteristics and the risk of dislocation post-THA (43, 59, 65, 66, 67) (Table 3). A recent systematic review reporting on most of the available literature confirmed the comprehensive relationship between spinopelvic dynamics and dislocation-risk post-THA (68). A comprehensive assessment of the sagittal plane is more likely to identify factors associated with instability (66).

The spinopelvic parameters that are directly associated with increased risk of dislocation are lumbo-pelvic mismatch (PI – LL > 10°), high PT (>19°), low SS, and small (i.e., negative) APPt (43, 59, 65, 66, 67). These characteristics can all be identified from a single, standing, spinopelvic radiograph. In addition, the presence of spinal fusion and/or degeneration would be detected from such radiographs. Also, the standing CSI has been associated with the direction of instability. A high CSI when standing (>245°) is associated with increased risk of anterior instability, whilst low CSI when standing (<205°) is associated with increased risk of posterior instability (66). The association between PI and hip instability is not as clearly defined. However, there have been reports of increased instability risk with either high (anterior instability) or low (posterior instability) PI values (67).

In addition, assessment of THA patients with instability in different positions illustrates several dynamic differences. Patients with unstable hips are more likely to have greater amount of pelvic flexion (reduction in PT when flexed-seated) and higher hip user values (65, 66). This is typically accompanied with, and likely a result of, spinal stiffness.

There is limited data on the association of the spinopelvic characteristics on patient-reported outcomes. Spinopelvic characteristics are not associated with pre-operative hip symptoms (42, 49). However, patients with persistent or new spinopelvic hypermobility (standing to relaxed-seated) post-THA show inferior patient-reported outcomes (45). This is thought to be due to the subclinical impingement post-THA. In patients with increased PT to accommodate for the seated position, the standing cup AI has been shown to be smaller. A low cup anterior inclination is likely to lead to impingement and a greater change in PT to accommodate the flexed femur and pain. Spinopelvic characteristics have also been reported with resolution of back pain post-THA (69, 70). Patients with stiff spinopelvic characteristics pre-THA are less likely to have a significant improvement in the spinal symptoms post-THA (69). This is likely to be secondary to the increased presence of degenerative lumbar changes in these patients.

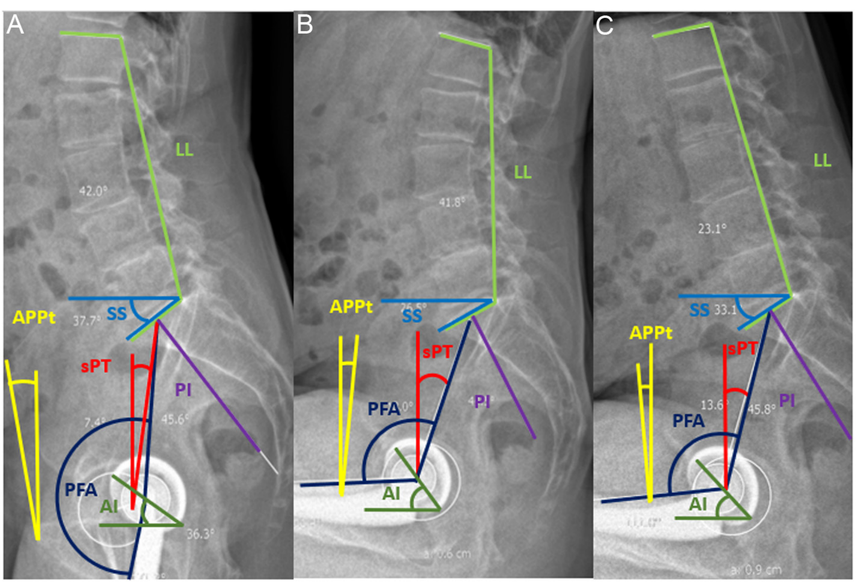

Figure 4
Measurements for radiographic spinopelvic parameters in the (A) standing, (B) upright seated, and (C) deep-flexed-seated position for pathological spinopelvic mobility in a hip osteoarthritis patient 1-year post-THA.

Table 3 Studies that have reported on spinopelvic characteristics amongst dislocating primary THAs, without the cohort being dominated by spinal arthrodesis patients, including pertinent findings of parameters of relevance illustrating instability.

Study	Design	Cohort description					Sagittal characteristics of relevance
		TD	AD	PD	THA	Controls	
Grammatopoulos *et al.* (66)	RMCS	50	21	29		200	Strongest predictors of instability: PI – LL >10°; $CSI_{standing}$ of <216° for posterior instability ; $CSI_{standing}$ of >244° for anterior instability
Vigdorchik *et al.* (65)	RCCS	48				9414	Adverse pelvic characteristics (APPt ≤ -15; lumbar stiffness; PI ≤ 41° or ≥70°; PI - LL ≥ 20) more prevalent in 48% of the dislocating hips (48% vs 13%; $P < 0.0001$)
Snijders *et al.* (83)*	RCS			15	233		Lower PI; lower SS; and lower inclination when standing; lower inclination and AI when seated
Ike *et al.* (67) *	RCS	41			200		Low-PI hips was the most predictive of the risk of impingement, and post-operatively these hips had the most outliers from the functional safe zone
Dagneuaux *et al.* (77)	RCS	33			41		High PI; sacro-spinal angle <172°; PI – LL > 15°
Heckmann *et al.* (43) *	RCS	20	9	11			Anterior instability: $PFA_{standing}$ >200.6° and $CSI_{standing}$ >241.6° ; posterior instability: $CSI_{relaxed\text{-}seated}$ <158.5°
DelSole *et al.* (19)	RCS	10				97†	High sPT; high PI – LL mismatch; high T1-pelvic angle.

AD, anterior dislocation; APPt: anterior pelvic plane tilt; LL, lumbar lordosis; PD, posterior dislocation; PI, pelvic incidence; RCCS, retrospective case–control study; RCS, retrospective cohort study; RMCS, retrospective matched cohort study; sPT, spinopelvic tilt; SS, sacral slope; TD, total dislocators.
*Some overlap in studies (cohort described in more than one study); †non-dislocators (all had degenerative spine).

Classifications to characterize spinopelvic characteristics

Researchers over the past decade have described several classifications for the study of the hip–spine interaction (39, 59, 71, 72, 73). Classifications are important as they allow clinicians/scientists to better understand anatomical relationships and mechanisms; further advance communications in the topic of interest; and ideally guide practice. The ones most frequently cited are detailed in Table 4. All classification systems suffer from limitations that need to be taken into consideration if they to be used in clinical practice. For example, the Bordeaux classification is a theoretical classification, based on level 5 evidence and little validation with clinical or anatomical studies (72). The classifications provided by Phan *et al.*, Stefl *et al.*, and Vigdorchik *et al.* have many similarities, provide valuable information, are of higher level of evidence, and are easier to be incorporated into practice (39, 59, 71). However, significant limitations with their use include the assumptions made with the study of the relaxed-seated radiographs for the presence of a stiff spine and the movement of the pelvis pre-THA. Furthermore, the modifications suggested by the authors for cup targets in the magnitude of only 5° relative to the APP for the given hip–spine subgroups (59, 71) are (i) very difficult to achieve in the absence of advanced technology (navigation/robotics) since they fall within inter-surgeon ability to judge any given angles (74); (ii) non-evidence based on their origin (rationale is based on means of native anatomy (59) – but huge variability exists even for primary osteoarthritis (75)) and (iii) non-validated, to date, in cohorts operated other than with a posterior approach, with the use of standard bearings and without the aid of advanced technology (59).

As our understanding of the hip–spine disease evolves, it is likely that a more comprehensive classification system that incorporates the relative position of the femur–pelvic–spine relationship and the likely post-THA changes will act as a better guide of practice. As more prospective studies, with higher level of data, on the subject are published, our understanding and ability to classify individuals better is likely to improve.

Functional acetabular orientation

To reduce dislocation and improve outcome, several approaches have been described. These include the preferential use of the anterior muscle sparing approach (76), dual mobility bearings (77), and the use of advanced technology to aid with component positioning and hip reconstruction (59). The use of advanced technology has been reported to improve accuracy (78); however what cup orientation target to aim for has been a matter of debate. The functional cup orientation is a term commonly used in the literature and describes the patient-specific, optimal, cup orientation having considered individual anatomical factors; in theory, the functional cup orientation would lead to superior function. Several ways to determine the functional cup orientation have been described in the literature, and the most used are included in Table 5 (78). To date, most technologies use the APPt intraoperatively to improve accuracy and adjust for standing PT, whilst aiming for a radiographic orientation of 40° inclination and 20° anteversion (78). The authors are of the opinion that a prescribed 'one-cup-orientation-for-all' is unlikely to be the functional cup orientation as it fails to consider the highly variable anatomy and individual kinematics. In line with this view, some take into consideration quasi-static standing and

Table 4 Classification systems used to characterize spinopelvic characteristics.

Study	X-rays required	Characteristics considered	Thresholds used	Groups defined	Treatment suggestions	Strengths	Limitations
Phan *et al.* (71)	Standing and relaxed -seated spinopelvic views	Sagittal spinal balance; flexible/rigid spinopelvic junctions	Standing PT < 25°, PI – LL < 10° Rigidity or stiffness not defined	I. Flexible/balanced; II. Rigid/balanced; III. Flexible/ unbalanced; IV. rigid/unbalanced	Anteversion; I. 5–25°; II. 15–25°; III. Spine first: 15–25°, hip first: 5–25°; IV. Same as III.	Simple; addresses tilt and mobility; first functional classification	Conceptual based on the literature review Non-validated basic guidelines
Stefl *et al.* (39)	–Supine AP pelvis –Iliac oblique Judet view –Standing and relaxed-seated spinopelvic views	Spinopelvic mobility: –Spatial position of standing/seated SS –Delta SS mobility between standing/ seated	SS standing/seated: stuck standing both >30°, stuck sitting both <30°, delta SS ≤5 fused, <10° stiff, 11–29° normal, and >30° hypermobile	1. Normal and hypermobile variant 2. Stuck standing +/– stiffness 3. Stuck sitting +/– stiffness 4. Kyphotic sitting 5. Fused hips	–Normal hips/mobility inclination: 40° anteversion: 20° –Hypermobile +/– kyphotic 35–40° inclination, 15–20° anteversion –Stiff 45° inclination 20–25° anteversion	Versatile; clear recommendations; combined anteversion recommendations	Retrospective radiographic study; not validated
Riviere *et al.* (84)	Standing and relaxed-seated spinopelvic views	PI PI – LL ΔSS Sagittal vertical axis (SVA)	PI < 30°, >65° PI – LL > 10° ΔSS < 10° Abnormal SVA > 5 cm	A. Normal, PI > 30 PI < 30; B. <10° ΔSS, normal; C. PI – LL > 10°, ΔSS < 10°, normal SVA; D. PI – LL > 10°, ΔSS < 10° abnormal SVA; Fused. Instrumented or biologic fusion	A. Parallel to TAL 40° inclination; B and PI < 30°: Increase cup version to TAL 0.35°/1°ΔSS is <20°; C and D Decrease cup version to TAL 0.35°/1° standing SS is <75% of PI; D and PI < 30°: Inclination 40–50	Addresses all facets of spinopelvic system	Complex system Not validated
Vigdorchik *et al.* (58)	Standing and relaxed-seated spinopelvic views	Spinal balance and pelvic mobility	PI – LL >10° (normal or flatback)	Normal and flexible	Inclination: 40°; anteversion: 20–25°;	Simple	Assessments made on relaxed seated (refer to text)
				Normal and stiff ‘Stuck-standing’	Inclination: 45°; Anteversion: 25–30°	Easy parameters to measure	Not accounting for spine mobility, functional position of pelvis (PT) or femur (PFA);
			SS < 10° (flexible or rigid)	Flatback and flexible	Inclination: 40°; Anteversion: 20–25°	Logical	Targets too small for non-robotic technology or manual techniques
				Flatback and stiff ‘Stuck-sitting’	Inclination: 40–45°; Anteversion: 25–30°		Recommendations not evidence based (yet)

TAL, transverse acetabular ligament.

Table 5 Description of available systems to determine functional cup orientation.

Method/ technology	Steps to achieve functional component orientation	Targets	Limitations
CORIN OPS	Stand, flexed-seated, step-up spinopelvic views, CT scan; Modified anatomic range of motion to impingement computer simulation	Cup orientation as determined by computer simulation including combined version	Requires exact PSI fit; limited pre/post-operative validation
NaviSwiss Naviplan and Hip Navigation	Standing and relaxed-seated spinopelvic views; input SS stand, seated, APP; options with and without CT scans; set individual coronal cup orientation desired by surgeon	Coronal cup inclination, anteversion with 3D assessment allowing surgeon alterations	Not accounting for femoral version; potential for registration error and loss of array fixation; limited validation
IntelliJoint VIEW, Hip Navigation	Standing AP pelvis, standing, relaxed sitting spinopelvic views Input SS stand, seated, APP tilt angles	Coronal and sagittal cup angles based on undefined algorithm	Not accounting for femoral version; potential for registration, loss of array fixation; limited validation
VELYS Hip Navigation with Cuptimize planning	AP pelvis supine, standing, standing, and relaxed-seated spinopelvic views; Set individual supine coronal cup orientation desired by surgeon	Fluoroscopic control matched to AP standing Software conversion alerts for standing anteversion >35°, seated <20°	Not accounting for femoral version; parallax and electronic fluoroscopic distortion; limited validation
Hip align	Adjusted APP to standing pre-operative pelvic tilt; surgeon selected supine coronal cup orientation	Functional standing adjusted coronal inclination and anteversion	Not accounting for femoral version; non-functional orientation; potential for errors in APP registration, positioning errors and loss of array fixation
RI.HIP Modeler Hip Navigation	Standing and relaxed-seated spinopelvic views; input SS stand, seated, APPt angles; anatomic activity-specific range of motion to impingement computer simulation	Coronal APP and FPP inclination and anteversion Cup anteversion modification from estimated femoral version angles Based off Stefl, Dorr group recommendations	Potential for errors in registration; limited validation
Mako Total Hip 4.0	Standing, relaxed-seated spinopelvic views, CT scan; Modified anatomic range of motion to impingement computer simulation	Coronal cup inclination, anteversion as determined by computer simulation including combined anteversion in supine, standing, and seated postures	Potential loss of array fixation; potential for errors in registration; limited validation
Zimmer ONE Planner and ROSA Hip	Standing, relaxed-seated spinopelvic views, AP pelvis of the surgeon preferred position	Per delta SS mobility values: ΔSS<10° – 45–50° inclination, 20–25° anteversion ΔSS 10–30° – 35–45° inclination, 5–25° anteversion ΔSS >30° – 35–40° inclination, 15–20° anteversion	Not accounting for femoral version; potential for errors in registration; errors in parallax and electronic fluoroscopic distortion; limited validation
Grammatopoulos *et al.* (66)	Set individual standing cup orientation desired by surgeon (coronal target); Measure patient's standing PFA on standing spinopelvic view; determine target cup AI required to meet CSI target (sagittal target); Use nomogram to aim cup orientation that satisfies coronal and sagittal targets	Cup inclination: 40 ± 10° (as per surgeon's choice) CSI: 205–245° (all) 220–245° (deg, spine)	Not accounting for femoral version; assumes minimal change in PFA post-THA; not approach dependent; limited validation
Bodner (79)	Standing and relaxed-seated spinopelvic views to measure PI, SS, and PFA standing and seated; supine and standing AP pelvis to correlate respective cup positions; modified Budin view for femoral anteversion	Geometric algorithm determining sacro-acetabular angle, tilt, and mobility-corrected AI standing and seated, then outlier modified for femoral version for combined anteversion and PFA for CSI and then adjusted for 1-year predictive ΔSS, PFA change	Not approach dependent; not validated clinically; requires manual calculation
Sutter *et al.* (80)	Standing and relaxed-seated spinopelvic views; APP standing and relaxed seated	Mathematical model provides adjusted coronal functional anteversion compared to population-based means data	Not accounting for femoral version; not approach dependent; lacks validation
Tang *et al.* (81)	Standing and relaxed-seated spinopelvic views; standing and seated pelvic tilt ; modified range of motion to impingement computer simulation	Mathematical algorithm to determine the functional area of the safe zone	Not approach dependent; minimal clinical validation

PSI, patient specific instrumentation.

seated views and perform impingement modeling to define patient-specific targets. In the recent years, several authors have also proposed for ways of determining the optimum functional, cup orientation (Table 5) (12, 44, 66, 67, 79, 80, 81). Aiming to achieve an optimum CSI when standing within 205–245° (with narrower target for those with spinal disease) whilst ensuring the coronal targets of cup orientation targets are achieved (inclination/version of 40/20 ± 10°) is our preferred method (66) (Fig. 5). It is worth noting that in most patients, cup

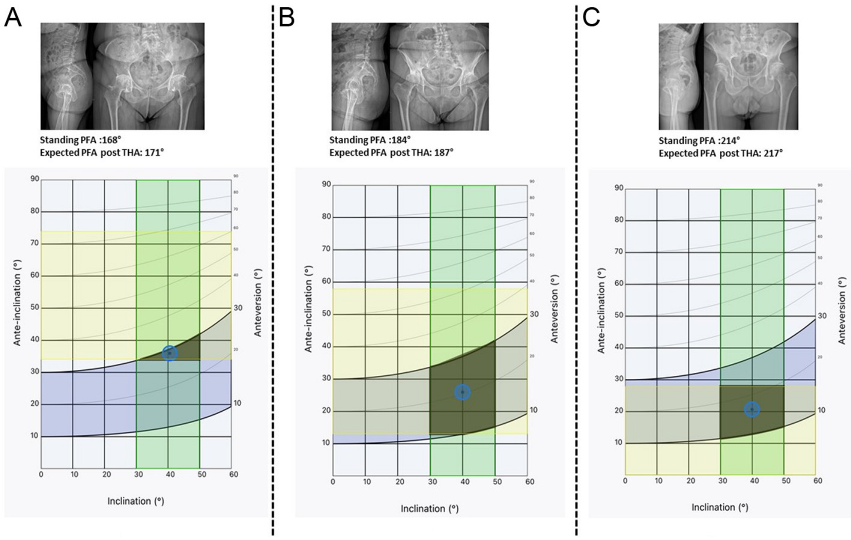

Figure 5
Radiographs (AP pelvis and standing spinopelvic views) and patient-specific nomograms (inclination/anteversion and ante-inclination) of three patients prior to undergoing a THA. Nomograms illustrate target standing inclination (green zone; 30–50°), standing anteversion (blue zone; 10–30°), and patient-specific target cup ante-inclination (as per individual PFA; thus, variable in size and number; yellow zone). Target cup orientation should satisfy all three parameters/targets, and the surgeon should aim for the middle of shaded area of all three to increase chances of obtaining target. Most patients (≈80%) presenting for THA are like patient B (PFA: 182 +/– 10°), and thus satisfying coronal targets (inclination/anteversion) would also satisfy sagittal (ante-inclination) targets.

orientations within acceptable targets, achieved with manual techniques (inclination/anteversion: 38/18° ± 7) (8), would also satisfy sagittal targets. It is in a minority of patients (those at risk highlighted above) that the optimal target is narrower and appropriate pre-operative identification and intraoperative execution would improve outcome (reduce impingement/pain and dislocation). To date, very few of the methods described on functional cup orientation have been validated with prospective studies (82) – future studies are likely to provide insight and guide practice.

Conclusions

In conclusion, the hip–spine interaction poses interesting challenges for the arthroplasty surgeon, requiring an informed assessment of both the coronal and sagittal plane in pre-operative planning. Our understanding of the topic has significantly improved over the recent years, but numerous questions remain. Well-designed prospective studies are necessary to help us identify and define how to incorporate the sagittal plane in our pre-operative planning to define the optimum orientation for improved patient outcome and bearing behavior; only then would the advantages associated with navigation/robotics reach their maximum potential.

ICMJE conflict of interest statement
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