DISSERTATION

Analysis of predictive factors of hip instability in patients undergoing primary total hip arthroplasty

Analyse prädiktiver Faktoren der Hüftinstabilität bei Patient:innen, die sich einer primären Hüft-Totalendoprothese unterziehen

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List of Abbreviations

Total hip arthroplasty (THA)

Body mass index (BMI)

Combined sagittal index (CSI)

Sacro-acetabular angle (SAA)

Functional pelvic plane (FPP)

Sacral slope (SS)

Anterior plane pelvic tilt (APPT)

Anterior pelvic plane (APP)

Ante-inclination (AI)

C7-Sagittal vertical axis (C7-SVA)

Pelvic femoral angle (PFA)

Pelvic incidence (PI)

Cervical lordosis (CL)

Thoracic kyphosis (TK)

Lumbar lordosis (LL)

Osteoarthritis (OA)

Lewinnek safe zone (LSZ)

C7-central sacral vertical line (C7-CSVL)

Degenerative intervertebral disc disease (DDD)

Receiver operating characteristic (ROC)

Area under the ROC Curve (AUC)

Intraclass correlation coefficient (ICC)

Interquartile range (IQR)

Standard deviation (SD)

Confidence interval (CI)

Dual mobility (DM)

Computed tomography (CT)

American Society of Anesthesiologists (ASA)

Abstract (auf Deutsch)

Hintergrund. Ein spinopelvines Ungleichgewicht ist einer der Faktoren, die zur Hüftinstabilität nach Implantation einer Hüfttotalendoprothese (TEP) führen. Allerdings gibt es bisher keinen praktikablen Ansatz, um das Luxationsrisiko anhand spinopelviner Faktoren vorherzusagen. Ziel dieser Studie war es, die statistischen Merkmale prä- und postoperativen Bewegungen des Beckens und der Hüfte zu untersuchen, herauszufinden, ob postoperative abnormale Bewegungen des Beckens und der Hüfte durch präoperative Faktoren vorhergesagt werden können, und festzustellen, wie der Beckeninklinationswinkel (PI) zur Hüftinstabilität beiträgt.

Methoden. Es wurde eine prospektive Beobachtungsstudie mit 193 Patient:innen durchgeführt, die eine primäre TEP erhielten. Vor und nach der Operation wurden biplanare Stereoradiographien in stehender und entspannter sitzender Position durchgeführt. Die Beweglichkeit des Beckens (∆SS) wurde als der Unterschied des Sakralwinkels (SS) zwischen den Positionen definiert. Es wurden Grenzwertoptimierungskurven (ROC) erstellt, um Vorhersagen über postoperative spinopelvine Abnormalitäten zu treffen.

Ergebnisse. Nach der TEP nahmen die Beweglichkeit des Beckens und der sitzende Becken-Femur-Winkel (PFA) signifikant zu, während der stehende PFA signifikant abnahm. Ein präoperativer stehender PFA-Schwellenwert von ≥192,4° sagte die postoperative Hüfthyperextension mit einer Sensitivität von 83,3% und einer Spezifität von 91,4% voraus (AUC=0,904). Der kombinierte Schwellenwert eines präoperativen sitzenden PFA von ≤113,1° hatte eine Sensitivität von 80,0% und eine Spezifität von 66,7% bei der Vorhersage einer postoperativen Hüfthyperflexion (AUC=0,752). Der kombinierte Schwellenwert für ein Alter ≥74 Jahre, ein präoperatives ∆SS von ≤7,5° und KL-Grad der Lendenwirbelsäule ≥ 2 zeigte eine Sensitivität von 84,2% und eine Spezifität von 75,9% bei der Vorhersage einer postoperativen Beckensteifigkeit (AUC=0,850). Ein präoperativer sitzender Sakralwinkel (SS) von ≤9,2° zeigten eine kombinierte Sensitivität von 80,0% und eine Spezifität von 91,3% bei der Vorhersage einer postoperativen kyphotischen Hyperbeweglichkeit (AUC=0,878). Der PI hatte keine Verbindung zur

Position der Azetabulumkomponente, zeigte jedoch eine moderate Korrelation mit prä/post-PFA. Darüber hinaus bestand eine moderate Korrelation zwischen PI und dem kombinierten sagittalen Index (CSI) im Stehen (r=0,377) und eine geringe Korrelation mit dem sitzenden CSI (r=0,228).

Schlussfolgerungen. Die Bewegung des Beckens und der Hüfte verändert sich nach einer TEP. Die oben genannten Parameter können Hüftchirurg:innen dabei helfen, eine postoperative Hüftinstabilität aufgrund abnormaler Becken- und Hüftbewegungen zu antizipieren. Der Einfluss des PI auf die Hüftbewegung anstelle der Position der Azetabulumkomponente kann eine Verbindung zwischen PI und dem Risiko einer Luxation herstellen.

Abstract

Background. Spinopelvic imbalance is one of the factors leading to hip instability after total hip arthroplasty (THA). However, to date, there is no feasible approach to predict the risk of dislocation caused by spinopelvic factors. The aims of this study were to investigate the statistical characteristics of pre- and postoperative pelvic and hip motion, whether postoperative abnormal pelvic and hip motion can be predicted by preoperative factors, and how PI contributes to hip instability.

Methods. A prospective observational study was conducted in 193 patients receiving primary THA. Biplanar stereo radiography was performed in the standing and relaxed sitting positions before and after surgery. Pelvic mobility (ΔSS) was defined as the sacral slope (SS) difference between the positions. Receiver operating characteristic (ROC) analysis was conducted to identify predictors of postoperative spinopelvic abnormalities.

Results. After THA, pelvic mobility and sitting pelvic femoral angle (PFA) increased significantly, and standing PFA decreased significantly. A preoperative standing PFA threshold of ≥192.4° accurately predicted postoperative hip hyperextension with 83.3% sensitivity and 91.4% specificity (AUC=0.904). The threshold of preoperative sitting PFA ≤113.1°had 80.0% sensitivity and 66.7% specificity in predicting postoperative hip over-flexion (AUC=0.752). The combined threshold of age at surgery ≥74 years old, pre-ΔSS ≤7.5° and KL grade of lumbar spine ≥2 showed 84.2% sensitivity and 75.9% specificity in predicting postoperative pelvic stiffness (AUC=0.850). Preoperative sitting SS ≤9.2° exhibited 80.0% sensitivity and 91.3% specificity in predicting postoperative kyphotic hypermobility (AUC=0.878). PI had no association with the acetabular component position, but had moderate correlation with pre/post-PFA. Furthermore, PI was moderately correlated with the standing combined sagittal index (CSI) (r=0.377) and poorly correlated with sitting CSI (r=0.228).

Conclusions. Hip and pelvic motion change after THA. The abovementioned parameters may assist hip surgeons in anticipating postoperative hip instability due to abnormal pelvic and hip motion. The influence of PI on the hip motion rather than the acetabular

component position may establish a connection between PI and dislocation risk.

1. Introduction

1.1. Total hip arthroplasty (THA) instability and dislocation

1.1.1. Prevalence of THA instability

Since the 1960s, THA has been used for the treatment of hip osteoarthritis. Through the continuous innovation of prostheses as well as surgical progress, THA has become one of the most successful surgeries in the field of orthopedics(1). According to reports, more than 280,000 patients in the United States receive THA each year, while the number of revision THAs is as high as 40,000 annually(2). As the number of primary THAs continues to grow, so does the number of patients undergoing revision hip replacements, with the proportion of revision hips in the United States projected to increase by 137% from 2005 to 2030(3). Even though the procedure is now well-established, there still is a variety of complications (including infection, dislocation, osteolysis, and mechanical loosening) that can cause failure and require revision surgery. Of these, dislocation is the most frequent etiology for revision surgery, accounting for 22.5%(4). The incidence of dislocation after primary THA is approximately 0.3% to 10%, with up to 28% requiring revision surgery(5). At one month and one year following surgery, the cumulative risk of a first-time dislocation was 1% and 1.9%, respectively(6). Over the following 25 years, the risk increased to 7% at a consistent rate of roughly 1% every five years(6). Even though the incidence of dislocation is presently decreasing as surgical techniques develop and prosthesis designs advance, the growth in primary THA surgeries has led to a net rise in unstable THAs(4, 7, 8).

Patients can be significantly affected by the complication of THA dislocation. The potential effects of THA dislocation are as follows(9): 1) Patients may experience severe pain in the hip and surrounding areas, which can limit their mobility and significantly impact on their quality of life and independence; 2) Dislocation increases the risk of falls, which can lead to additional injuries such as fractures or soft tissue damage; 3) Dislocation may require revision surgery to stabilize the hip joint, which can prolong the recovery process and expose patients to the risks associated with additional surgical procedures; 4) Dealing with the physical limitations and chronic pain caused by THA dislocation can have a psychological impact (such as frustration and anxiety) on patients. In addition to these individual consequences, THA instability causes a high burden on the whole socioeconomic system as early dislocation resulted in a 342% increase in the cost of primary THA(10). For surgeons to better understand dislocation mechanisms and create efficient preventative measures to reduce the associated economic and personal implications, the underlying etiology of the dislocations warrants further comprehensive investigation.

1.1.2. Early and late dislocations

Dislocation may occur at any time after the primary replacement. Marius et al.(11) indicated that late dislocation was more frequent than early dislocation, with late dislocation being defined as a dislocation that occurred five years or more after primary replacement. The risk of late dislocation is higher in female and younger patients(11). Late dislocation after THA may occur due to various surgical or prosthetic factors, such as acetabular components initially positioned incorrectly, loosening as components migrate or move positions, and polyethylene liner deterioration. Additional causes include previous subluxation, severe trauma, or major neurological dysfunction(11). Early dislocation is predisposed by female gender, advanced age, cognitive dysfunction, a history of alcohol abuse, and a preoperative diagnosis of femoral head necrosis, acute proximal femoral fracture/nonunion, and inflammatory arthritis(6, 12). Closed reduction may produce good outcomes in cases of early dislocation, and benefits from the development of scar tissue that aids in stabilizing the hip joint following reduction(13). In contrast, revision arthroplasty surgery is more likely to be necessary with late reduction. Recurrent dislocations account for 61% of late dislocations, while patients with late dislocations make up 33% of those who need surgical intervention for treatment. Late dislocations reoccur in 55% of cases(11).

1.1.3. Risk factors for dislocations

A comprehensive understanding of the risk factors for dislocation allows surgeons to focus on controllable aspects. Risk factors have traditionally been divided into three categories: patient factors, implant factors and surgeon factors(14).

Patient factors

A high American Society of Anesthesiologists (ASA) score, neuromuscular disorders and a history of spinal disease have been identified as risk factors for early- and late-term THA instability (15). Gillinov et al.(16) investigated 3,630 patients with hip dislocation and found that early dislocation was correlated with younger age (<65 years), female sex, body mass index < 20 kg/m^2, and higher Elixhauser comorbidity index. In contrast, Ding et al.(17) demonstrated that age ≥75 years was associated with a higher risk for early dislocation. After retrospectively reviewing 178 hip dislocations after THA, Yoshimoto et al.(18) identified age as one independent risk factor for any dislocation: for every 10-year increase in age, the risk of dislocation increased 2.9-fold.

Implant factors

The implant factor that most affects stability is the size of the head. Several studies showed that a small femoral head tends to have a higher dislocation rate than a large one(19-21).Jameson et al.(22) reported that patients with femoral heads ≥ 36 mm have a lower early dislocation rate than those with femoral heads < 36 mm. The femoral component offset is also a non-negligible part of the implant factor. Sufficient offset restores soft-tissue tension to maintain hip joint stability, and decreases the early dislocation rate by increasing the range of non-impingement hip motion(23). Lipped acetabular liners were designed to increase the coverage of the socket to improve posterior stability. According to a national collaborative registry study, posterior approach THAs with 10° or 15° lipped liners have lower instability rates than neutral liners, whereas offset reorienting liners have a higher instability rate(24).

Surgeon factors

The average volume of operations performed generally reflects the surgeon's surgical experience. In a United States study of nearly 59,000 primary THA procedures, surgeons who performed five or fewer THA procedures per year had higher early dislocation rates compared to surgeons who performed more than 50 procedures(25). A THA surgical volume threshold of 35 cases per year was discovered in an analysis of almost 38,000 patients, below which the early dislocation incidence rose from 1.3% to 1.9%. The average operating time is generally shorter for skilled surgeons(26). Arthur et al.(7), in a review of 39,217 primary TKAs, found that procedures that last for 180 minutes or more have been associated with a higher risk of early dislocation compared to those lasting less than 180 minutes.

The direct anterior approach for THA quickly gained popularity due to its lower rate of early- and late-term dislocation and reduced soft tissue trauma(27). However, several studies found that after enhancing the posterior capsular repair, the early dislocation rates of THAs utilizing the posterior approach were comparable to those using the direct anterior approach(28-30). When adopting a posterior approach, it is suggested that surgeons enhance posterior capsular repair procedures to lower the risk of early posterior dislocation(31).

There are still significant variations in the components' orientation, despite a safe zone being established for the anteversion of the acetabular and femoral components(32). A femoral component with a too large or small combined anteversion and acetabular components outside of the safety zone could lead to impingement, instability, and an increased risk of dislocation(33, 34).

1.1.4. A potential risk factor for dislocation - spinopelvic imbalance

Even though numerous risk factors have been identified, and the corresponding precautions have been taken to reduce the incidence of dislocation, as the demand for THA continues to rise, with increasing expectations for successful outcomes, it is increasingly important to identify and address all potential risk factors that may contribute to dislocation. Therefore, these potential risk factors need to be identified to enhance dislocation prevention strategies.

Lewinnek et al.(35) originally proposed the concept of a ‘safe zone’ for the acetabular cup orientation in 1978. For the following 40 years, surgeons utilized this universal safe zone as a reference standard for placing acetabular components, since it had a considerably lower rate of dislocation than other orientations(35). Studies, however, have indicated that a ‘safe zone’ may in fact not be safe(36-39). In a study of 9,784 primary THAs, 58% of 206 dislocations had acetabular components in the Lewinnek safe zone, with an average cup inclination of 44° and an average anteversion of 15°(36). Esposito et al.(37) compared acetabular component positions in 147 patients with dislocation from 7,040 primary THAs with those without dislocation and found no differences. A target value of cup inclination of 40° ± 10° and anteversion of 15° ± 10° may be beneficial but should not be regarded as a safe zone. Wera et al.(40) analyzed 75 patients undergoing revision surgery for dislocations, and of these, 70 had a clear etiology, including acetabular cup malposition, femoral component malposition, abductor deficiency, impingement, and late polyethylene wear, while the remaining five had an unidentified etiology.

Recent studies have indicated that the interaction between the pelvis and lumbar spine may account for these unexplained prosthesis dislocations(41-43). The kinematics of the lumbar spine strongly influence the motion of the pelvis when moving from standing to sitting positions, which is why once the kinematics of the lumbar spine alter, pelvic motion is affected accordingly(43). Several studies have shown that spinal degeneration and a history of lumbar spinal surgery, such as lumbar fusion, might compromise pelvic motion after THA, placing the acetabular component in a position that is functionally unsafe(44-47). Spinopelvic imbalances, which place the acetabular component in the Lewinnek safe zone but outside the functional safe zone, are a potential cause of dislocation(38, 48). The conventional definition of the safe zone refers to the two-dimensional X-ray image and assumes that the acetabular component is in a stationary state. Placing the acetabular component in the functional safe zone requires adequate consideration of the dynamic relationship in the spinopelvic complex, and its impact on THA stability.

1.2. Spinopelvic complex

1.2.1. Compensatory mechanisms of the spinopelvic complex

The balanced alignment of the axial skeleton enables humans to stand and walk upright. The skeletal balance chain runs from the feet through the lower extremities (ankle, knee, and hip), using the pelvis as a hinge to connect the spinal segments, and then to the skull. Due to the complex adaptive interaction of the components above and below the pelvis to keep the sagittal balance, the human body is able to maintain the gravity line within the 'cone of economy' with the minimum amount of energy expenditure(49). Some spinal disorders (such as spinal degeneration) may cause alignment imbalances and lead to a loss of lumbar lordosis, which may cause the gravity line to shift forward and trigger a series of compensatory mechanisms (**Figure 1**) to counteract the forward movement of the trunk alignment(50). Compensation begins with hyperextension of the cervical spine and a decrease in thoracic kyphosis. If this is not enough to counteract the malalignment, the pelvis and hip will participate in compensation, manifesting as pelvic retroversion and hip extension. If these mechanisms are still insufficient, a backward lean of the trunk due to flexion of the knee and ankle joints will occur to achieve an upright posture and a horizontal gaze(50). These compensatory mechanisms effectively maintain the gravity line directly above the femoral head and contribute to restoring the sagittal balance of the spine, minimizing the negative effects of sagittal imbalance(51).

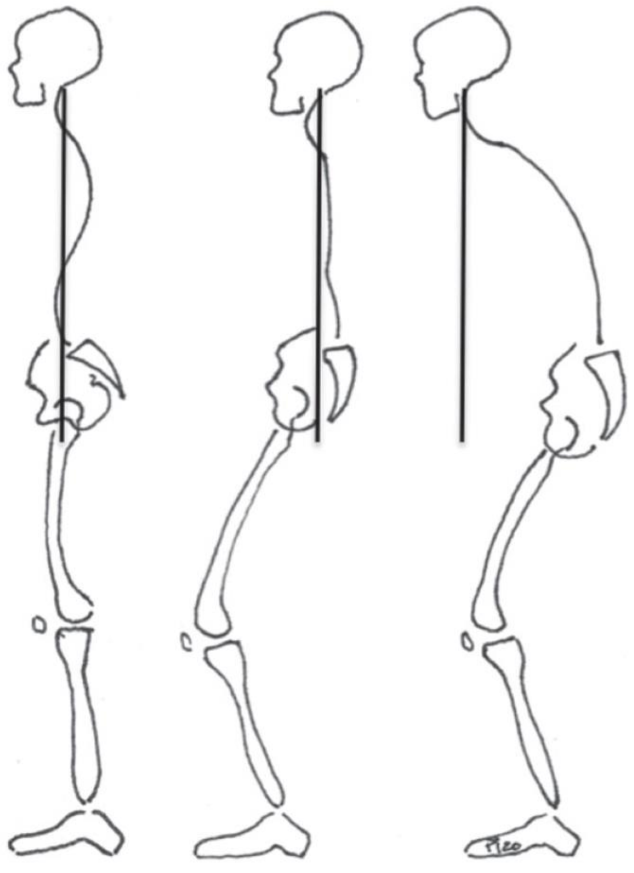

Figure 1. Illustration of a series of compensatory mechanisms caused by an imbalance of spinal alignment.

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(a) Well-balanced alignment puts the gravity line within the 'cone of economy.' (b) Sagittal malalignment triggers a series of compensatory mechanisms to maintain balance: hyperextension of the cervical spine, thoracic kyphosis reduction, posterior pelvic tilt, hip hyperextension, and knee/ankle flexion. (c) The compensation mechanisms are insufficient to maintain the body erect, and the gravity line moves forward.

1.2.2. History of spinopelvic complex recognition

Early studies on the spine only descriptively explored the mean and dispersion of sagittal parameters, which were very scattered due to the diversity of human spine morphology, and the results of these studies were insufficient to accurately represent the normal situation in humans when standing up straight(53-55). Later studies discovered that changes in the pelvic position appear to be substantially correlated with sagittal spine parameters(56-58). The pelvis, which functions as a hinge connecting the spine and lower limbs, is crucial in maintaining the gravity line within the 'cone of economy' when individuals walk upright and maintain sagittal balance(56, 58). Legaye et al.(59)were the first to demonstrate the correlation between the sagittal characteristics of the spine and pelvic morphology, and discovered that the pelvis functions as a fundamental factor influencing the spine.

Pelvic incidence represents the pelvis' morphology in the sagittal view, which is a crucial parameter for understanding the role of pelvis functions in the interplay of the spinopelvic complex (59, 60). The ability of the spinopelvic complex to maintain sagittal balance under the principle of economy is determined by the value of pelvic incidence, which is a constant anatomical parameter. A low pelvic incidence indicates that when standing, the lumbar curve becomes flat and the sacral slope declines (**Figure 2**). Here, the spinal and pelvic capacity for adaptation is limited, and the body's postural alignment is vulnerable to imbalance. A high pelvic incidence indicates a larger sacral slope and lumbar lordosis. In this situation, the spinopelvic parameters have a higher potential for adaptation to prevent the occurrence of sagittal imbalance(60). The pelvic incidence has a constant relationship with two other positioning parameters and any change in either of these parameters will affect the other parameters(59, 60): pelvic incidence=sacral slope + pelvic tilt. Based on this strong correlation chain, the spine, pelvis, and hip joints make up the spinopelvic complex(61, 62). When changing postures, a stiff spine will limit the movement of the pelvis and hip joints, and vice versa. A stiff hip joint will also restrict the mobility of the spine and pelvis. Surgeons have gradually discovered that the role of the spinopelvic complex cannot be ignored in total hip arthroplasty(61). After a total hip replacement, changes in the mobility of the spine and pelvis might result in impingement, a critical risk factor for postoperative dislocation(61).

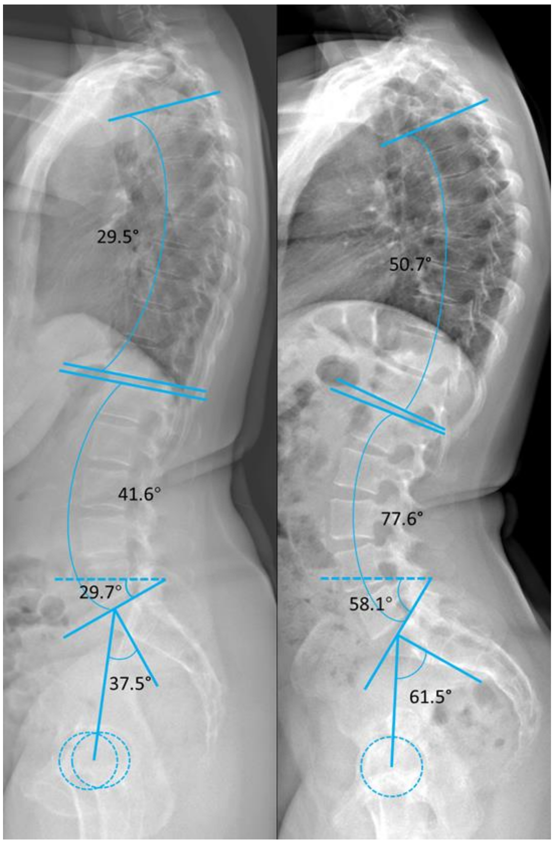

Figure 2. Illustration of how pelvic incidence affects the spinopelvic complex.
A low pelvic incidence (37.5°) indicates a flat spinal curvature and a small sacral slope, while a high pelvic incidence (61.5°) indicates a larger spinal curvature and sacral slope.

1.2.3. Spinopelvic parameters

The definitions of commonly used spinopelvic parameters are presented here to assist in understanding the mechanisms of the spinopelvic complex (**Table 1, Figure 3**). Many terms have been presented, though the usage of some of them has not been standardized. To assess pelvic rotation between postures, the anterior plane pelvic tilt (APPT), spinopelvic tilt (SPT), and the sacral slope (SS) are used, which should be highlighted because they are easily confused. During computer-assisted THA, the anterior pelvic plane (APP) is defined as the line connecting the midpoint of the two anterior superior iliac spines to the pubic symphysis and commonly utilized as a reference plane for navigating acetabular component placement. APPT, which is defined as the angle between the vertical reference line and the APP, is frequently used by arthroplasty surgeons to assess pelvic rotation. Confusingly, spine surgeons tend to use SPT to measure pelvic rotation, which is defined as the angle between the vertical reference line and the line connecting the midpoint of the superior endplate of S1 to the center of the femoral head. The SS is the third way to describe pelvic rotation, which is the angle between the horizontal reference line and the tangent of the superior endplate of S1. A decrease in SS, an increase in SPT, and a posterior rotation of the APP all represent a posterior rotation of the pelvis and an increase in functional acetabular anteversion.

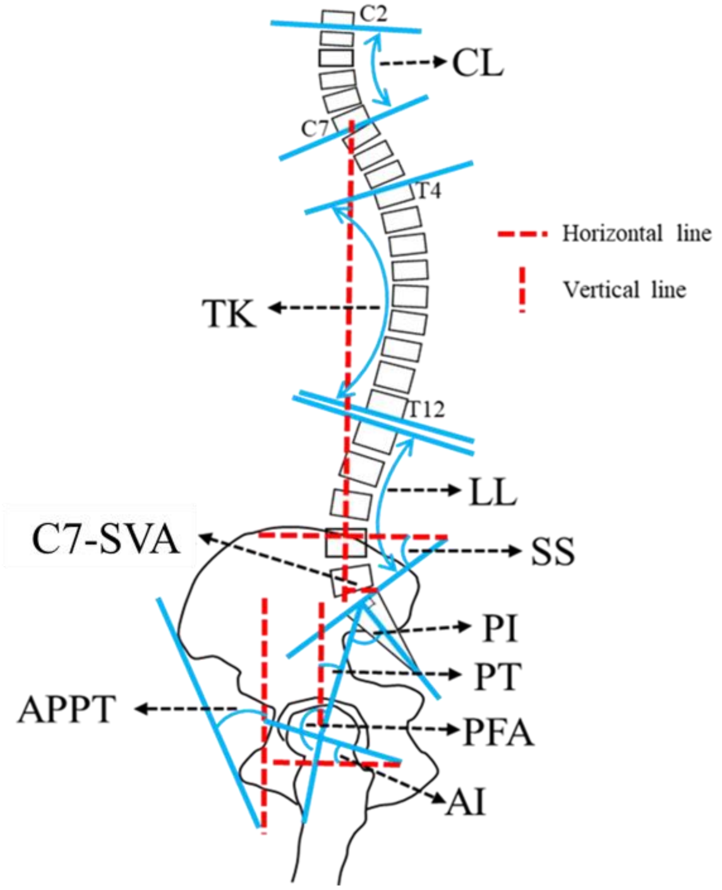

Figure 3. Illustration of the measurement method of spinopelvic parameters.
CL cervical lordosis, *TK* thoracic kyphosis, *LL* lumbar lordosis, *C7-SVA* C7-sagittal vertical axis, *SS* sacral slope, *PT* pelvic tilt, *APPT* anterior plane pelvic tilt, *PI* pelvic incidence, *AI* ante-inclination, *PFA* pelvic femoral angle.

Table 1. Glossary of spinopelvic parameters

Term	Definition
Cervical lordosis (CL)	Angle between the inferior endplate of C2 and inferior endplate of C7
Thoracic kyphosis (TK)	Angle between the superior endplate of T4 and inferior endplate of T12
Lumbar lordosis (LL)	Angle between the superior endplate of L1 and superior endplate of S1

Sacral slope (SS)	Angle between the horizontal reference line and the tangent of the superior endplate of S1
(Spino)Pelvic tilt ((S)PT)	Angle between the vertical reference line and the line connecting the midpoint of the superior endplate of S1 to the center of the femoral heads
Anterior plane pelvic tilt (APPT)	Angle between the vertical reference line and the line connecting the midpoint of the two anterior superior iliac spines to the pubic symphysis
Pelvic incidence (PI)	Angle between the line connecting the midpoint of the S1 endplate to the center of the femoral heads and the vertical line of the superior endplate of S1
Pelvic femoral angle (PFA)	Angle between the line connecting the midpoint of the S1 endplate to the center of the femoral heads and a 10 cm line from the femoral head to the ventral cortex of the femur
Ante-inclination (AI)	Angle between the line connecting the posterior inferior edge of the acetabulum to the anterior superior edge and the horizontal reference line
C7-Sagittal vertical axis (C7-SVA)	Horizontal distance between the superior posterior corner of the S1 endplate and a plumb line from the center of the C7 vertebral body
Sacro-acetabular angle (SAA)	Angle between the line connecting the anterior superior and posterior inferior borders of the acetabulum and the tangent line of the S1 superior endplate in the sagittal plane
Combined sagittal index (CSI)	A combined angle of the ante-inclination and the pelvic femoral angle in the sagittal plane

While the computer navigation-assisted technique uses APP as a reference for ante-inclination of the acetabular component, conventional surgery uses the transverse acetabular ligament. However, APP or the transverse acetabular ligament are no longer a reliable reference if a sagittal imbalance of the spine exists simultaneously. Spinal deformities may cause pelvic rotation, thus the APP or the transverse acetabular ligament would be no longer in a stable neutral position, which leads to a deviation in the functional anteversion of the acetabulum. Therefore, the "functional pelvic plane" (FPP), or the coronal plane of the human body, was recommended as the 0° reference plane(63, 64).

The sacro-acetabular angle (SAA) and combined sagittal index (CSI) are combined parameters. SAA is the sum of SS and ante-inclination (AI), which is defined as the angle between the line connecting the anterior superior and posterior inferior borders of the acetabulum and the tangent line of the S1 superior endplate in the sagittal plane. The acetabulum is stationary relative to the S1 upper endplate, so SAA is a fixed angle which represents the slope of the acetabulum in the sagittal plane relative to the S1 endplate. Increased SAA corresponds to an increased acetabular opening. The combined sagittal index (CSI), which is a combined parameter of femoral position and sagittal acetabular orientation, was introduced to evaluate the risk of postoperative instability. The acetabulum has a limited clearance (55°-70°) for femoral movement without impingement, thus the CSI is used to define the functional safe zone(38). Patients with a standing CSI outlier (>243°, upper range of AI 45° and upper range of PFA 197°) are at risk for anterior late dislocation, while those with a sitting CSI outlier (<151°, lower range of AI 41° and lower range of PFA 110°) are at risk for posterior late dislocation(38) (**Figure 4**).

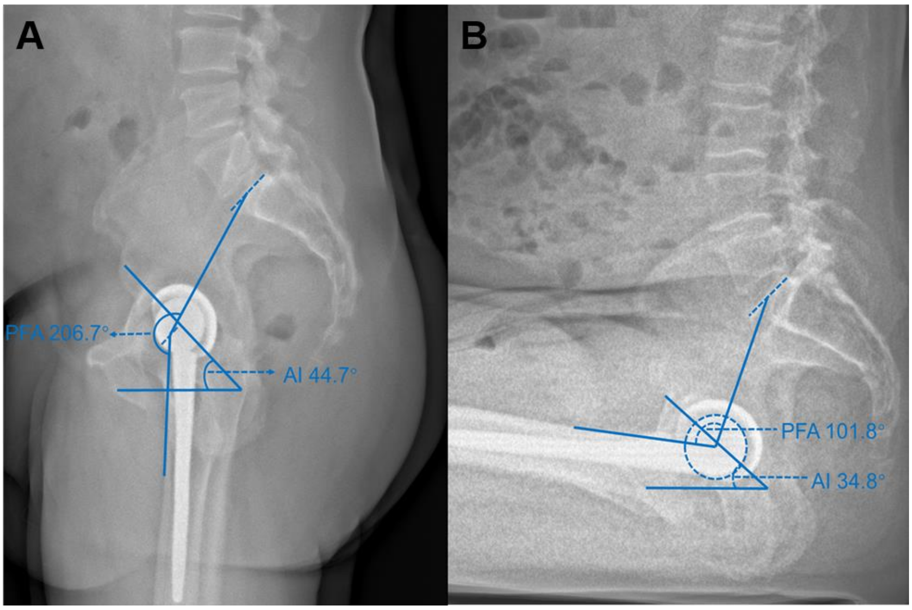

Figure 4. Illustration of CSI as a parameter to evaluate the risk of dislocation.

A. The standing CSI is 251.4°, which is above the upper limit. AI is within normal limits, but PFA above normal limits. Therefore, hip hyperextension is the main reason for the risk of anterior dislocation. B. The sitting CSI is 136.6°. AI, PFA and CSI are all below the lower limit. Therefore, inadequate opening of the acetabular component and excessive hip flexion are the main reasons for the risk of posterior dislocation.

1.3. Radiographic evaluation

For decades, the conventional safe zone for surgeons to place acetabular implants was based on supine pelvic radiographs. With the gradual deepening of the understanding of pelvic motion, the concept of a ‘functional safe zone’ was introduced by hip surgeons in THA, which replaced the conventional safe zone as the new reference standard for acetabular implantation. Several studies have indicated that the pelvis rotates when the individual moves from a supine position to a standing position(61), and especially in THA candidates, the proportion of the rotation angle exceeding 10° can be as high as 19%(65). Every 1° sagittal rotation of the pelvis results in a functional change of 0.7° in acetabular anteversion and 0.3° in acetabular inclination(66). This may prompt the safe zone in the supine position to no longer be safe in the standing position. A standing AP pelvis X-ray is therefore highly suggested to evaluate the functional position of the acetabulum preoperatively.

The EOS^{TM} imaging system has become an essential way to evaluate and follow up spinopelvic parameters in patients undergoing THA since it can concurrently capture two orthogonal AP and lateral radiographs, enabling a depiction of the whole spinopelvic complex in both standing and sitting positions(67). Compared with traditional X-rays, it significantly decreases the dose of X-rays that patients are exposed to, but acquires similar accuracy and reproducibility to traditional X-rays in evaluating spinopelvic and acetabular parameters, which is why it is recommended as an alternative tool for traditional X-rays in THA(68, 69). In addition, the EOS^{TM} imaging system reconstructs 3D radiography based on dual synchronous standing frontal and lateral X-ray imaging of the patient and thus enables the achieving of similar accuracy to CT in measuring hip parameters, including acetabular anteversion and inclination (and thus ante-inclination), as well as femoral anteversion, but with a lower radiation dose and expenditure than CT(70).

1.4. Normal spinopelvic motion

The spine-pelvis-hip complex moves simultaneously and harmoniously thanks to the pelvis, which acts as a 'gear' connecting the spine and hip joints. Dynamic spinopelvic motion is significantly influenced by pelvic morphology and pelvis motion. As mentioned above, PI is a constant parameter to describe the sagittal morphology of the pelvis(59). By employing PI as a connection, the mutual relation between the spinopelvic parameters is established. There is a geometrical correlation between PI, SS, and PT(PI=PT+SS). The two parameters of SS and PT, therefore, are intrinsically linked(59). A drop in one parameter will cause a corresponding rise in the other, and vice versa. As early as 1982, Stagnara et al.(55) demonstrated the strong correlation between lumbar lordosis and sacral slope. When the SS increases, the lordosis of the lumbar spine become more pronounced. Conversely, when the sacral slope decreases, the lumbar curvature becomes flat. PI is related to SS, and then to LL based on the aforementioned correlation(71). Numerous formulae have been developed to explain the mathematical relation between PI and LL(72-74). However, a very simplistic PI-based equation (LL = PI ± 9°) for estimating lumbar lordosis is widely accepted(73). The sagittal plane of the spine is regarded as balanced and normally aligned if the value of PI minus LL is less than 9(75), while it needs to be highlighted that a PI-LL mismatch (defined as pelvic incidence minus lumbar lordosis) of >10° may imply a flatback spinal deformity(75, 76). The lumbar lordosis starts from the upper endplate of S1 and ends at the inflection point from lumbar lordosis to thoracic kyphosis, and is divided into two parts (lower lumbar arch and upper lumbar arch) by the lumbar apex(77). The variety of the lower lumbar arch depends on the slope of the sacral endplate and again on PI(78). In this way, a high PI indicates a high SS, a pronounced curvature of the lower lumbar arch, a higher lumbar apex, a longer lower lumbar arch, and more lumbar vertebrae involved in the compensatory mechanism, which enhances the compensatory ability of the spinopelvic complex. Conversely, a low PI indicates a low SS, a flat curvature of the lower lumbar arch, a lower lumbar apex, a shorter lower lumbar arch, and fewer lumbar vertebrae engaged in the compensatory mechanism(77, 79). Based on the correlation between pelvic incidence and spine sagittal profile, Roussouly et al.(80) classify the sagittal spine profile into five different types. This intrinsically tight connection has also been observed in the hip joint. When the pelvis is rotated posteriorly in the sagittal plane, the acetabulum opening is accompanied by an increase in anteversion and inclination, whereas when the pelvis is rotated anteriorly, acetabular anteversion and inclination decrease. Every 1° sagittal rotation of the pelvis results in a functional change of 0.7° in acetabular anteversion and 0.3° in acetabular inclination(66).

Based on the correlation between the aforementioned spinopelvic characteristics, when the posture transitions from standing to sitting, the spine, pelvis, and hips move in concert to maintain sagittal alignment and balance(81)(**Table 2, Figure 5**). Normal standing posture has been observed with the lumbar spine in lordosis, anterior pelvic tilt, and hip joints in extension. This position places the body's line of gravity over the acetabulum and again over femoral head, maintaining an upright position with economical energy expenditure. When moving from standing to sitting, the lumbar lordosis decreases, the pelvis rotates posteriorly, and the hip joints flex. The SS of normal standing is 40°, and it is reduced to 20° due to pelvic posterior rotation when sitting. When the posture is altered, the difference in SS (ΔSS) between standing and sitting indicates the rotation of the pelvis, and its normal range is 10°-30°. Posterior rotation of the pelvis reduces SS by 20° while increasing acetabular ante-inclination (AI) by 17° to provide space for the hip to flex. This mechanism allows the femur to flex in an impingement-free motion during postural changes(81-83). A normal pelvic femoral angle (PFA) is 180° in standing and 125° in sitting, and a normal hip range of motion from standing to sitting (ΔPFA) is 55°-70°. When deep sitting (sitting on a chair and picking up objects on the floor), hip flexion increases to 85°(83). Compared with the standing position, the pelvis is rotated anteriorly by less than 5°, and the lumbar lordosis is increased by only 3°- 5° in the supine position(61), which is the reason why research on the supine position has not been given much attention. The combined sagittal index (CSI) is the combined parameter of AI and PFA, which is 218° in standing and 180° in sitting. CSI is a newly introduced concept for guiding THA acetabular placement in a functional safe zone to avoid impingement-related late dislocations(38, 48).

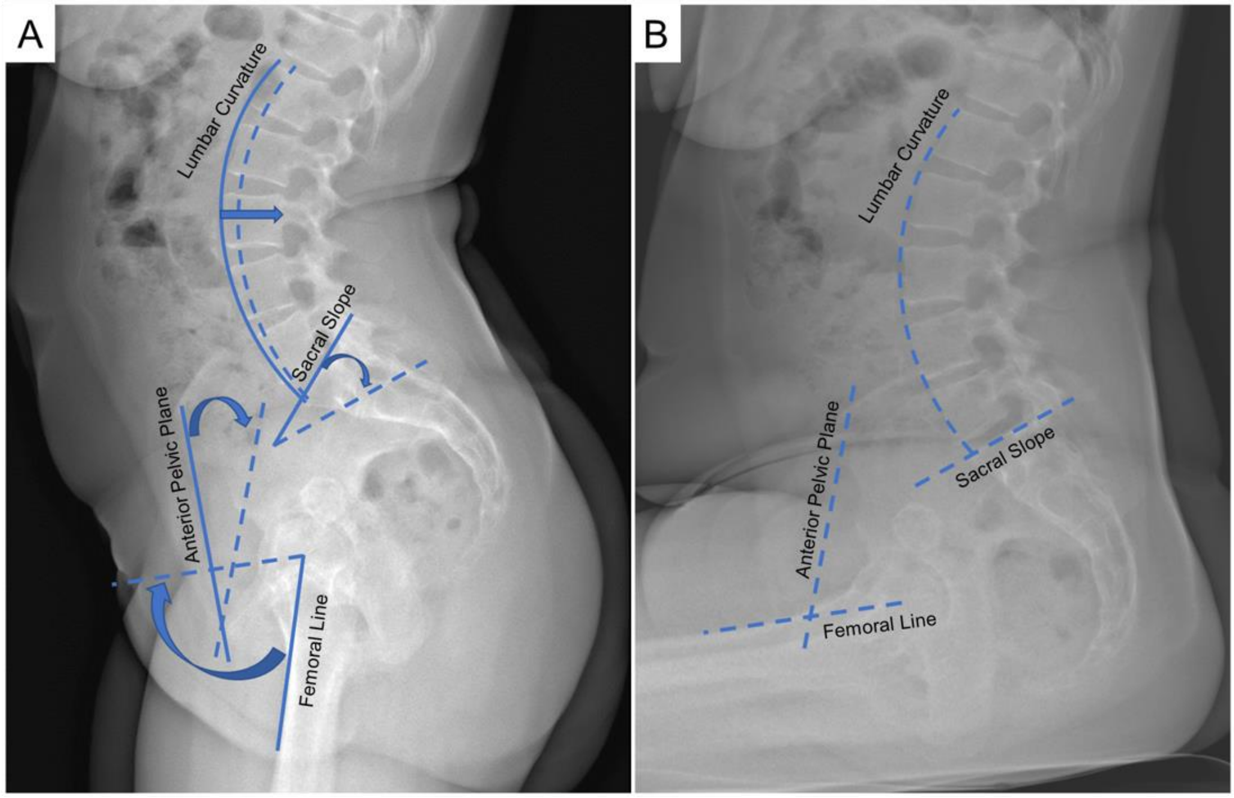

Figure 5. Illustration of dynamic spinopelvic motion from standing to sitting.
The lumbar curvature becomes flat, the sacral slope decreases, the anterior pelvic plane moves posteriorly, and the hip flexion increases. The spinopelvic complex is depicted with solid lines in the standing position and dotted lines in the sitting position.

Table 2. The normal range of spinopelvic parameters

Term	**Normal range**		
	Standing	Sitting	Difference between standing and sitting
Sacral slope (SS)	30-50	11-29	10-30
Pelvic incidence (PI)	42-64	42-64	-
Combined sagittal index (CSI)	203-233	162-198	-
Pelvic femoral angle (PFA)	177-197	110-140	55-70
Ante-inclination (AI)	25-45	41-63	-
Adapted from Stefl et al. **(84)** 2017			

1.5. Abnormal spinopelvic motion

The spine, hips, and pelvis work coordinately to maintain the dynamic balance of spinopelvic motion, but pathological and surgical factors can alter the posture and range of motion of the spine and pelvis, resulting in abnormal spinopelvic motion(85, 86). Spinal degeneration or spinal fusion decreases mobility and results in improper spinopelvic posture as a result of compensatory rotation of the pelvis, which maintains the sagittal balance while using minimal energy(51).

As mentioned above, the pelvis functions as a 'gear' connecting the spine (lumbosacral junction as a posterior hinge) and hip joints (anterior hinge). An abnormal motion of one part of the kinetic chain causes the remaining parts to compensate(62). Spinal degenerative changes or fusion surgery can lead to a sagittal imbalance with reduced lumbar lordosis, decreased motion of the stiff lumbar spine from standing to sitting, and thus fewer changes in the SS. In this situation, the posterior rotation (and thus increasing acetabular opening) of the pelvis is reduced, while hip flexion is increased as a compensatory mechanism, which in turn increases the risk of anterior impingement(87). In the case of a stiff lumbar spine with a more vertical sacrum, when going from sitting to standing, the anterior rotation of the pelvis (and thus decreasing acetabular functional anteversion) is reduced due to the decreased motion of the lumbar spine. The compensatory mechanism forces the hip joint to extend, increasing the risk of posterior impingement(87). Hip surgeons have shown particular interest in abnormal pelvic motion because dislocation following THA might result from anterior or posterior impingement(38, 48).

Both the pelvic rotation and sagittal balance of the spine can be impacted by hip parameters. Hip flexion contractures in individuals with severe hip osteoarthritis (OA) restrict hip motion, particularly extension. Under this circumstance, the compensatory mechanism decreases PT, increases SS, and thus increases lumbar spine lordosis in order to maintain an upright posture and achieve a horizontal gaze(88, 89). Spinal sagittal malalignment is more prevalent in patients with severe hip OA(88). Spine surgeons should be aware that THA can improve lumbosacral mobility affected by preoperative hip contractures(84), which may impact the sagittal balance established by prior spine surgery(61, 90).

Individuals with low PI (PI<40°), and thus with low SS and low LL, have a lower potential ability to retrovert the pelvis when changing posture from standing to sitting, also causing stiffness of the lumbar-pelvic complex. Due to a flat spine and restricted pelvic rotation, potential compensatory mechanisms of both the spine and the pelvis are quickly exhausted. More hip flexion is thus involved in the compensatory process. In this situation, the process of altering the posture is mainly supported by femoral mobility, which is why individuals are then referred to as “hip users”(91). When spinal degeneration and low PI coexist, the lumbar-pelvic complex becomes stiffer, the pelvis excessively retroverts while standing(44), and the acetabulum becomes more vertical (and functional acetabular anteversion increases), which causes anterior edge loading (thus leading to bearing wear) (92, 93) and raises the risk of anterior dislocation(42). While sitting, the hip is over-flexed to compensate for the stiffness of the pelvis and lumbar spine. The acetabulum is closed, leaving an uncovered posterior portion of the acetabulum (thus increasing the posterior edge loading), raising the risk of anterior impingement and posterior dislocation(61, 91). Individuals with high PI (PI>40°), and thus with high SS and high LL, have a high potential ability to rotate the pelvis posteriorly, so the reduction of the lumbar lordosis and the posterior rotation of the pelvis are primarily responsible for the postural transition from standing to sitting. Only a little femoral flexion is required. These individuals are referred to as “spine users”(91). Even in the presence of lumbar spine degeneration, the remaining compensatory capacity of the lumbar spine and pelvis in these individuals is not easily exhausted in response to daily posture change(52).

1.6. Classifications of spinopelvic motion

The current challenge presented to hip surgeons is how to implement individualized surgical plans and optimize the placement of the acetabular component for individuals who have various abnormal spinopelvic motions to minimize the risk of postoperative dislocation. To help surgeons manage patients with abnormal spinopelvic motion, several classification systems have been proposed.

Based on the variation in SS between standing and sitting (ΔSS), Stefl et al.(84) divided spinopelvic motion into three categories: normal, hypermobile, and stiff. Normal spinopelvic motion is defined as a value of ∆SS between 10 and 30°. Hypermobile spinopelvic motion is characterized by a ∆SS exceeding 30°, which is considered a normal variation if not caused by kyphosis. The risk of dislocation after THA can be decreased in individuals with normal hypermobility since these individuals are actually "spine users" and have a high potential for compensatory ability in their spine and pelvis. Hypermobility with kyphotic or overly flat (sitting SS <10°) lumbar spine in the sitting position is considered an abnormal variant because hypermobile kyphotic hips with excessive posterior pelvic rotation will result in a more vertical acetabular component, and a 'drop out' dislocation may happen if the ante-inclination angle is greater than 75 degrees during sitting(84). Stiff spinopelvic motion, which is defined as ∆SS less than 10°, is divided into three patterns: fixed anterior tilt, fixed posterior tilt, and neutral stiff. Fixed anterior tilt is also called ‘stuck standing’, that is, the pelvis is fixed in an anteriorly tilted position, and the SS does not drop below 30° even when sitting. These individuals have a ∆SS of <10° and an SS of >30° in both standing and sitting positions. Fixed posterior tilt is also called ‘stuck sitting’, in which the pelvis is stuck in a posteriorly tilted position and the SS will not rise over 30° even when the individual is standing. These individuals have a ∆SS of <10° and an SS of <30° in both standing and sitting positions. Neutral stiff individuals have a standing SS of >30° and a sitting SS of <30° as well as a ∆SS of <10°. Fused hips refer to individuals who have severe stiffness (ΔSS is less than 5°) due to surgical or biological fusion.

Phan et al.(94) recommended that individuals undergoing THA be classified into four categories: flexible and balanced, rigid and balanced, flexible and unbalanced, or rigid and unbalanced. In addition to spinal flexibility, this classification also takes the sagittal deformity of the spine into account, both of which are key factors affecting spinopelvic mobility. Balanced sagittal spinal alignment is characterized by PT <25° and PI–LL <10°, while individuals with unbalanced alignment have a PT of >25° and a PI–LL of >10°. Patients in the flexible and balanced category have intact spinal function and thus sufficient compensatory capacity to fully accommodate postural changes. In the rigid and balanced category, although patients still maintain balanced sagittal alignment in the standing position, they have lost the ability to compensate for positional changes due to significant degeneration and fusion of the lumbosacral joint. Patients in the rigid and unbalanced category have a stiff ‘flat-back’ spine.

Luthringer et al.(63) divided the classification approach into two steps. The first step is to determine whether the patient has a flat-back deformity (PI-LL > 10°), while the second step is to determine whether there is spinal stiffness (ΔSS <10°). Normal alignment is represented by ‘1’, while flatback deformity is represented by ‘2’. Normal mobility is represented by ‘A’, while stiff spine is represented by ‘B’. According to this combined classification method, patients are classified into four categories (1A, 1B, 2A, 2B).

The premise in utilizing these classification schemes in guiding THA surgery is that the mobility and sagittal balance of the spine is fixed before and after surgery. The fact is, however, that age or spinal surgery may lead to reduced mobility and sagittal imbalance of the spine, which may alter the individual's classification and increase the risk of late dislocation(95). In addition, spinopelvic mobility and sagittal spine alignment may alter in patients undergoing THA procedures. Stefl et al.(84) found that despite the effects of degenerative spinal disease, the proportion of patients with normal spinal mobility after THA increased from 54% to 80%, which should be attributed to the release of the contracted hip joint during the operation. Muellner et al.(90) found that THA results in a significantly improved lumbar flexibility: the LL in the standing position increases, while it decreases in the sitting position. To date, no study has evaluated whether changes in spinopelvic mobility and sagittal spinal alignment lead to postoperative deviation of the acetabular component from the pre-determined safe zone.

1.7. Managing abnormal spinopelvic motion

The position of the acetabular component may be negatively impacted by an abnormal spinopelvic motion, which may contribute to THA dislocation(94). Nearly all studies of abnormal spinopelvic motion have focused on the underlying mechanism by which it leads to post-THA impingement (prosthetic or bony impingement)(48, 84, 96, 97).

When a dislocation occurs, the impingement breaks through the biological limits of the joint capsule, mechanical constraints of the prosthesis, and muscular tension restrictions around the hip joint(98). However, there is currently no reliable imaging technology to identify impingement(99). CSI is considered the most effective predictor of impingement and is recommended to be used to guide intraoperative acetabular component placement(38, 48). The patient may be at risk of posterior impingement if the predicted postoperative standing CSI is greater than 243°(38). In this situation, it is necessary to minimize the functional anteversion of the acetabular prosthesis properly during implantation to prevent posterior impingement. The patient is at risk of anterior impingement when the predicted postoperative sitting CSI is less than 151°(38). To prevent anterior impingement, the acetabular component should be implanted more openly in this circumstance. Patients at potential risk of dislocation should be screened preoperatively and a specific acetabular implant strategy should be developed to achieve postoperative impingement-free motion. Several authors have proposed potential solutions based on their respective classification systems.

Stefl et al.(84) proposed an acetabular component placement solution based on spinopelvic mobility. For a normal hip, a 40° inclination, 20° anteversion, and 25° to 45° combined anteversion are recommended, and this protocol also applies to the kyphotic hip with normal mobility. For a hypermobile hip (either normal or kyphotic), the authors recommend that the acetabular component should be placed at a 35° to 40° inclination and 15° to 20° anteversion to prevent a vertical position and thus "drop out" dislocation due to excessive pelvis posterior rotation while sitting. In individuals with a stiff hip, restricted pelvic motion prevents the acetabular component from opening during sitting, so more anteversion and inclination are required to compensate for the loss of the acetabular angle to prevent impingement. However, the linear polyethylene wear significantly increases with an inclination angle of ≥ 45°(93), so the authors recommend increasing the inclination angle closer to 45° and setting the anteversion angle at 20° to 25°, thus with a combined anteversion of between 35° and 50°. In individuals with a kyphotic and fixed posterior tilt hip, a high anteversion and inclination are needed to spare more clearance for hip flexion while sitting, which is controversial since a vertical acetabular component is inherent with a high risk of “drop out” dislocation. The authors considered using dual mobility articulation as the best solution for this situation. In addition, the authors classified the imbalance’s severity into three categories based on the consequence following the ideal placement of the acetabular component: pathological, dangerous, or inconsequential. In patients with pathological imbalance, the ideal acetabular position cannot offset the risk of impingement. In patients with dangerous imbalance, precise acetabular position is required to overcome the risk of impingement. Inconsequential imbalances result from incorrect measurements and have no clinical significance.

Phan et al.(94) suggested that the orientation of the acetabular component should be determined according to spinal flexibility and spinal sagittal balance. Patients with a flexible spine and balanced sagittal alignment have full potential compensation ability to accommodate daily posture changes. The authors recommend a safe anteversion zone of 5° to 25° to be the same as the standard LSZ. For rigid and balanced patients, a higher anteversion was required to compensate for the insufficient opening of the acetabular component while sitting. The authors recommend a higher portion of the conventional safe zone, with an anteversion of 15° to 25°. Since sagittal imbalance exists in both flexible/unbalanced and rigid/unbalanced spines, the authors recommend spinal correction surgery to restore sagittal alignment before THA, which could put them into the rigid/balanced category. If hip surgery is performed first, the anteversion of the acetabular component should be reduced to avoid limited extension and posterior impingement when standing. However, the imbalanced spine may need to be realigned following THA, which could cause hip instability and impingement and therefore necessitate revision surgery to adjust the orientation of the acetabular component.

Lutheringer et al.(63) proposed treatment protocols like those of Phan et al. but differed in that they involved the functional pelvic plane (FPP) as a reliable reference line for acetabular cup implantation. For individuals in group 1A (normal alignment and mobility), the authors recommend that the anteversion should be set at 20-25° relative to

FPP. For individuals in group 1B (normal alignment and stiff mobility), the recommended anteversion increased to 30° to protect against anterior impingement due to the stiff spine. For individuals in group 2A (flatback deformity and normal mobility), the APP tilts posteriorly relative to the coronal plane due to spinal deformity, so the reference line for the acetabular anteversion must be the FPP. The recommended anteversion was 25-30° relative to the FPP. Individuals in group 2B (flatback deformity and stiff mobility) have a very narrow anteversion safe zone; the authors noted that a target anteversion of 30° relative to the FPP would result in a more vertical acetabular component due to posterior pelvic rotation in standing. Therefore, these patients are at high risk for impingement, which is why dual mobility prostheses are highly recommended.

Dual mobility articulation has two special design features that contribute to hip stability: increased head/neck ratio and jump distance, which theoretically increase the impingement-free range of motion and reduce the incidence of dislocation in high-risk patients(100). Several authors recommended this prosthesis for patients at high risk of dislocation due to spinal stiffness and/or sagittal imbalance(61, 63, 101-105). However, although satisfactory outcomes have been achieved with dual mobility articulation in primary THA at high risk of dislocation (including abductor insufficiency, and severe cognitive and neuromuscular disease)(106) as well as revision surgery for infection or recurrent dislocation(107), no studies have evaluated the results of primary THA with dual mobility articulation in patients with high-risk abnormal spinopelvic motion. Increasing offset has been recommended to protect patients at high risk against dislocation(23, 108, 109). On the impingement modeling, it has been observed that for every 1° offset increase, the impingement-free motion increases by 5°(23). However, if the offset increases by over 10mm, there is a trade-off of potentially declining postoperative Harris Hip Scores(110) which is why the surgeon must balance the impingement-free range of motion with the clinical outcome.

A protocol for planning the acetabular orientation according to pelvic mobility and spinal balance may effectively reduce the risk of instability to some extent, however, preoperative pelvic mobility and spinal balance are not an adequate basis for acetabular implant planning. Since dislocation occurs postoperatively, a prerequisite for surgical planning based on a preoperative classification should be that preoperative assessments of pelvic mobility and spinal balance are highly representative of the postoperative situation. However, existing studies have demonstrated that pelvic mobility and spinal balance may be altered by THA as a result of hip pain relief and improved hip mobility(84, 90), which may cause the classification to switch from one category to another postoperatively, thus leading to errors in preoperative clinical decision-making. In addition, further evaluation of high-risk patients is needed to optimize prosthesis selection based on risk-benefit. Although the improved design of modern dual mobility articulation has significantly reduced the incidence of wear and intra-prosthetic dissociation compared with earlier designs(111), and there have been no adverse reports for this prosthesis when used in younger patients(112, 113), current studies only support the use of this prosthesis in patients at high risk of postoperative dislocation(114). Therefore, further research is needed to optimize the acetabular implant scheme for high-risk patients and narrow the indications for the selection of dual mobility articulation in order to avoid inappropriate use.

1.8. Aims and hypothesis

Recent studies have proven that the functional safe zone is more reliable in predicting potential hip instability than the LSZ(38, 48). The acetabular component orientation is determined by the surgeon, which is why the PFA is the only intrinsic factor directly affecting the functional safe zone. In addition, a previous study reported that hip hyperextension and over-flexion were the main causes of CSI outliers and therefore dislocations(115).This point of view was well confirmed by Tezuka et al.(38), who found that an increased hip flexion and extension was the best predictor of the functional safe zone outlier. However, no studies have yet focused on hip motion to screen out patients with a high risk of THA instability.

Abnormal pelvic mobility may lead to dislocation after THA due to anterior or posterior impingement(48). Therefore, some authors recommended using pelvic mobility to predict the risk of postoperative dislocation and placing the acetabular component according to preoperative pelvic mobility(84, 91). However, the scientific evaluation regarding pelvic mobility is still insufficient, and some studies found that pelvic mobility alters after THA(84, 96), which may lead to errors in preoperative clinical decision-making.

PI is an anatomical parameter commonly used by spine surgeons, and previous studies have confirmed PI as the third predictive parameter of impingement risk after THA (38). However, few studies have focused on its effect on spinopelvic motion.

The aims of this study therefore were to investigate the characteristics of preoperative and postoperative pelvic and hip motion, the relationships between preoperative factors and postoperative abnormal pelvic and hip motion, whether postoperative abnormal pelvic and hip motion may be predicted by preoperative factors, and how PI contributes to hip instability.

2. Methods

2.1. Participants

After acquiring institutional ethics board approval (EA2/142/17), we prospectively enrolled patients who underwent primary THA in our department between September 2019 and November 2020. During this period, a total of 327 consecutive THAs were performed on 322 patients. The study was conducted according to the Declaration of Helsinki and written informed consent was obtained from all patients. The inclusion criteria were: 1) age over 18 years; 2) patients receiving unilateral THA for primary hip OA or OA secondary to dysplasia of the hip (Crowe grade I), or other hip diseases without influence on posture. The exclusion criteria were: 1) history of previous hip surgery, including ipsilateral osteotomy and osteosynthesis; 2) history of ankylosing spondylitis, history of previous spine surgery; 3) neurologic or musculoskeletal disorders, or disorders that may affect the spinopelvic motion; 4) bilateral planned THA; 5) revision THA; 6) poor quality or incomplete imaging.

2.2. Surgical procedures

The operations were performed by four board-certified experienced surgeons in the supine position via an anterolateral approach. The prosthetic components were determined based on the individual requirements and planned preoperatively utilizing TraumaCad (Brainlab, Munich, Germany). The acetabular component was anatomically placed at a target orientation of 40° inclination and 20° anteversion without the assistance of a navigation technique. Cemented fixation techniques were performed in the case of a Type C femur according to the Dorr classification. All patients underwent rehabilitation according to the same program after surgery.

2.3. Radiographic protocol

Within three days preoperatively and five to seven days postoperatively, all 193 patients received standing and sitting biplanar anterior-posterior and lateral plane 2D radiographs of the full spine imaging including the pelvis up to the proximal tibia using a low-dose stereo-radiography system (EOS, Paris, France). The patients' posture was standardized according to the same protocol when acquiring the imaging data: The standing position involved standing in a relaxed position, looking forward and placing the hands on a support. The sitting position involved sitting on an adjustable height stool in a relaxed position with the femurs parallel to the floor, knees bending 90°, and feet flat on the floor.

2.4. Measurement parameters

The following parameters were measured on EOS images pre- and postoperatively (**Figure 6, Table 1** for definition): C7-Sagittal vertical axis (C7-SVA), C7-central sacral vertical line (C7-CSVL), cervical lordosis (CL), thoracic kyphosis (TK), lumbar lordosis (LL), pelvic incidence (PI), sacral slope (SS), ante-inclination (AI), and pelvic femoral angle (PFA). We used the symbol '∆' to indicate the difference of the same parameter between standing and sitting positions. All parameters were measured by an experienced orthopedic surgeon using the Merlin Diagnostic Work center (Phoenix PACS, Freiburg, Germany), and 25% of the dataset was randomly selected for independent measurement by a second experienced orthopedic surgeon.

Coronal malalignment was defined as a lateral displacement of the trunk relative to the midline of the pelvis by more than 20mm(C7-CSVL>20mm)(116, 117). Sagittal malalignment was defined as a value of C7-SVA of more than 50mm(118). Hip mobility was defined as the difference between $PFA_{standing}$ and $PFA_{sitting}$ ($\Delta PFA = PFA_{standing} - PFA_{sitting}$). According to previous studies(48, 84), a $PFA_{standing}$ of >197° and a $PFA_{sitting}$ of <110° were defined as hyperextension and over-flexion abnormality, respectively. In this study, the investigation of hip motion focused on $PFA_{standing}$, $PFA_{sitting}$, and hip mobility (∆PFA). Pelvic mobility was defined as the difference between $SS_{standing}$ and $SS_{sitting}$ ($\Delta SS = SS_{standing} - SS_{sitting}$). Normal pelvic mobility was defined as a value of ∆SS between 10 and 30°. Stiff and kyphotic hypermobile were two patterns of pelvic mobility imbalance: 1) Stiff pelvic mobility was defined as a ∆SS less than 10°, and 2) kyphotic hypermobile pelvic mobility was characterized by a ∆SS exceeding 30° but with the absolute $SS_{sitting}$ ≤5°

(84). Positional pelvic imbalance was divided into three categories: 1) the pelvis in the fixed anterior category was fixed in an anteriorly tilted position, and the $SS_{sitting}$ did not drop below 30°; 2) the pelvis in the fixed posterior category was stuck in a posteriorly tilted position, and the $SS_{standing}$ did not rise over 30°; 3) the kyphotic pelvis had an absolute $SS_{sitting}$ of ≤5°.

PI was divided into three categories (low PI≤41°, high PI≥65° and normal PI between 42° to 64°)(115). Since PI is a fixed anatomical parameter(59), PI values were calculated as the average of preoperative and postoperative PI to reduce measurement bias. PI-LL mismatch was calculated as PI minus LL, with ≤10° indicating balanced sagittal alignment and >10° indicating unbalanced sagittal alignment.

The Kellgren-Lawrence (KL) grade system was applied to assess the severity of degenerative intervertebral disc disease (DDD)(119). The Kellgren and Lawrence grading system was used to classify the severity of hip osteoarthritis(120).

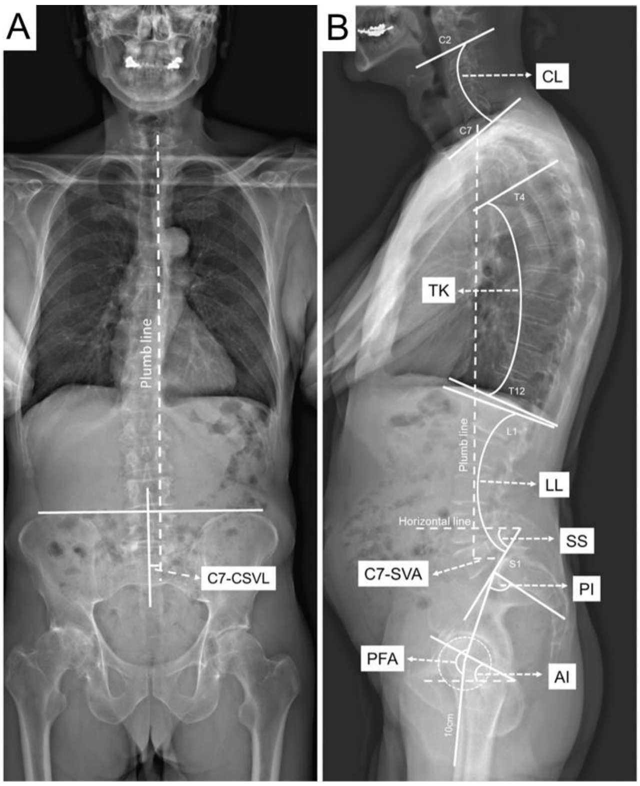

Figure 6. Illustration of the measurement of key spinopelvic parameters in EOS images. A) Measurement method of C7-CSVL in the standing AP EOS radiography. B) The following parameters are measured in the lateral EOS radiography: CL, TK, LL, SS, PI, PFA, AI, C7-SVA.

2.5. Statistical analysis

SPSS version 26.0 (IBM Corporation, NY, USA) was used for all statistical analyses. Descriptive statistics were used to summarize and describe changes in pelvic and hip motion before and after THA. The Shapiro-Wilk test was conducted to check if variables were normally distributed. Levene's test was used to check the equality of the variances of two or more groups. The unpaired t-test was used to compare the difference between two independent groups with normal distribution. The corrected t-test (Welch's t-test) was used when assuming heterogeneous variance. The Mann-Whitney U test was used to compare the difference between two independent groups with skewed distribution. One-way analysis of variance (ANOVA) was used to compare the difference between three or more groups in which variables were normally distributed. The Bonferroni test was used for post hoc analysis when assuming homogeneous variance, whereas the Games-Howell test was used when assuming heterogeneous variance. The Kruskal-Wallis H test was used to determine the difference between three or more groups where variables were not normally distributed, and the Bonferroni test was used for pairwise comparisons. To analyze the difference between two groups of paired continuous variables, the paired t-test was used when the variables were normally distributed. Otherwise, the paired samples Wilcoxon signed-rank test was used instead.

Before performing multiple regression analysis, Spearman's rank correlation coefficient was used to analyze the correlation between variables. Multiple linear regression analysis was conducted to assess the correlation between postoperative factors (pelvic mobility, pelvic position, hip mobility, and femur position) and preoperative factors.

The receiver operating characteristic (ROC) curve was drawn, and the area under the ROC curve (AUC) and diagnostic ability was calculated to analyze the feasibility of predicting postoperative abnormalities (pelvic positional/mobility imbalance and abnormal hip mobility) using the factors screened out by multivariate linear regression analysis.

The correlations between spinopelvic mobility imbalance and PI, as well as between positional imbalance and PI, were evaluated using the Chi-square test. The intraclass correlation coefficient (ICC) was used to analyze inter-rater reliability.

All tests were two-sided, and the threshold for significance level was set at 0.05.

3. Results

3.1. Patient demography and reliability analysis

3.1.1 Patient demography

After patients who met the exclusion criteria had been eliminated, this study eventually included 193 patients who met the inclusion criteria, of whom there were 140 with primary osteoarthritis of the hip, 21 with hip dysplasia, 14 with avascular necrosis of the femoral head, nine with femoroacetabular impingement type CAM, five with rheumatoid arthritis and four with post-traumatic arthritis. The 193 patients (103 female and 90 male) had a mean age of 66.1 years (range, 18 to 88 years), a mean BMI of 26.8 kg/m^2 (range, 16.7 to 51.7 kg/m^2). Details of prostheses used and fixation techniques are shown in **Table 3**.

Table 3. Details of prostheses used and fixation techniques, and their quantities

Fixation techniques	**Number (N)**	
Cementless Fixation Technique	191	
Cemented Fixation Technique	1	
Inverse Hybrid Fixation Technique	1	
Component	**Number (N)**	**Manufacturer**
Implanted cups		
Allofit Cup	192	Zimmer Biomet, Warsaw, USA
TMT Cup	1	
Implanted inlays		
UHMWPE-Inlay	190	Various, depending on the other components
Ceramic-Inlay	3	

Implanted heads		
Ceramic head	193	Biolox Delta, CeramTec, Plochingen, Germany
Implanted stems		
SL-Plus MIA Standard Offset Stem	111	Smith & Nephew, London, UK
SL-Plus MIA Lateral Offset Stem	15	
SLR-Plus Stem	1	
Avenir Standard Offset Stem	14	Zimmer Biomet, Warsaw, USA
Avenir Lateral Offset Stem	1	
Avenir Complete Standard Offset Stem	41	
Avenir Complete High Offset/ Coxa Vara Stem	10	

3.1.2. Reliability analysis of radiographic parameters

All investigated radiographic parameters showed good to excellent inter-observer reliability (**Table 4**).

Table 4. Results of the inter-rater reliability analysis

	Preoperative		**Postoperative**	
	ICC	95% CI	ICC	95% CI
C7-Sagittal Vertical Axis	0.957	0.936-0.971	0.929	0.895-0.953
C7-Central Sacral Vertical Line	0.956	0.920-0.974	0.968	0.951-0.979
Cervical Lordosis	0.696	0.551-0.796	0.849	0.768-0.901
Thoracic Kyphosis	0.890	0.838-0.926	0.942	0.914-0.961
Lumbar Lordosis	0.945	0.918-0.963	0.940	0.911-0.960
Pelvic Incidence	0.688	0.563-0.782	0.822	0.698-0.891
Sacral Slope	0.895	0.829-0.934	0.935	0.850-0.966
Ante-Inclination	0.921	0.882-0.947	0.954	0.930-0.969

Pelvic Femoral Angle	0.949	0.923-0.966	0.955	0.933-0.970

ICC Intra-class correlation coefficient; *CI* confidence interval.

ICC was used to calculate inter-rater reliability between observers. ICC< 0.40 indicates poor reliability; 0.40≤ICC< 0.60 indicates fair reliability; 0.60≤ICC< 0.74 indicates good reliability; ICC≥ 0.75 indicates excellent reliability(121).

3.2. Hip motion before and after THA

3.2.1. Standing and sitting PFA changes from pre- to postoperatively

Preoperative PFA $_{standing}$ was significantly greater than postoperative PFA $_{standing}$ (P<0.001). The mean (SD) of the preoperative standing PFA was 179.30° (11.14), whereas the mean (SD) of the postoperative standing PFA was 175.32° (10.81). The trend that standing PFA became statistically smaller after THA can be observed in the 95% confidence interval and percentiles. **Figure 7** shows that a decreasing trend was not observed in all patients, and in some patients, the standing PFA increased. Approximately 5% of patients had a standing PFA of >197° preoperatively, which decreased by 2% after surgery (**Table 5**).

Table 5. Descriptive statistics of preoperative and postoperative standing PFA

	pre-PFA $_{standing}$	**post-PFA $_{standing}$**	**p-value**
Mean ± SD	179.30±11.14	175.32±10.81	<0.001*
95% confidence interval	177.72-180.89	173.79-176.86	
Percentiles			
5%	160.26	160.05	
10%	164.22	162.68	
25%	172.30	168.70	
50%	179.20	175.90	
75%	186.80	181.95	
90%	192.50	187.26	
95%	197.03	192.60	

*Significant difference

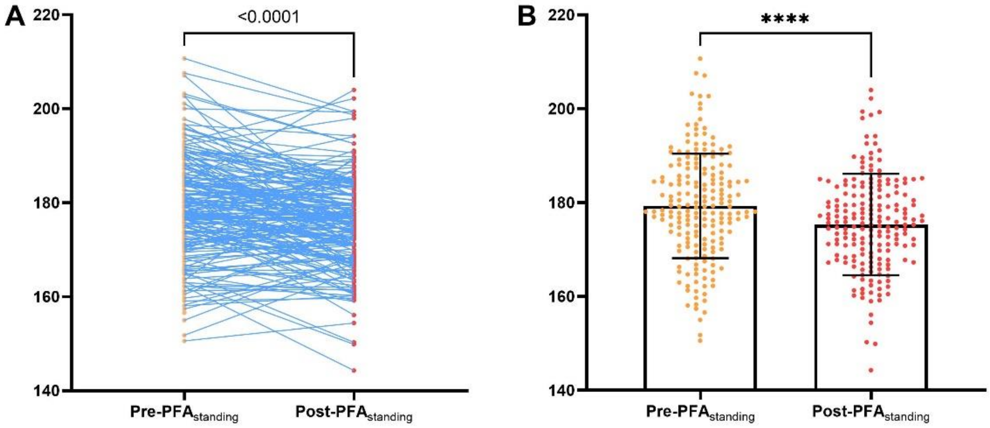

Figure 7. Descriptive statistics of pre- and postoperative standing PFA.
The blue line in Figure A represents the change of standing PFA before and after surgery in the same patient, and the mean and standard deviation are used to compare the differences in Figure B.

Preoperative sitting PFA was statistically smaller than postoperative sitting PFA (P=0.048). The trend that preoperative $PFA_{sitting}$ was smaller than postoperative $PFA_{sitting}$ can be seen in the 95% confidence interval and percentiles. **Figure 8** shows the change in sitting PFA before and after surgery. About 17% of patients had a sitting PFA of <110° preoperatively, dropping by 7% after THA (**Table 6**).

Table 6. Descriptive statistics of preoperative and postoperative sitting PFA

	pre-PFA sitting	**post-PFA sitting**	**p-value**
Mean ± SD	123.28±13.28	125.16±12.55	0.048*
95% confidence interval	121.40-125.17	123.38-126.94	
Percentiles			
5%	103.11	105.17	
10%	106.18	110.74	
25%	113.30	117.20	
50%	123.80	124.50	
75%	131.55	132.85	
90%	140.26	142.46	
95%	145.73	147.82	

*Significant difference

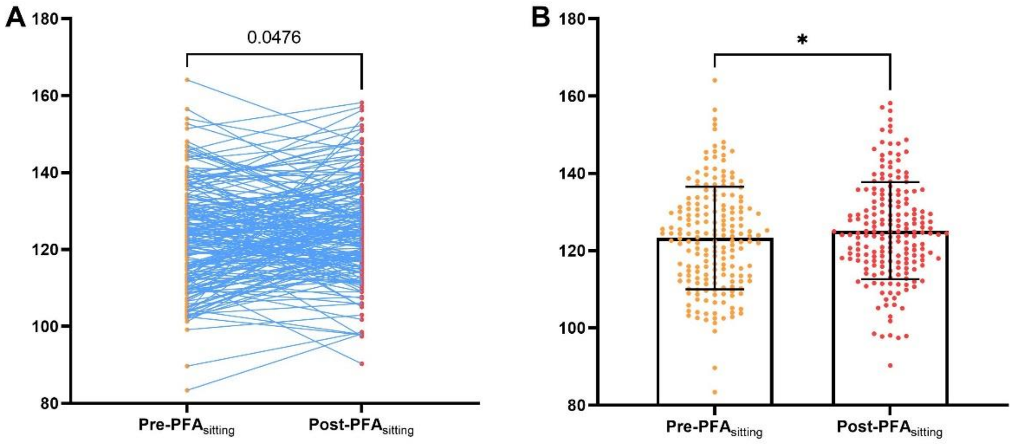

Figure 8. Descriptive statistics of pre- and postoperative sitting PFA.
The blue line in Figure A represents the change of sitting PFA before and after surgery in the same patient, and the mean and standard deviation are used to compare the differences in Figure B.

Hip mobility significantly increased after THA ($p<0.001$). The 95% confidence interval of preoperative ΔPFA was greater than postoperative ΔPFA. **Figure 9** shows the change in hip mobility before and after surgery (**Table 7**).

Table 7. Descriptive statistics of preoperative and postoperative hip mobility

	Pre-ΔPFA	**Post-ΔPFA**	**p-value**
Mean ± SD	56.02±15.46	50.23±13.57	<0.001*
95% confidence interval	53.83-58.22	48.31-52.16	
Percentiles			
5%	26.52	26.69	
10%	35.28	33.00	
25%	46.85	41.30	
50%	56.70	51.30	
75%	67.60	60.25	
90%	75.00	66.64	
95%	81.03	70.14	

*Significant difference

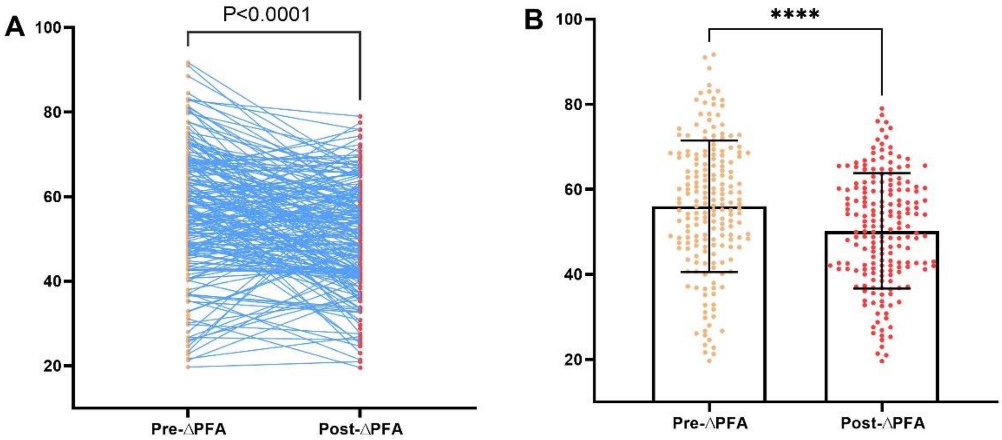

Figure 9. Descriptive statistics of pre- and postoperative hip mobility.

The blue line in chart A represents the change of hip mobility before and after surgery in the same patient, and the mean and standard deviation are used to compare the differences in chart B.

3.2.2. Effect of coronal and sagittal spinal alignment on hip motion

Coronal alignment: No significant difference was found in pre- and postoperative hip motion between the C7-CSVL balance group and the C7-CSVL imbalance group (**Table 8**). **Sagittal alignment:** The postoperative PFA $_{sitting}$ in the balanced group (122.64±10.33) was significantly lower than the imbalance group (127.65±14.02) (P=0.005) (**Table 9**).

Table 8. The effect of preoperative C7-CSVL imbalance on hip motion

		C7-CSVL		**p-value**
		Balanced(n=165)	Imbalanced(n=28)	
Pre-op	‡PFA $_{standing}$	179.21±11.22	179.89±10.85	0.765
	‡PFA $_{sitting}$	122.75±13.28	126.43±13.07	0.176
	‡ΔPFA	56.46±15.47	53.46±15.43	0.344
Post-op	†PFA $_{standing}$	175.30(14.10)	176.60(10.00)	0.367
	‡PFA $_{sitting}$	125.38±12.20	123.86±14.63	0.556
	†ΔPFA	50.10(18.65)	52.75(20.78)	0.251

Δ=standing-sitting

†The variables in these subgroups were not normally distributed, so the Mann-Whitney U test was conducted to calculate the difference between subgroups, and the median (IQR) was used to describe the statistical distribution.

‡The variables in these subgroups were normally distributed, the unpaired t-test was conducted to calculate the difference between subgroups, and the mean(±SD) was used to describe the statistical distribution.

Table 9. The effect of preoperative C7-SVA imbalance on hip motion

		C7-SVA		**p-value**
		Balanced(n=96)	Imbalanced(n=97)	
Pre-op	‡PFA $_{standing}$	179.88±11.70	178.74±10.58	0.477
	‡PFA $_{sitting}$	121.70±12.45	124.86±13.93	0.098
	†ΔPFA	57.05(20.35)	56.40(21.00)	0.145
Post-op	†PFA $_{standing}$	175.10(13.30)	176.70(13.70)	0.340
	‡PFA $_{sitting}$	122.64±10.33	127.65±14.02	0.005*
	†ΔPFA	53.60(20.93)	49.70(17.05)	0.050

*Significant difference

Δ=standing-sitting

†The variables in these subgroups were not normally distributed, so the Mann-Whitney U test was conducted to calculate the difference between subgroups, and the median (IQR) was used to describe the statistical distribution.

‡The variables in these subgroups were normally distributed, so the unpaired t-test was conducted to calculate the difference between subgroups. The variance between the subgroup of postoperative PFA $_{sitting}$ was heterogeneous, so Welch's t-test was used. The mean(±SD) was used to describe the statistical distribution.

3.2.3. Correlation between postoperative hip motion and preoperative spinopelvic factors

The preoperative factors correlating with **postoperative PFA $_{standing}$** were age, ΔLL, SS $_{sitting}$, ΔSS, PFA $_{standing}$, PFA $_{sitting}$, ΔPFA, PI $_{standing}$, PI $_{sitting}$ and ΔAI. Of these, PFA $_{standing}$ had a good correlation with postoperative PFA $_{standing}$ (r=0.587). The preoperative factors correlating with **postoperative PFA $_{sitting}$** were ΔLL, SVA $_{standing}$, SVA $_{sitting}$, SS $_{standing}$, ΔSS, PFA $_{standing}$, PFA $_{sitting}$, ΔPFA, PI $_{standing}$, PI $_{sitting}$ and ΔAI. Of these, PFA $_{sitting}$ was moderately correlated to postoperative PFA $_{sitting}$ (r=0.442). The preoperative factors correlating with **postoperative ΔPFA** were age, LL $_{sitting}$, ΔLL, SS $_{sitting}$, ΔSS, PFA $_{standing}$, PFA $_{sitting}$, ΔPFA, AI $_{standing}$, AI $_{sitting}$ and ΔAI (**Table 10**).

Table 10. Correlation between postoperative hip motion and age as well as preoperative spinopelvic parameters

	Postoperative hip motion					
	PFA$_{standing}$		PFA$_{sitting}$		∆PFA	
Pre-op	r value	p-value	r value	p-value	r value	p-value
Age	0.147	0.041*	-0.065	0.368	0.183	0.011*
LL$_{sitting}$	0.138	0.056	-0.128	0.077	0.237	0.001*
∆LL	-0.204	0.004*	0.168	0.019*	-0.319	<0.001*
SVA$_{standing}$	0.082	0.256	0.183	0.011*	-0.097	0.180
SVA$_{sitting}$	0.128	0.075	0.251	<0.001*	-0.100	0.167
SS$_{standing}$	0.089	0.217	0.177	0.014*	-0.096	0.184
SS$_{sitting}$	0.186	0.010*	-0.040	0.578	0.200	0.005*
∆SS	-0.154	0.033*	0.214	0.003*	-0.337	<0.001*
PFA$_{standing}$	0.587	<0.001*	0.239	0.001*	0.210	0.003*
PFA$_{sitting}$	0.191	0.008*	0.442	<0.001*	-0.286	<0.001*
∆PFA	0.245	0.001*	-0.178	0.013*	0.381	<0.001*
PI$_{standing}$	0.464	<0.001*	0.346	<0.001*	0.020	0.785
PI$_{sitting}$	0.430	<0.001*	0.352	<0.001*	-0.007	0.925
AI$_{standing}$	0.072	0.321	-0.098	0.174	0.145	0.045*
AI$_{sitting}$	-0.069	0.342	0.115	0.112	-0.154	0.033*
∆AI	0.143	0.048*	-0.194	0.007*	0.292	<0.001*

0.7</r/<1 indicates ‘strong’ correlation; 0.5</r/<0.7 indicates ‘good’ correlation; 0.3</r/<0.5 indicates ‘fair’ or ‘moderate’ correlation; /r/<0.3 indicates ‘poor’ correlation(121).

*Significant correlation

Spearman’s rank correlation coefficient was used to analyze the correlation between postoperative hip motion and preoperative spinopelvic factors.

3.2.4. Multiple linear regression analysis

To avoid multicollinearity among independent variables, the correlation among preoperative factors was evaluated using Spearman’s rank correlation coefficient before performing multiple regression analysis. Among the independent variables related to the dependent variable, we screened out all the independent variables that strongly correlated (r>0.7) with each other, and one of them was reserved in the multiple regression analysis as needed. For **postoperative PFA $_{standing}$** as the dependent variable, the preoperative independent variables involved in the regression analysis were as follows: age at surgery, SS $_{sitting}$, ΔSS, PFA $_{standing}$, PFA $_{sitting}$, PI $_{standing}$, the extent of contralateral hip osteoarthritis, and the extent of degenerative intervertebral disc disease. For **postoperative PFA $_{sitting}$** as the dependent variable, the preoperative independent variables involved in the regression analysis were as follows: SVA $_{standing}$, SVA $_{sitting}$, PI $_{standing}$, ΔSS, PFA $_{standing}$, PFA $_{sitting}$, the extent of contralateral hip osteoarthritis, and the extent of degenerative intervertebral disc disease. For **postoperative ΔPFA** as the dependent variable, the preoperative independent variables involved in the regression analysis were as follows: age at surgery, SS $_{sitting}$, ΔSS, PFA $_{standing}$, PFA $_{sitting}$, AI $_{standing}$, AI $_{sitting}$, the extent of contralateral hip osteoarthritis, and the extent of degenerative intervertebral disc disease. When conducting the multiple regression analysis, we observed that the Durbin-Watson values were all below 2, and the VIF values of all independent variables were around 1, which confirmed that there was no strong correlation or collinearity among the independent variables.

Based on the results of multiple linear regression analysis (**Table 11**), the prediction formula of postoperative PFA $_{standing}$ was: 82.015 + (0.471 × pre-PFA $_{standing}$) + (0.324 × pre-PI $_{standing}$) - (0.250 × KL grade of contra-lateral hip (Grade 4)) - (0.163 × KL grade of lumbar spine (Grade 1)). This regression model was statistically significant (F=38.952, p<0.001). The independent variable in the equation explains 49.7% of the variation in the dependent variable (adjusted R^2=0.497). The linear relationship between pre- and postoperative standing PFA, as well as postoperative standing PFA and preoperative standing PI, is shown in **Figure 10**.

According to multiple linear regression analysis (**Table 12**), the prediction formula of postoperative PFA $_{sitting}$ was as follows: 56.265 + (0.284 × pre-SVA $_{sitting}$) + (0.519 × pre-PFA $_{sitting}$) - (0.190 × KL grade of contra-lateral hip (Grade 1)). This regression model was statistically significant (F=34.243, p<0.001). The independent variable in the equation explains 34.2% of the variation in the dependent variable (adjusted R^2=0.342). The linear relationship between postoperative PFA $_{sitting}$ and preoperative SVA $_{sitting}$, as well as postoperative PFA $_{sitting}$ and PFA $_{sitting}$, is shown in **Figure 11**.

Based on the results of multiple linear regression analysis (**Table 13**), the prediction formula of postoperative ∆PFA was: 31.861 + (0.297 × pre-PFA $_{standing}$) - (0.352 × pre-PFA $_{sitting}$) - (0.284 ×KL grade of contra-lateral hip (Grade 4)). This regression model was statistically significant (F=22.090, p<0.001). The independent variable in the equation explains 24.8% of the variation in the dependent variable (adjusted R^2=0.248). The linear relationship between postoperative ∆PFA and preoperative PFA $_{standing}$, as well as postoperative ∆PFA and preoperative PFA $_{sitting}$, is shown in **Figure 12**.

Table 11. Multiple linear regression analysis for predicting postoperative standing PFA

Variables	**Multiple linear regression analysis model (R^2 =0.497)**			
	Unstandardized coefficients		Standardized coefficients	p-value
	B	SE	β	
Intercept	82.015	9.181	-	-
KL grade of contra-lateral hip (Grade 4)	-10.757	2.227	-0.250	<0.001*
KL grade of lumbar spine (Grade 1)	-10.103	3.213	-0.163	0.002*
PFA $_{standing}$	0.457	0.057	0.471	<0.001*
PI $_{standing}$	0.274	0.062	0.324	<0.001*

*Statistical significance

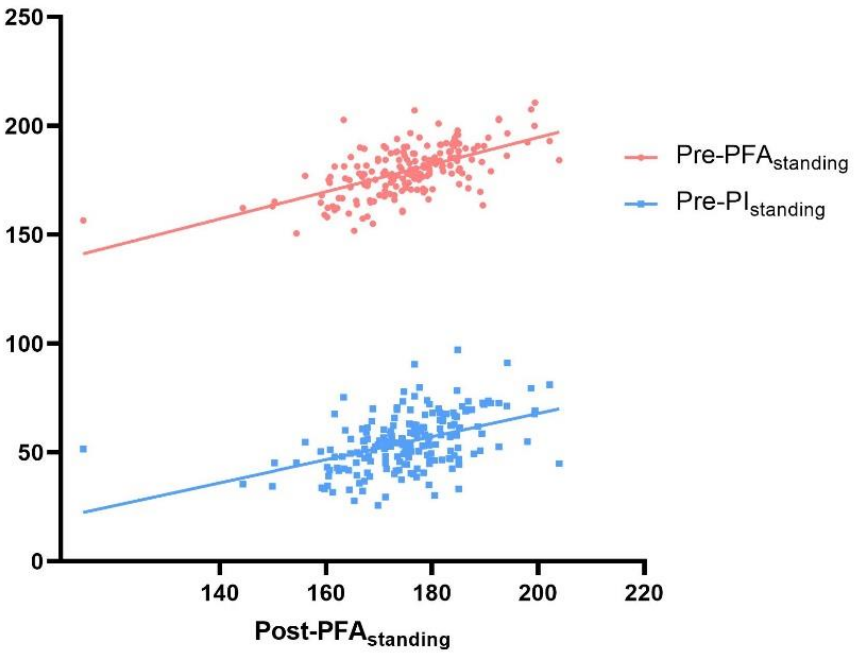

Figure 10. The linear relationship between postoperative standing PFA and preoperative standing PFA, as well as between postoperative standing PFA and preoperative standing PI.

Table 12. Multiple linear regression analysis for predicting postoperative sitting PFA

Variables	**Multiple linear regression analysis model (R^2 =0.342)**			
	Unstandardized coefficients		Standardized coefficients	p-value
	B	SE	β	
Intercept	56.265	7.269	-	-
KL grade of contra-lateral hip (Grade 1)	-23.450	7.243	-0.190	<0.001*
$SVA_{sitting}$	0.123	0.026	0.284	<0.001*
$PFA_{sitting}$	0.491	0.056	0.519	0.001*

* Statistical significance

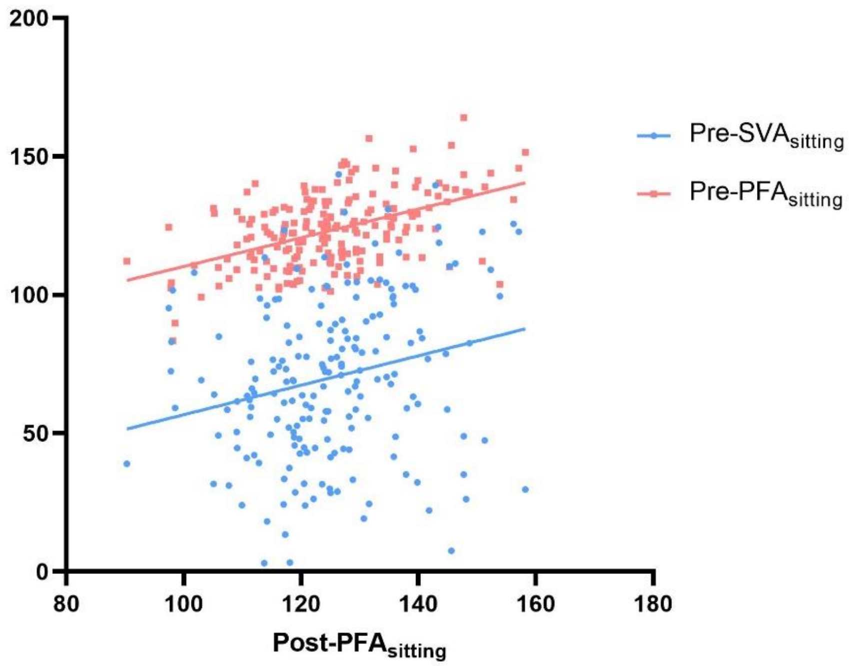

Figure 11. The linear relationship between postoperative sitting PFA and preoperative sitting SVA, as well as between postoperative sitting PFA and preoperative sitting PFA.

Table 13. Multiple linear regression analysis for predicting postoperative ∆PFA

Variables	**Multiple linear regression analysis model (R^2 =0.248)**			
	Unstandardized coefficients		Standardized coefficients	p-value
	B	SE	β	
Intercept	31.861	14.713	-	-
KL grade of contra-lateral hip (Grade 4)	-15.339	3.383	-0.284	<0.001*
PFA $_{standing}$	0.361	0.078	0.297	<0.001*
PFA $_{sitting}$	-0.360	0.065	-0.352	<0.001*

* Statistical significance

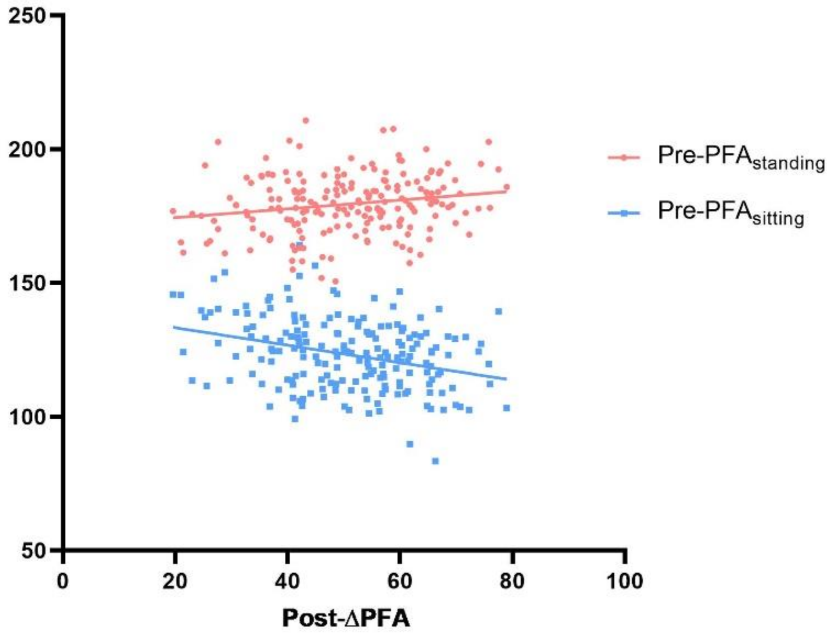

Figure 12. The linear relationship between postoperative ΔPFA and preoperative standing PFA, as well as between postoperative ΔPFA and preoperative sitting PFA.

3.2.5. Prediction of postoperative hip hyperextension and over-flexion

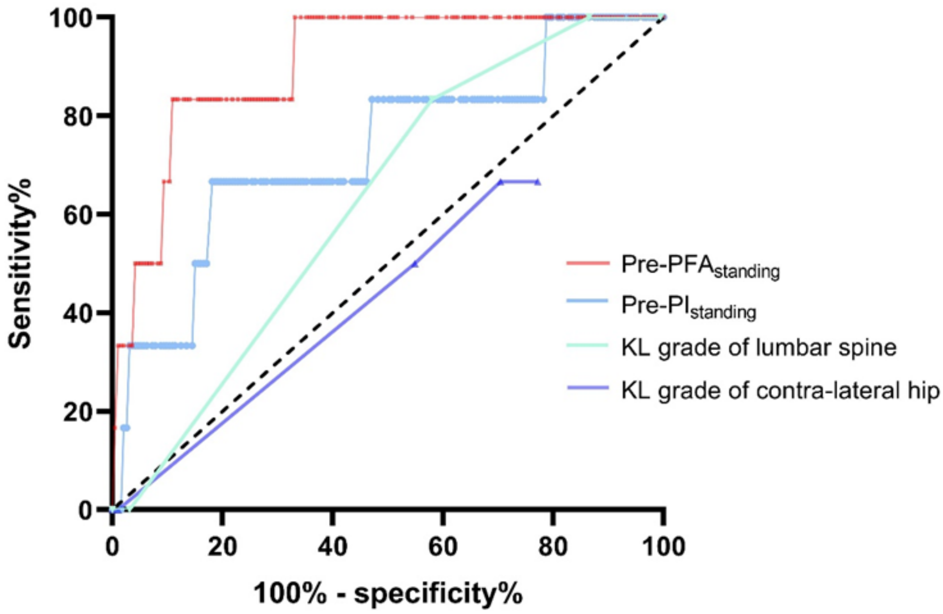

Figure 13. The performance of preoperative factors to predict postoperative hyperextension abnormalities.

The performance of **preoperative PFA $_{standing}$** was excellent (AUC=0.904, $p<0.001$, 95% CI = 0.811 to 0.997) in diagnosing postoperative hyperextension abnormalities. The maximal Youden index (0.747) corresponded to a preoperative PFA $_{standing}$ optimum threshold of ≥192.4°. This optimum threshold demonstrated 83.3% sensitivity and 91.4% specificity in predicting postoperative hyperextension abnormalities. (**Table 14, Figure 13**).

Table 14. The performance of factors to predict postoperative hyperextension abnormalities

Pre-op factors	**AUC**	**95% Confidence interval**	**p-value**
PI $_{standing}$	0.730	0.508-0.952	0.055
***PFA $_{standing}$**	**0.904**	**0.811-0.997**	**<0.001**
KL grade of contra-lateral hip	0.565	0.335-0.796	0.584
KL grade of lumbar spine	0.620	0.440-0.799	0.319

* The optimum threshold of pre-PFA standing was ⩾ 192.4°, with an 83.3 % sensitivity and a 91.4 % specificity in predicting postoperative hyperextension.

The interpretation of AUC was as follows: 0.9-1 indicated 'excellent' performance, 0.8-0.9 indicated 'good' performance, 0.7-0.8 demonstrated 'fair' performance, 0.6-0.7 presented 'poor' performance, and 0.5-0.6 denoted 'failed' performance(122).

The performance of **preoperative PFA $_{sitting}$** was fair (AUC=0.752, p<0.001, 95% CI = 0.629 to 0.875) in diagnosing postoperative over-flexion abnormalities. The maximal Youden index (0.467) corresponded to a preoperative PFA $_{sitting}$ optimum threshold of ≤113.1°. This optimum threshold demonstrated 80.0% sensitivity and 66.7% specificity in predicting postoperative over-flexion abnormalities. (**Table 15, Figure 14**).

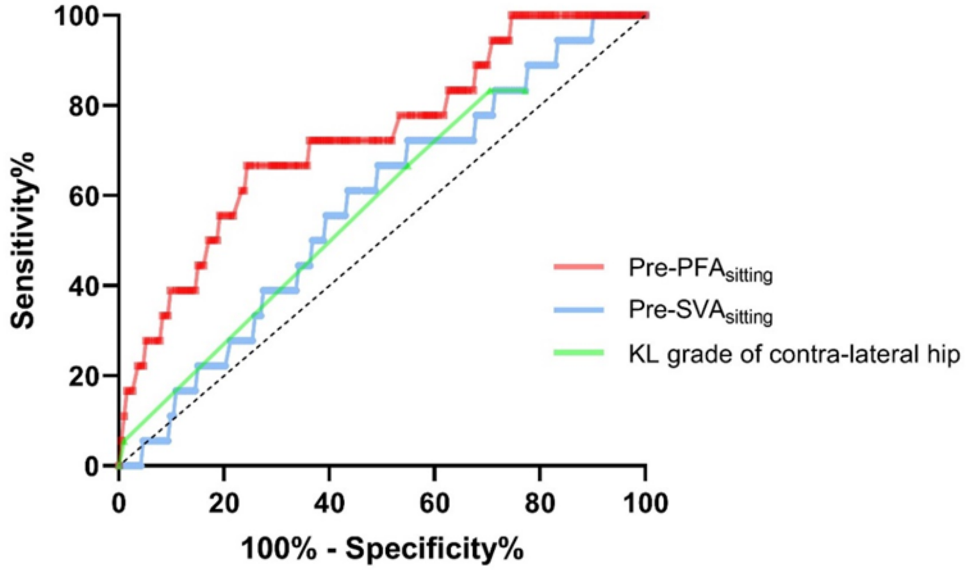

Figure 14. The performance of preoperative factors to predict postoperative over-flexion abnormalities.

Table 15. The performance of preoperative factors to predict postoperative over-flexion abnormalities

Pre-op factors	AUC	95% Confidence interval	p-value
SVA $_{sitting}$	0.578	0.450-0.707	0.271
***PFA $_{sitting}$**	**0.752**	**0.629-0.875**	**<0.001**
KL grade of contra-lateral hip	0.515	0.388-0.642	0.831

* The optimum threshold of pre-PFA sitting was 113.1°, with an 80.0% sensitivity and 66.7% specificity in predicting postoperative over flexion abnormalities..

The interpretation of AUC was as follows: 0.9-1 indicated 'excellent' performance, 0.8-0.9 indicated 'good' performance, 0.7-0.8 demonstrated 'fair' performance, 0.6-0.7 presented 'poor' performance, and 0.5-0.6 denoted 'failed' performance(122).

3.3. Pelvic motion before and after THA

3.3.1. Changes in pelvic motion from pre- to postoperatively

SS $_{standing}$ significantly increased after THA (p<0.001). The mean (± SD) preoperative SS $_{standing}$ was 40.94±10.55, whereas the mean (± SD) postoperative SS $_{standing}$ was 42.91±9.87. The increasing trend of SS $_{standing}$ after surgery can be observed in the 95%

confidence interval and percentiles (5%-90%) (**Table 16, Figure 15**)

Preoperative SS $_{sitting}$ was significantly greater than postoperative SS $_{sitting}$ ($p<0.001$). The mean (± SD) preoperative SS $_{sitting}$ was 22.92±12.04, whereas the mean (± SD) postoperative SS $_{sitting}$ was 20.51±12.26. The decreasing trend that postoperative SS $_{sitting}$ was lower than preoperative SS $_{sitting}$ can be observed in the 95% confidence interval and percentiles (**Table 17, Figure 16**).

Pelvic mobility (∆SS) significantly increased after the operation (pre/post 18.0°/22.4°, $p<0.001$). The 95% confidence interval of preoperative pelvic mobility was greater than postoperative pelvic mobility. Postoperatively, the proportion of patients with a ∆SS of <10° decreased from 25% to 10%, while the proportion of patients with a ∆SS of >30° increased from 10% to 25% (**Table 18**). **Figure 17** shows the change in ∆SS before and after surgery.

Table 16. Descriptive statistics of pre- and postoperative standing SS

	Pre-SS $_{standing}$	**Post-SS $_{standing}$**	**p-value**
Mean ± SD	40.94±10.55	42.91±9.87	<0.001*
95% confidence interval	39.44-42.44	41.51-44.31	
Percentiles			
5%	22.43	26.65	
10%	28.90	30.12	
25%	33.85	36.55	
50%	41.10	42.90	
75%	47.10	49.45	
90%	55.42	55.14	
95%	59.64	58.78	

*Significant difference

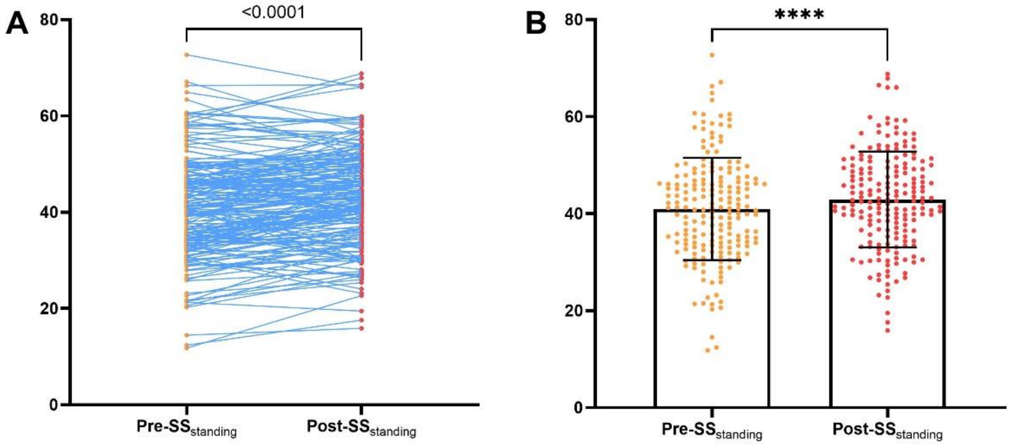

Figure 15. Descriptive statistics of pre- and postoperative standing SS.

Table 17. Descriptive statistics of pre- and postoperative sitting SS

	Pre-SS sitting	**Post-SS sitting**	**p-value**
Mean ± SD	22.92±12.04	20.51±12.26	<0.001*
95% confidence interval	21.21-24.63	18.77-22.25	
Percentiles			
5%	4.15	1.86	
10%	8.02	5.58	
25%	15.40	12.35	
50%	22.20	19.70	
75%	29.95	29.15	
90%	38.70	35.36	
95%	46.22	42.42	

*Significant difference

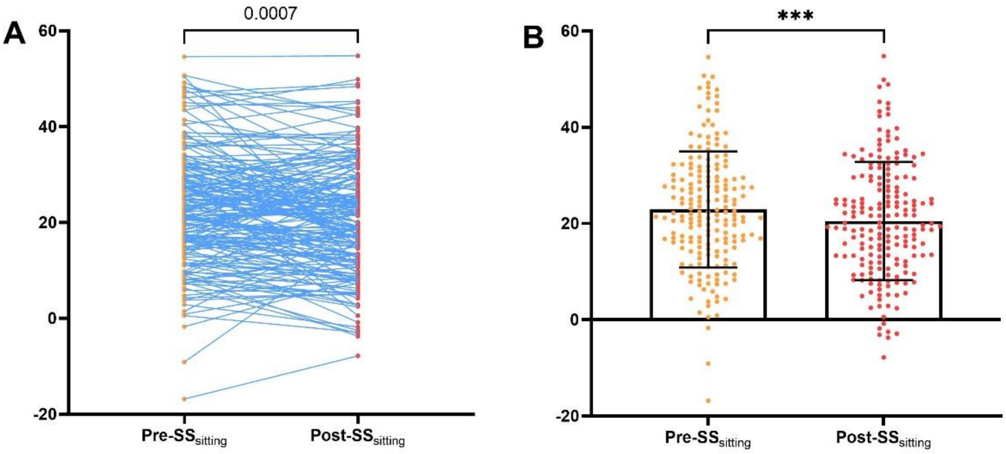

Figure 16. Descriptive statistics of pre- and postoperative sitting SS.

Table 18. Descriptive statistics of pre- and postoperative ∆SS

	Pre-∆SS	Post-∆SS	p-value
Mean ± SD	18.02±10.18	22.40±10.28	<0.001*
95% confidence interval	16.57-19.46	20.94-23.86	
Percentiles			
5%	3.31	7.17	
10%	4.88	9.82	
25%	10.40	14.80	
50%	18.00	20.90	
75%	24.10	29.75	
90%	30.68	36.28	
95%	38.39	40.33	

*Significant difference

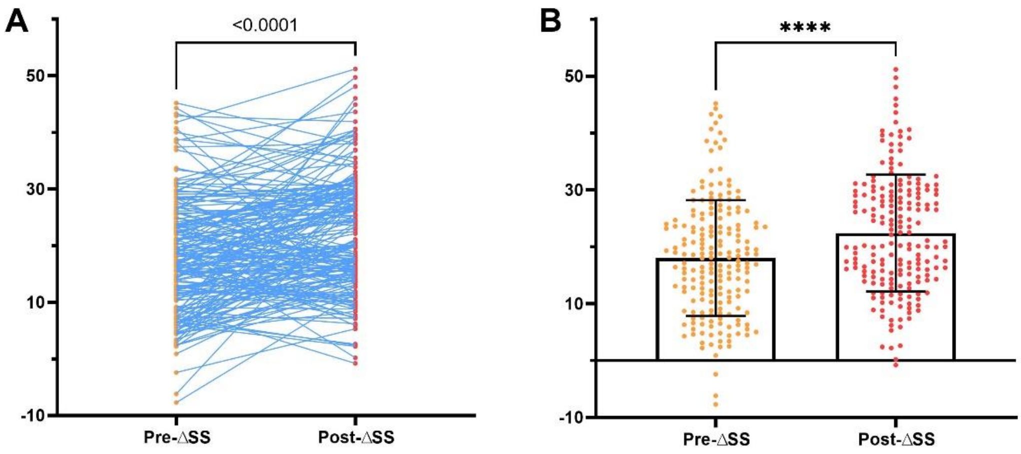

Figure 17. Descriptive statistics of pre- and postoperative ΔSS.

3.3.2. Effect of coronal and sagittal spinal malalignment on pelvic motion

Coronal alignment: No significant difference was found in pre- and postoperative pelvic motion between the C7-CSVL balance group and the C7-CSVL imbalance group (**Table 19**). **Sagittal alignment:** There was no significant difference in pre- and postoperative pelvic motion between the C7-SVA balance group and the C7-SVA imbalance group (**Table 20**).

Table 19. The effect of preoperative C7-CSVL imbalance on pelvic motion

		C7-CSVL		p-value
		Balanced(n=165)	Imbalanced(n=28)	
Pre-op	‡SS $_{standing}$	41.13±10.38	39.86±11.67	0.560
	†SS $_{sitting}$	23.26±11.42	20.93±15.28	0.445
	‡ΔSS	17.86±10.08	18.94±10.87	0.607
Post-op	‡SS $_{standing}$	43.11±9.56	41.78±11.64	0.512
	†SS $_{sitting}$	19.70(15.75)	18.45(25.02)	0.728
	†ΔSS	20.60(14.80)	23.70(16.93)	0.714

Δ=standing-sitting

†The variables in these subgroups were not normally distributed, so the Mann-Whitney U test was conducted to calculate the difference between subgroups, and the median (IQR) was used to describe the statistical distribution.

‡The variables in these subgroups were normally distributed, so the unpaired t-test was conducted to calculate the difference between subgroups. The mean(±SD) was used to describe the statistical distribution.

Table 20. The effect of preoperative C7-SVA imbalance on pelvic motion

		C7-SVA		p-value
		Balanced(n=96)	Imbalanced(n=97)	
Pre-op	†SS $_{standing}$	41.15(12.05)	40.80±15.90	0.976
	‡SS $_{sitting}$	23.34±11.28	22.51±12.80	0.631
	†ΔSS	17.10(11.85)	18.80(14.95)	0.611
Post-op	‡SS $_{standing}$	43.41±9.56	42.42±10.19	0.486
	†SS $_{sitting}$	20.70(16.13)	19.40(18.60)	0.992
	‡ΔSS	23.06±10.01	21.75±10.56	0.375

Δ=standing-sitting

†The variables in these subgroup were not normally distributed, so the Mann-Whitney U test was conducted to calculate the difference between subgroups, and the median (IQR) was used to describe the statistical distribution.

‡The variables in these subgroups were normally distributed, so the unpaired t-test was conducted to calculate the difference between subgroups. The mean(±SD) was used to describe the statistical distribution.

3.3.3. The effect of pelvic mobility on the postoperative CSI

No significant difference was found in postoperative CSI $_{standing}$ between different **preoperative** pelvic mobility groups (stiff/normal/hypermobile, p=0.291) and in postoperative CSI $_{sitting}$ between the stiff and the normal group (p=0.086) (**Table 21**).

The proportion of patients with stiff pelvic mobility decreased significantly after THA, from 23.3% (45/193) to 9.8% (19/193), while the proportion of patients in the hypermobile category increased significantly, from 10.4% (20/193) to 21.2% (41/193) (p<0.001). A significant difference in CSI $_{standing}$ was found between groups according to **postoperative** pelvic mobility (p=0.036). CSI $_{sitting}$ in the stiff group was significantly lower than in the normal and hypermobile groups (stiff/normal 166.2/179.4, p=0.005; stiff/hypermobile 166.2/201.8, p<0.001). No significant difference was found in PFA $_{sitting}$ between the stiff group and normal group based on postoperative pelvic mobility (p=0.067). AI $_{sitting}$ in the stiff group was statistically lower than in the normal and hypermobile groups (stiff/normal 48.9/55.3, p=0.013; stiff/hypermobile 48.9/69.4, p<0.001) (**Table 22**).

Table 21. Comparison of the effect of preoperative pelvic mobility imbalance on postoperative CSI

Post-op	Preoperative pelvic mobility			p-value	p-value, pairwise comparisons		
	Stiff (N=45)	Normal (N=128)	Hypermobile (N=20)		Stiff vs. Normal	Stiff vs. Hypermobile	Normal vs. Hypermobile
†$PFA_{standing}$	175.90(13.70)	176.05(14.40)	174.15(9.90)	0.541	-	-	-
†$PFA_{sitting}$	124.20(21.30)	124.20(13.57)	129.85(21.17)	0.088	-	-	-
†ΔPFA	56.50(23.75)	51.75(17.80)	41.00(13.63)	0.005*	0.617	0.003*	0.018*
‡$AI_{standing}$	32.33±8.49	33.58±9.94	31.21±8.12	0.493	-	-	-
‡$AI_{sitting}$	52.94±11.79	58.10±12.01	65.58±9.03	<0.001*	0.012*	<0.001*	0.009*
‡ΔAI	-20.61±9.88	-24.52±9.12	-34.37±10.59	<0.001*	0.018*	<0.001*	<0.001*
†$CSI_{standing}$	207.60(17.25)	208.80(17.92)	205.25(10.00)	0.291	-	-	-
‡$CSI_{sitting}$	175.25±22.61	183.29±17.73	196.95±18.18	0.001*	0.086	<0.001*	0.012*

Δ=standing-sitting; CSI=PFA+AI.

*Significant difference

†The variables in these subgroups were not normally distributed, so the Kruskal-Wallis H test was conducted to calculate the difference between subgroups, and the Bonferroni test was conducted for post hoc analysis. The median (IQR) was used to describe statistical distribution.

‡The variables in these subgroups were normally distributed, so the one-way analysis of variance (ANOVA) was conducted to calculate the difference between subgroups, and the Bonferroni test was conducted for post hoc analysis. The mean (±SD) was used to describe statistical distribution.

Table 22. Comparison of the effect of postoperative pelvic mobility imbalance on postoperative CSI

Post-op	Postoperative pelvic mobility			p-value	p-value, pairwise comparisons		
	Stiff (N=19)	Normal (N=133)	Hypermobile (N=41)		Stiff vs. Normal	Stiff vs. Hypermobile	Normal vs. Hypermobile
†$PFA_{standing}$	177.20(12.50)	176.70(13.10)	172.20(11.90)	0.002*	1.000	0.028*	0.002*
†$PFA_{sitting}$	114.20(14.50)	123.80(14.00)	130.40(12.85)	<0.001*	0.067	<0.001*	<0.001*
†ΔPFA	61.80(15.20)	54.10(18.50)	37.10(15.65)	<0.001*	0.040*	<0.001*	<0.001*
‡$AI_{standing}$	36.58±9.53	32.24±9.40	34.00±9.29	0.133	-	-	-
‡$AI_{sitting}$	48.92±10.34	55.30±10.37	69.41±10.35	<0.001*	0.013*	<0.001*	<0.001*
‡ΔAI	-12.34±6.85	-23.06±7.91	-35.41±7.99	<0.001*	<0.001*	<0.001*	<0.001*
†$CSI_{standing}$	216.20(20.40)	208.30(18.70)	205.70(11.10)	0.036*	0.508	0.044*	0.168
‡$CSI_{sitting}$	166.22±15.00	179.35±17.95	201.80±13.33	<0.001*	0.005*	<0.001*	<0.001*

Δ=standing-sitting; CSI=PFA+AI.
*Significant difference
†The variables in these subgroups were not normally distributed, so the Kruskal-Wallis H test was conducted to calculate the difference between subgroups, and the Bonferroni test was conducted for post hoc analysis. The median (IQR) was used to describe statistical distribution.
‡The variables in these subgroups were normally distributed, so one-way analysis of variance (ANOVA) was conducted to calculate the difference between subgroups, and the Bonferroni test was conducted for post hoc analysis. Mean (±SD) was used to describe statistical distribution.

3.3.4. Correlation between postoperative pelvic motion and preoperative spinopelvic factors

The preoperative factors correlating with **postoperative SS $_{standing}$** were BMI, LL $_{standing}$, LL $_{sitting}$, ΔLL, SS $_{standing}$, SS $_{sitting}$, PI $_{standing}$ and PI $_{sitting}$. LL $_{standing}$ and SS $_{standing}$ were strongly correlated to postoperative SS $_{standing}$ (r=0.744 and r=0.829, respectively).

The preoperative factors correlating with **postoperative SS $_{sitting}$** were age, TK $_{sitting}$, ΔTK, LL $_{standing}$, LL $_{sitting}$, ΔLL, SS $_{standing}$, SS $_{sitting}$, ΔSS, PI $_{standing}$, PI $_{sitting}$, AI $_{sitting}$ and ΔAI. LL $_{sitting}$ and SS $_{sitting}$ correlated well with postoperative SS $_{sitting}$ (r=0.664 and r=0.654, respectively).

The preoperative factors correlating with **postoperative ΔSS** were age, ΔTK, LL $_{sitting}$, ΔLL, SS $_{standing}$, SS $_{sitting}$, ΔSS, PFA $_{standing}$, PFA $_{sitting}$, ΔPFA, AI $_{standing}$, AI $_{sitting}$ and ΔAI. ΔLL and ΔSS were moderately correlated to postoperative ΔSS (**Table 23**).

Table 23. Correlation between postoperative pelvic motion and preoperative spinopelvic factors

	Postoperative pelvic motion					
	SS $_{standing}$		SS $_{sitting}$		ΔSS	
Pre-op factors	r value	p-value	r value	p-value	r value	p-value
Age	-0.136	0.059	0.226	0.002*	-0.395	<0.001*
BMI	-0.157	0.030*	-0.120	0.097	0.014	0.851
TK $_{sitting}$	0.056	0.441	0.188	0.009*	-0.132	0.066
ΔTK	-0.008	0.914	-0.157	0.029*	0.147	0.042*
LL $_{standing}$	0.744	<0.001*	0.478	<0.001*	0.112	0.121

$LL_{sitting}$	0.538	<0.001*	0.664	<0.001*	-0.261	<0.001*
ΔLL	0.151	0.036*	-0.256	<0.001*	0.433	<0.001*
$SS_{standing}$	0.829	<0.001*	0.457	<0.001*	0.206	0.004*
$SS_{sitting}$	0.599	<0.001*	0.654	<0.001*	-0.209	0.004*
ΔSS	0.125	0.084	-0.275	<0.001*	0.448	<0.001*
$PFA_{standing}$	-0.032	0.663	0.119	0.099	-0.194	0.007*
$PFA_{sitting}$	0.134	0.064	-0.072	0.319	0.197	0.006*
ΔPFA	-0.117	0.105	0.137	0.057	-0.280	<0.001*
$PI_{standing}$	0.652	<0.001*	0.494	<0.001*	0.007	0.924
$PI_{sitting}$	0.664	<0.001*	0.493	<0.001*	0.011	0.884
$AI_{standing}$	-0.044	0.541	0.136	0.059	-0.190	0.008*
$AI_{sitting}$	0.039	0.590	-0.165	0.022*	0.222	0.002*
ΔAI	-0.096	0.185	0.269	<0.001*	-0.390	<0.001*

0.7</r/<1 indicated ‘strong’ correlation; 0.5</r/<0.7 indicated ‘good’ correlation; 0.3</r/<0.5 indicated ‘fair’ or ‘moderate’ correlation; /r/<0.3 indicated ‘poor’ correlation(121).

*Significant correlation

Spearman’s rank correlation coefficient was used to analyze the correlation between postoperative pelvic motion and preoperative spinopelvic factors.

3.3.5. Multiple linear regression analysis

To avoid multicollinearity among independent variables, the correlation among preoperative factors was evaluated using Spearman’s rank correlation coefficient before performing multiple regression analysis. Among the independent variables related to the dependent variable, we screened out all the couple independent variables that strongly correlated (r>0.7) with each other, and one of them was reserved in the multiple regression analysis as needed.

For **postoperative $SS_{standing}$** as the dependent variable, the preoperative independent variables involved in the regression analysis were as follows: BMI, $SS_{standing}$, $SS_{sitting}$, ΔLL, the extent of contralateral hip osteoarthritis, and the extent of degenerative intervertebral disc disease.

For **postoperative SS $_{sitting}$** as the dependent variable, the preoperative independent variables involved in the regression analysis were as follows: Age, TK $_{sitting}$, ∆TK, SS $_{standing}$, SS $_{sitting}$, AI $_{sitting}$, the extent of contralateral hip osteoarthritis, and the extent of degenerative intervertebral disc disease.

For **postoperative ∆SS** as the dependent variable, the preoperative independent variables involved in the regression analysis were as follows: Age, ∆TK, ∆SS, PFA $_{standing}$, PFA $_{sitting}$, AI $_{standing}$, AI $_{sitting}$, the extent of contralateral hip osteoarthritis, and the extent of degenerative intervertebral disc disease.

When conducting the multiple regression analysis, we observed that the Durbin-Watson values were all below 2, and the VIF values of all independent variables were around 1, which confirmed that there was no strong correlation or collinearity among the independent variables.

Based on the multiple linear regression analysis results (**Table 24**), the prediction formula of postoperative SS $_{standing}$ was: 11.354 + (0.724 × pre-SS $_{standing}$) + (0.187 × pre-SS $_{sitting}$) + (0.080 × KL grade of contra-lateral hip (Grade 4)). This regression model was statistically significant (F=147.383, p<0.001). The independent variable in the equation explains 75.3% of the variation in the dependent variable (adjusted R^2=0.753). Postoperative SS $_{standing}$ and preoperative SS $_{standing}$, as well as postoperative SS $_{standing}$ and preoperative SS $_{sitting}$, were positively correlated (**Figure 18**).

Based on the multiple linear regression analysis' results (**Table 25**), the prediction formula of postoperative SS $_{sitting}$ was: -14.409 + (0.223 × pre-SS $_{standing}$) + (0.559 × pre-SS $_{sitting}$) + (0.191 × age) - (0.144 × KL grade of contra-lateral hip (Grade 4)). This regression model was statistically significant (F=21.861, p<0.001). The independent variable in the equation explains 54.4% of the variation in the dependent variable (adjusted R^2=0.544). The postoperative SS $_{sitting}$ and age as well as preoperative SS $_{standing}$, and preoperative SS $_{sitting}$, showed a significant positive correlation (**Figure 19**).

Based on the results of the multiple linear regression analysis (**Table 26**), the prediction formula of postoperative ∆SS was: 30.509 + (0.401 × pre-∆SS) - (0.308 × age)

+ (0.227 × KL grade of contra-lateral hip (Grade 4)) + (0.122 ×KL grade of lumbar spine (Grade 1)). This regression model was statistically significant (F=8.025, p<0.001). The independent variable in the equation explains 38.2% of the variation in the dependent variable (adjusted R^2=0.382). The pre- and postoperative ΔSS were positively correlated, whereas the postoperative ΔSS and age were negatively correlated (**Figure 20**).

Table 24. Multiple linear regression analysis for predicting postoperative standing SS

Variables	Multiple linear regression analysis model (R^2 =0.753)			
	Unstandardized coefficients		Standardized coefficients	p-value
	B	SE	β	
Intercept	11.354	1.438	-	-
KL grade of contra-lateral hip (Grade 4)	3.146	1.431	0.080	0.029*
$SS_{standing}$	0.677	0.042	0.724	<0.001*
$SS_{sitting}$	0.153	0.037	0.187	<0.001*

* Statistically significant

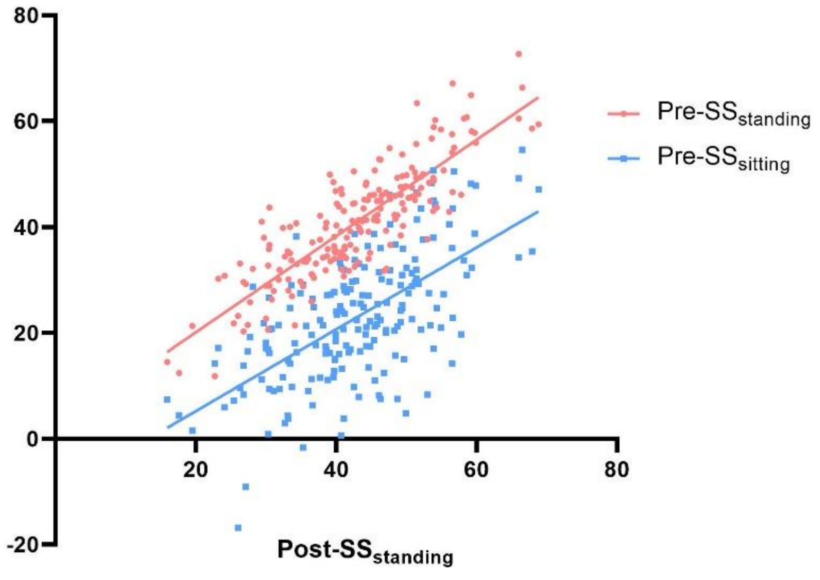

Figure 18. Illustration of the linear relationship between pre- and postoperative standing SS as well as postoperative standing SS and preoperative sitting SS.

Table 25. Multiple linear regression analysis for predicting postoperative sitting SS

Variables	Multiple linear regression analysis model (R^2 =0.544)			
	Unstandardized coefficients		Standardized coefficients	p-value
	B	SE	β	
Intercept	-14.409	4.182	-	-
KL grade of contra-lateral hip (Grade 4)	-7.023	2.489	-0.144	0.005*
Age	0.182	0.052	0.191	0.001*
$SS_{sitting}$	0.569	0.063	0.559	<0.001*
$SS_{standing}$	0.259	0.075	0.223	0.001*

* Statistically significant

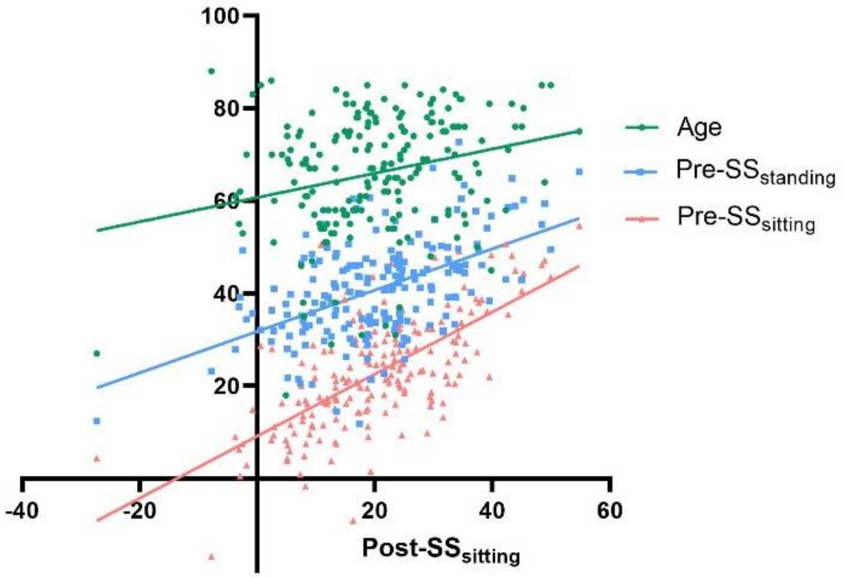

Figure 19. Illustration of the linear relationship between postoperative sitting SS and preoperative standing SS, preoperative sitting SS, and age.

Table 26. Multiple linear regression analysis for predicting postoperative ΔSS

Variables	Multiple linear regression analysis model (R^2 =0.382)			
	Unstandardized coefficients		Standardized coefficients	p-value
	B	SE	β	
Intercept	30.509	3.472	-	-
KL grade of contra-lateral hip (Grade 4)	9.288	2.352	0.227	<0.001*
KL grade of lumbar spine (Grade 1)	7.224	3.393	0.122	0.035*
Age	-0.246	0.047	-0.308	<0.001*
ΔSS	0.406	0.058	0.401	<0.001*

OA osteoarthritis; DDD degenerative intervertebral disc disease.

* Statistically significant

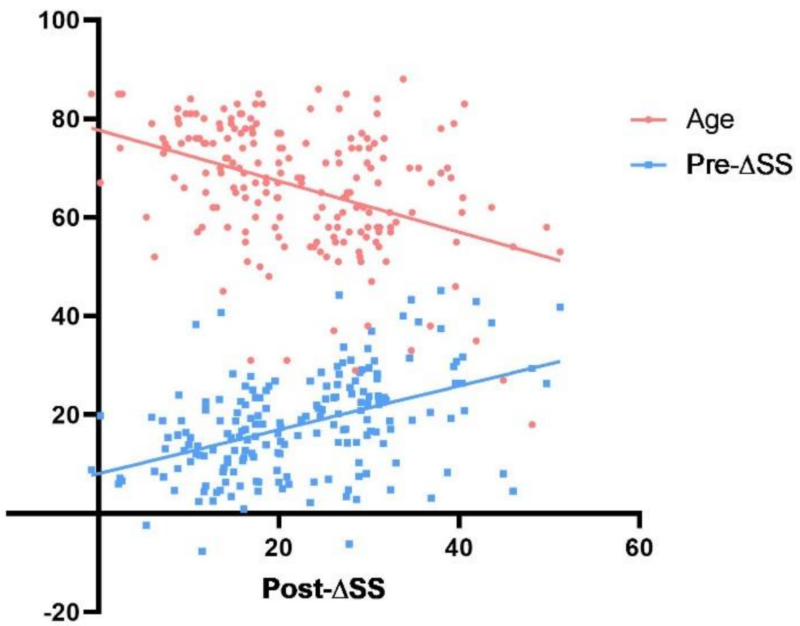

Figure 20. Illustration of the linear relationship between postoperative ΔSS and age at surgery, as well as pre- and postoperative ΔSS.

3.3.6. Prediction of postoperative stiff pelvic mobility and kyphotic hypermobility

In predicting postoperative stiff pelvic mobility, the performance of **age** was fair

(AUC=0.723, p=0.001, 95% CI = 0.611 to 0.835). The optimum threshold for age was ≥73.0 years old with the Youden index at the top point (0.415). This cutoff point demonstrated 73.7% sensitivity and 67.8% specificity in predicting postoperative stiff pelvic mobility.

The predictive performance of the **preoperative ∆SS** was poor (AUC=0.688, p=0.007, 95% CI =0.589 to 0.787). The optimum threshold for preoperative ∆SS was ≤20.2°, where the Youden index was biggest (0.384). This optimum threshold demonstrated 43.7% sensitivity and 94.7% specificity in predicting postoperative stiff pelvic mobility. **The combined factors** had a good diagnostic performance (AUC=0.850, p<0.001, 95% CI = 0.782 to 0.918). The optimum threshold of the combined factors was age at surgery ≥74 years old, pre-∆SS ≤7.5° and KL grade of lumbar spine ≥2, with an 84.2% sensitivity and 75.9% specificity. (**Table 27, Figure 21**).

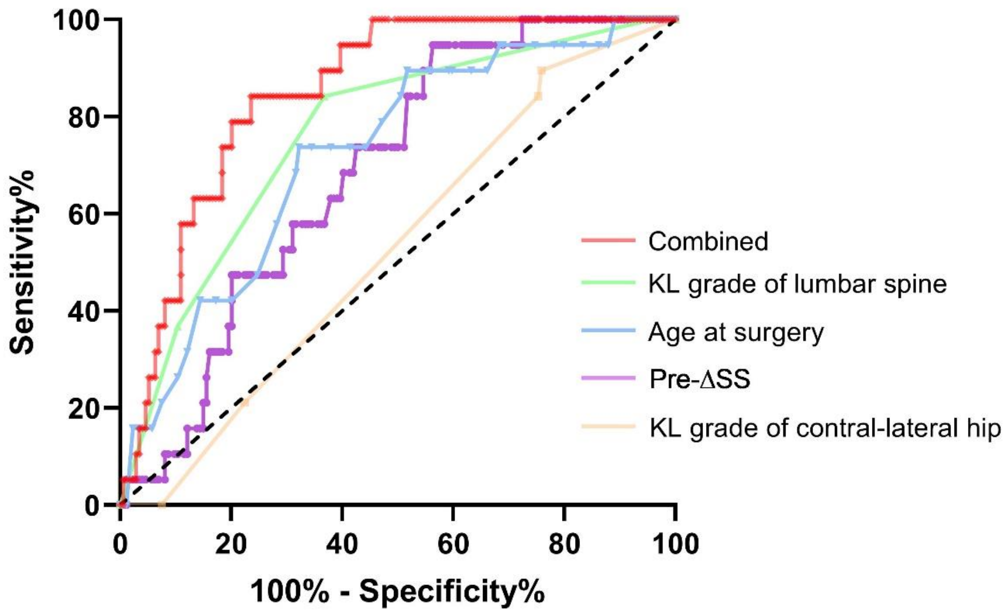

Figure 21. ROC for predicting postoperative stiff pelvic mobility.

Table 27. The performance of preoperative factors to predict postoperative stiff pelvic mobility

Pre-op factors	AUC	95% Confidence interval	p-value
Age(years)	0.723	0.611-0.835	0.001
∆SS	0.688	0.589-0.787	0.007
KL grade of contra-lateral hip	0.528	0.407-0.648	0.692
KL grade of lumbar spine	0.765	0.658-0.872	<0.001
***Combined**	**0.850**	**0.782-0.918**	**<0.001**

* The optimum threshold of the combined factors was age at surgery ≥74 years old, pre-∆SS ≤7.5° and KL grade of lumbar spine ≥2, with an 84.2% sensitivity and 75.9% specificity.

The interpretation of AUC was as follows: 0.9-1 indicated 'excellent' performance, 0.8-0.9 indicated 'good' performance, 0.7-0.8 demonstrated 'fair' performance, 0.6-0.7 presented 'poor' performance, and 0.5-0.6 denoted 'failed' performance(122).

The performance of the **preoperative ∆SS** was fair (AUC=0.727, p=0.016, 95% CI=0.539 to 0.915) in predicting postoperative kyphotic hypermobility. The optimum threshold for preoperative ∆SS was ≥ 29.4°, where the Youden index was at the top point (0.447). This cutoff point demonstrated a sensitivity of 54.9% and a specificity of 90.1% in predicting postoperative kyphotic hypermobility.

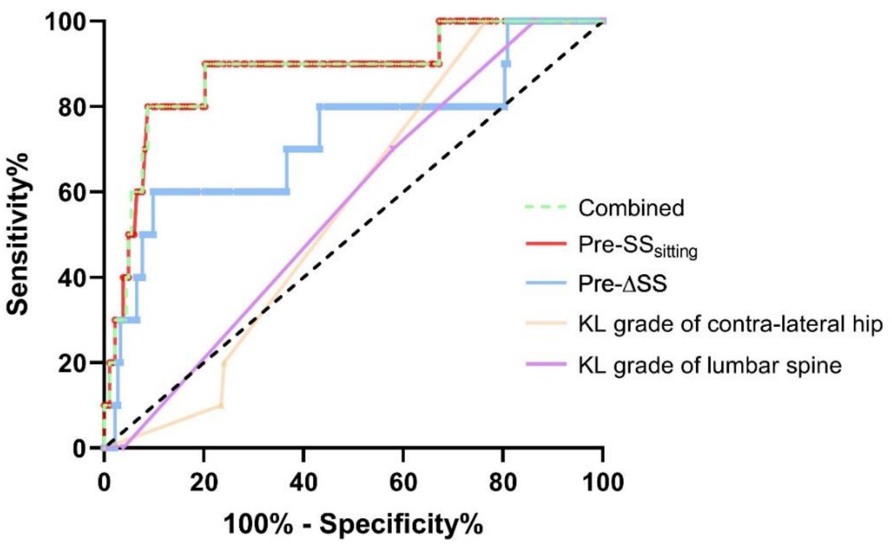

Figure 22. ROC for predicting postoperative kyphotic hypermobility.

The predictive performance of the **preoperative SS $_{sitting}$** was good (AUC=0.878, p<0.001, 95% CI =0.757 to 0.999). The optimum threshold for preoperative SS $_{sitting}$ was ≤ 9.2°, where the Youden index was maximum (0.662). This optimum threshold demonstrated 80.0% sensitivity, 91.3% specificity in predicting postoperative kyphotic hypermobility.

The combination of preoperative SS $_{sitting}$ and ∆SS also had a good diagnostic performance (AUC=0.878, p<0.001, 95% CI = 0.757 to 0.999). The combined factors had similar diagnostic performance with **preoperative SS $_{sitting}$.** (**Table 28, Figure 22**).

Table 28. The performance of preoperative factors to predict postoperative kyphotic hypermobility

Pre-op factors	**AUC**	**95% Confidence interval**	**p-value**
∆SS	0.727	0.539-0.915	0.016
***SS sitting**	**0.878**	**0.757-0.999**	**<0.001**
KL grade of contra-lateral hip	0.562	0.432-0.693	0.508
KL grade of lumbar spine	0.568	0.414-0.721	0.473
#Combined	0.878	0.757-0.999	<0.001

#Combined： the combination of ∆SS and SS sitting.

*The optimum threshold of pre-SS sitting was ≤9.2°, with an 80.0% sensitivity and 91.3% specificity.

The interpretation of AUC was as follows: 0.9-1 indicated 'excellent' performance, 0.8-0.9 indicated 'good' performance, 0.7-0.8 demonstrated 'fair' performance, 0.6-0.7 presented 'poor' performance, and 0.5-0.6 denoted 'failed' performance(122).

3.4. The influence of PI on pelvic motion and hip motion

3.4.1. Pre- and postoperative pelvic mobility imbalance by PI group

There was no significant difference between the PI groups in the preoperative frequency of pelvic mobility imbalance (p=0.070) (**Table 29**). The number of patients with kyphotic hypermobility after surgery increased from 7 to 10, while the number of patients with stiff pelvic mobility dropped from 45 to 19. No significant difference was found between the PI groups in the postoperative frequency of pelvic mobility imbalance (p=0.149) (**Table 30**).

Table 29. Preoperative pelvic mobility imbalance divided by PI group

	Low PI	**Normal PI**	**High PI**	**Total**
	N=26	N=128	N=39	N=193
Kyphotic Hypermobile	3	4	0	7
Stiff	9	28	8	45
Total	12	32	8	52

Table 30. Postoperative pelvic mobility imbalance divided by PI group

	Low PI	**Normal PI**	**High PI**	**Total**
	N=26	N=128	N=39	N=193
Kyphotic Hypermobile	3	6	1	10
Stiff	5	10	4	19
Total	8	16	5	29

3.4.2. Pre- and postoperative abnormal hip motion by PI group

In the preoperative distribution of abnormal hip motion, a significant difference was found between PI groups (p<0.001) (**Table 31**). The proportion of over-flexion abnormalities in the low PI group was significantly higher than in the other two groups. Although the proportion of hyperextension abnormalities in the high PI group was significantly higher than in the normal PI group, the proportion did not significantly differ between the low PI group and the high PI group.

The quantity of the hip hyperextension and over-flexion abnormalities decreased after surgery. A statistically significant difference was observed in the postoperative distribution of abnormal hip motion between PI groups (P=0.002) (**Table 32**). There was no significant difference in the distribution of hyperextension abnormalities between the three groups, but the proportion of over-flexion abnormalities was significantly greater in the low PI group than in the other two groups.

Table 31. Preoperative abnormal hip motion divided by PI group

	Low PI	Normal PI	High PI	Total
	N=26	N=128	N=39	N=193
Hyperextension	0[a, b]	2[b]	7[a]	9
Over-flexion	10[a]	20[b]	3[b]	33
Total	10	22	10	42

Letters a and b work as markers of significant difference. A different letter in the same column denotes a subset of PI categories whose column proportions differ significantly from each other at the 0.05 level.

Table 32. Postoperative abnormal hip motion divided by PI group

	Low PI	Normal PI	High PI	Total
	N=26	N=128	N=39	N=193
Hyperextension	0[a]	3[a]	3[a]	6
Over-flexion	8[a]	9[b]	1[b]	18
Total	8	12	4	24

Letters a and b work as markers of significant difference. A different letter in the same column denotes a subset of PI categories whose column proportions differ significantly from each other at the 0.05 level.

3.4.3. Pre- and postoperative pelvic motion and hip motion by PI group

The comparison of pre- and postoperative pelvic motion and hip motion between the three PI groups is shown in **Tables 33** and **34**. There was no significant effect of PI on pelvic mobility (ΔSS) or hip mobility (ΔPFA) before and after THA. We found that the pre/post-SS $_{sitting}$, pre/post-PFA $_{sitting}$, and CSI $_{sitting}$ in the low PI group were significantly lower than in the other groups, whereas the postoperative AI $_{sitting}$ had no significant difference with the other groups. The pre/post-SS $_{standing}$, pre/post-PFA $_{standing}$, and CSI $_{standing}$ in the high PI group was significantly greater than in the other groups. There was no significant difference in the postoperative AI $_{standing}$ between the three groups.

Table 33. Comparison of preoperative pelvic motion and hip motion divided by PI group

	PI Group			p-value	p-value, pairwise comparisons		
Pre-op	Low (N=26)	Normal (N=128)	High (N=39)		Low vs. Normal	Low vs. High	Normal vs. High
†**SS** standing	30.75(8.82)	40.95(11.85)	49.80(14.90)	<0.001*	<0.001*	<0.001*	<0.001*
‡**SS** sitting	12.18±9.76	21.89±10.06	33.49±11.60	<0.001*	<0.001*	<0.001*	<0.001*
‡**ΔSS**	16.84±11.16	18.31±9.90	17.85±10.59	0.795	-	-	-
‡**PFA** standing	172.58±9.94	178.22±9.72	187.36±12.04	<0.001*	0.011*	<0.001*	<0.001*
†**PFA** sitting	112.40(19.75)	122.40(17.15)	131.10(13.40)	<0.001*	0.045*	<0.001*	0.004*
†**ΔPFA**	58.20(25.53)	56.65(20.23)	56.10(19.80)	0.872	-	-	-

†The variables in these subgroups were not normally distributed, so the Kruskal-Wallis H test was conducted to calculate the difference between subgroups, and the Bonferroni test was conducted for post hoc analysis. The median (IQR) was used to describe the statistical distribution.

‡The variables in these subgroups were normally distributed, so one-way analysis of variance (ANOVA) was conducted to calculate the difference between subgroups, and the Bonferroni test was conducted for post hoc analysis. The mean(±SD) was used to describe the statistical distribution.

*Significant difference

Table 34. Comparison of postoperative pelvic motion and hip motion divided by PI group

	PI Group			p-value	p-value, pairwise comparisons		
Post-op	Low (N=26)	Normal (N=128)	High (N=39)		Low vs. Normal	Low vs. High	Normal vs. High
‡**SS** standing	31.32±7.44	42.51±8.04	51.96±7.93	<0.001*	<0.001*	<0.001*	<0.001*
†**SS** sitting	13.05(14.50)	18.85(14.40)	29.90(17.00)	<0.001*	0.039*	<0.001*	<0.001*
†**ΔSS**	18.60(15.18)	24.05(15.22)	19.90(13.70)	0.233	-	-	-
†**PFA** standing	167.05(13.37)	174.85(11.03)	183.50(12.80)	<0.001*	0.004*	<0.001*	<0.001*
†**PFA** sitting	115.05(18.13)	124.40(13.10)	129.40(19.70)	<0.001*	0.004*	<0.001*	0.021*
†**ΔPFA**	50.90(19.70)	50.05(19.82)	51.40(18.30)	0.590	-	-	-
‡**AI** standing	32.87±11.20	32.22±9.00	35.87±9.29	0.105	-	-	-
‡**AI** sitting	57.31±14.31	57.37±11.77	58.88±11.98	0.785	-	-	-
‡**ΔAI**	-24.44±9.75	-25.16±9.65	-23.01±11.77	0.510	-	-	-

†CSI standing	203.60(32.63)	207.15(14.50)	219.60(20.10)	<0.001*	0.525	<0.001*	<0.001*
‡CSI sitting	172.65±23.02	182.58±18.60	190.41±18.60	0.002*	0.017*	<0.001*	0.027*

†The variables in these subgroups were not normally distributed, so the Kruskal-Wallis H test was conducted to calculate the difference between subgroups, and the Bonferroni test was conducted for post hoc analysis. The median (IQR) was used to describe statistical distribution.
‡The variables in these subgroups were normally distributed, so one-way analysis of variance (ANOVA) was conducted to calculate the difference between subgroups, and the Bonferroni test was conducted for post hoc analysis. Mean (±SD) was used to describe statistical distribution.
*Significant difference

3.4.4. Pre- and postoperative pelvic motion and hip motion by PI-LL mismatch group

Patients in the PI-LL mismatch imbalanced group had significantly higher pre/post-PFA $_{standing}$ and CSI $_{standing}$ than the PI-LL mismatch balanced group. However, the postoperative AI $_{standing}$ did not differ significantly between the two groups (p=0.105). Although patients with PI-LL mismatch imbalance had greater pre/post-PFA $_{sitting}$, no significant difference was found in the CSI $_{sitting}$ between the two groups (P=0.175) (**Table 35**).

Table 35. The effect of preoperative PI-LL mismatch on pelvic motion and hip motion

		PI-LL mismatch		**p-value**
		Balanced(n=133)	Imbalanced(n=60)	
Pre-op	‡SS standing	41.38±9.76	39.98±12.16	0.434
	‡SS sitting	23.18±11.30	22.37±13.64	0.666
	‡ΔSS	18.20±10.04	17.61±10.54	0.710
Post-op	‡SS standing	43.62±9.26	41.34±11.01	0.137
	†SS sitting	20.00(15.70)	19.20(19.63)	0.946
	‡ΔSS	23.27±10.21	20.49±10.28	0.082
Pre-op	‡PFA standing	176.86±10.18	184.73±11.33	<0.001*
	‡PFA sitting	121.02±12.82	128.30±12.99	<0.001*
	‡ΔPFA	55.83±15.00	56.44±16.56	0.802
Post-op	†PFA standing	173.50(11.90)	179.80(10.38)	<0.001*

	‡PFA $_{sitting}$	123.27±11.63	129.33±13.57	0.003*
	†ΔPFA	50.90(18.90)	51.30(19.67)	0.682
	‡AI $_{standing}$	32.30±9.18	34.69±9.87	0.105
	‡AI $_{sitting}$	58.25±12.70	56.38±10.77	0.321
	‡ΔAI	-25.95±9.80	-21.69±10.23	0.006*
	†CSI $_{standing}$	206.00(15.70)	216.20(18.10)	<0.001*
	‡CSI $_{sitting}$	181.53±20.18	185.71±18.79	0.175

*Significant difference

Δ=standing-sitting.

†The variables in these subgroups were not normally distributed, so the Mann-Whitney U test was conducted to calculate the difference between subgroups, and the median (IQR) was used to describe the statistical distribution.

‡The variables in these subgroups were normally distributed, so the unpaired t-test was conducted to calculate the difference between subgroups. Mean(±SD) was used to describe the statistical distribution.

3.4.5. Correlation between pelvic incidence and spinopelvic factors

PI had a strong correlation with SS $_{standing}$, a good correlation with PT $_{standing}$, SS $_{sitting}$, LL $_{standing}$, and LL $_{sitting}$, a moderate correlation with PT $_{sitting}$, CSI $_{standing}$, PFA $_{standing}$, and PFA $_{sitting}$, and a poor correlation with CSI $_{sitting}$, but did not correlate with the motion of the acetabular component or the mobility of the spine, pelvis, and hip when changing the position from standing to sitting (**Table 36**).

Table 36. Correlation between pelvic incidence and spinopelvic factors

Pelvic incidence (PI)†					
Pre-op	r value	p-value	**Post-op**	r value	p-value
LL $_{standing}$	0.537	<0.001*	**LL $_{standing}$**	0.546	<0.001*
LL $_{sitting}$	0.528	<0.001*	**LL $_{sitting}$**	0.508	<0.001*
ΔLL	-0.070	0.335	**ΔLL**	-0.029	0.691
SS $_{standing}$	0.705	<0.001*	**SS $_{standing}$**	0.701	<0.001*
SS $_{sitting}$	0.615	<0.001*	**SS $_{sitting}$**	0.547	<0.001*
ΔSS	-0.018	0.801	**ΔSS**	-0.012	0.872
PT $_{standing}$	0.546	<0.001*	**PT $_{standing}$**	0.593	<0.001*
PT $_{sitting}$	0.408	<0.001*	**PT $_{sitting}$**	0.400	<0.001*

ΔPT	0.036	0.617	**ΔPT**	0.106	0.104
PFA $_{standing}$	0.401	<0.001*	**PFA** $_{standing}$	0.480	<0.001*
PFA $_{sitting}$	0.333	<0.001*	**PFA** $_{sitting}$	0.354	<0.001*
ΔPFA	0.018	0.799	**ΔPFA**	0.027	0.713
			AI $_{standing}$	0.075	0.302
			AI $_{sitting}$	-0.031	0.664
			ΔAI	0.108	0.137
			CSI $_{standing}$	0.377	<0.001*
			CSI $_{sitting}$	0.228	0.001*

†PI value was calculated as the mean of pre- and postoperative PI to reduce the measurement bias.

0.7</r/<1 indicates ‘strong’ correlation; 0.5</r/<0.7 indicates ‘good’ correlation; 0.3</r/<0.5 indicates ‘fair’ or ‘moderate’ correlation; /r/<0.3 indicates ‘poor’ correlation(121).

Δ=standing-sitting

*Significant correlation

4. Discussion

4.1. Main summary of the major results

Recent studies have shown that the functional safe zone which is defined by CSI (a combined parameter of PFA and AI) is more reliable in predicting potential hip instability than the Lewinnek safe zone(38, 48). As the orientation of the acetabular component is determined by the surgeon, the PFA becomes the only intrinsic factor directly affecting the functional safe zone. This point of view was confirmed by Tezuka et al.(38), who found that increased hip flexion and extension was the best predictor of the functional safe zone outlier. However, no studies have yet focused on hip motion to screen out patients with a high risk of THA instability. The results of this thesis revealed that when changing from standing to sitting, hip motion may differ after THA, and spinal sagittal imbalance may have influence on these changes. In addition, we not only found the preoperative factors to be related to femoral position and mobility, but also established a ROC model to predict postoperative hyperextension and over-flexion abnormality, which may provide a reference for optimizing the orientation of the acetabular component during operation and the selection of dual mobility prostheses.

Abnormal pelvic mobility may lead to dislocation after THA due to anterior or posterior impingement(48). Therefore, some authors recommend using pelvic mobility to predict the risk of postoperative dislocation and placing the acetabular component according to preoperative pelvic mobility(84, 91). However, scientific evaluation regarding pelvic mobility is still insufficient, and some studies found that pelvic mobility alters after THA(84, 96), which may lead to errors in preoperative clinical decision-making. We confirm this as a significant increase in pelvic mobility after THA was also observed in our study. In addition, we also screened for factors related to postoperative pelvic mobility and established a ROC model to predict postoperative stiff and kyphotic hypermobile pelvic mobility.

Pelvic incidence (PI) is a commonly used anatomical parameter used predominately by spine surgeons, and previous studies confirmed that PI was one of the predictive parameters of impingement risk after THA(38). However, few studies have focused on its effect on spinopelvic motion. Our study revealed that the proportion of patients with over-flexion abnormality was significantly higher in the low PI group than in other groups. In addition, the postoperative $PFA_{sitting}$ and $CSI_{sitting}$ was significantly lower in the low PI group than in other groups, but the postoperative $AI_{sitting}$ did not significantly differ between PI groups. Therefore, the increased hip flexion may put individuals with low PI at risk of posterior impingement following THA. We also found that PI had a moderate correlation with $CSI_{standing}$ and patients with high PI and PI-LL mismatch imbalance have higher $CSI_{standing}$, which may make it easier to break through the upper limit of the functional safe zone in the standing position and lead to hip instability.

4.2. Interpretation of results

4.2.1. Changes in pelvic and hip motion after THA

The functional safe zone is defined based on CSI, which is a combined parameter of femoral position and sagittal acetabular orientation. A postoperative functional safe zone outlier was defined as: standing CSI greater than 243° with an upper AI limit of 45° and an upper PFA limit of 197; sitting CSI less than 151° with a lower AI limit of 41° and a lower PFA limit of 110°(38, 48). Therefore, the orientation of the acetabular component and hip motion are two factors which could directly affect hip stability. Tezuka et al.(38) highlighted preoperative increased hip motion as the best predictor of postoperative functional safe zone outliers. However, our research revealed that although preoperative hip motion is correlated with postoperative hip motion, the hip motion may alter after THA. In line with a previous study(38), we observed approximately 13% of patients with hip hyperextension or over-flexion postoperatively. Approximately 5% of patients had a preoperative hip hyperextension, and this proportion decreased to 3% postoperatively. The proportion of patients with a preoperative hip over-flexion decreased after THA, but was still approximately 10%.

Hip surgeons are challenged to plan surgery in patients with hip hyperextension or over-flexion because the safe zone of sagittal functional anteversion of the acetabular component must be compressed to ensure the acetabular component placement within the functional safe zone. Previous studies have suggested that hip surgeons should place the acetabular component according to preoperative pelvic mobility(84, 94). However, the pelvic motion may change postoperatively(96), and sagittal pelvic mobility is positively correlated with the acetabular component (for every 20° of decreasing of the SS, the AI increases by 17°) (81-83), which makes it difficult to accurately place the acetabular component within a narrower safe zone. In the present study, we found that the magnitude and direction of postoperative pelvic motion changes were unpredictable. The general change trend was that the SS in the standing position increased after THA, the SS decreased in the sitting position, and the pelvic mobility increased. Therefore, when determining the acetabular implant plan based on preoperative pelvic mobility, potential changes in pelvic mobility caused by surgery should be considered, especially when the hip may be hyperextended or over-flexed after surgery.

Multiple studies have confirmed that pelvic stiffness can increase hip motion(44, 87, 123, 124), which may lead to impingement and cause THA instability(87). Although postoperative pelvic mobility is mainly influenced by preoperative mobility, we found that the proportion of patients with stiff pelvic mobility decreased significantly after THA, from 23.3% (45/193) to 9.8% (19/193), while the proportion of patients in the hypermobile category increased significantly, from 10.4% (20/193) to 21.2% (41/193) ($p<0.001$). Previous studies reported similar results that corroborate ours(96, 125). In addition, we found that $CSI_{sitting}$ in the stiff group was significantly lower than in the normal group (stiff/normal 166.2/179.4, $p=0.005$) according to postoperative pelvic mobility categories, while $CSI_{sitting}$ did not significantly differ between the stiff and normal groups based on preoperative pelvic mobility categories. Therefore, preoperative pelvic mobility is not a sufficient reference for assessing the risk of hip instability and guiding acetabular placement.

4.2.2. The influence of sagittal imbalance on hip instability

In the present study, we found that the spinopelvic motion was not affected by coronal but by sagittal imbalance. Previous studies have demonstrated that spinal degeneration decreases lumbar mobility, thereby increasing the risk of instability following THA, but the specific mechanisms have not been exhaustively elucidated(44, 109, 126). C7-SVA is a parameter for assessing the sagittal imbalance of the whole spine(127). In our correlation and multiple linear regression analyses, we observed that preoperative C7-SVA was one of the independent variables affecting postoperative sitting PFA, and the two were positively correlated. In addition, we found that patients in the C7-SVA imbalance group had a significantly higher postoperative $PFA_{sitting}$, but C7-SVA imbalance did not significantly affect the pelvic motion and $PFA_{standing}$.

Less hip flexion while sitting does not increase the risk of hip instability, but it may reduce the incidence of dislocation due to anterior impingement. Therefore, although C7-SVA imbalance could influence hip motion, it cannot be a predictive factor for hip instability. We also used another parameter, the PI-LL mismatch, to assess the effect of sagittal imbalance on the spinopelvic motion. An imbalanced PI-LL mismatch implies a flatback spinal deformity(75, 76). In the present study, we did not observe that PI-LL mismatch imbalance had a notable influence on pelvic or acetabular motion, but found that it increased hip extension, which resulted in a significantly greater CSI in the standing position than in the balanced group, implying that THA with PI-LL mismatch imbalance is more susceptible to anterior dislocation risk due to exceeding the upper limit of the functional safe zone.

Interestingly, by comparing the effects of C7-SVA imbalance and PI-LL mismatch on spinopelvic motion, we found that the PFA in standing position was not significantly affected by C7-SVA imbalance, but was significantly affected by PI-LL mismatch. Compensatory mechanisms for sagittal decompensation may explain this finding. Sagittal imbalance can cause the gravity line to shift forward and trigger a series of compensatory mechanisms to counteract the forward movement of the trunk alignment (45).

Compensation begins with hyperextension of the cervical spine and a decrease in thoracic kyphosis. If this is not enough to offset the malalignment, the pelvis and hip will participate in compensation, manifesting as pelvic retroversion and hip extension to achieve an upright posture and a horizontal gaze (45). We speculate that since C7-SVA is a parameter that assesses the whole sagittal spinal imbalance, the cervical and thoracic spine are involved in compensatory mechanisms that mitigate the effects on the pelvic and femoral position in the early stages of imbalance, so we did not observe significant effects of C7-SVA imbalance on pelvic and hip mobility. In contrast, the PI-LL mismatch positively correlated with PI(128), and our study revealed that PI was one of the independent parameters affecting standing PFA. Therefore, we observed a larger standing PFA in the imbalanced PI-LL mismatch group.

4.2.3. Preoperative factors affecting postoperative pelvic and hip motion

To investigate the preoperative factors that statistically influence postoperative pelvic and hip motion, we performed a multiple linear regression analysis. We found that preoperative factors affecting postoperative PFA in the standing position included the severity of degenerative intervertebral disc disease, the severity of contralateral hip osteoarthritis, PI, and $PFA_{standing}$. Furthermore, preoperative factors affecting postoperative PFA in the sitting position included $SVA_{sitting}$, $PFA_{sitting}$, and the severity of contralateral hip osteoarthritis, while preoperative factors affecting postoperative hip mobility (ΔPFA) included PFA while standing and sitting, and the severity of contralateral hip osteoarthritis. Postoperative SS in the standing position was affected by SS in the standing and sitting position and the severity of contralateral hip osteoarthritis, whereas postoperative SS in the sitting position was affected by age at surgery, SS in the standing and sitting position, and the severity of contralateral hip osteoarthritis. Preoperative factors affecting postoperative pelvic mobility (ΔSS) include age at surgery, pelvic mobility, the severity of degenerative intervertebral disc disease, and the severity of contralateral hip osteoarthritis.

Although further research is needed, the reasons why these preoperative factors affect postoperative pelvic and hip motion may be as follows. Hip flexion contractures and osteoarthritis-related pain in individuals with severe hip osteoarthritis restrict hip motion, particularly extension(125). Under these circumstances, the compensatory mechanism increases SS, and thus increases lumbar spine lordosis in order to maintain an upright posture and achieve a horizontal gaze(88, 89). Therefore, contralateral hip osteoarthritis (grade 4) has a negative effect on standing PFA, but a positive effect on standing SS.

Hip contracture and arthritis-related pain limits hip mobility while triggering compensatory mechanisms in the spinopelvic complex, resulting in increased pelvic mobility (129), which could be a reason why contralateral hip osteoarthritis (Grade 4) has a negative effect on postoperative hip mobility and a positive effect on pelvic mobility. Previous studies corroborate our findings that contralateral hip osteoarthritis is an important determinant of pelvic mobility and that hip mobility improves, pelvic mobility decreases and SS in the sitting position significantly increases after THA(130, 131).

In our multiple regression analysis, we also found preoperative spinal degeneration to be one of the factors influencing postoperative standing PFA, which further supports the argument mentioned above of the effect of PI-LL mismatch imbalance on hip extension. In line with previous studies(44, 124, 132), we also observed that preoperative spinal degeneration may decrease postoperative pelvic mobility.

The anatomical relationship of the pelvis may explain why PI is an influential factor in postoperative standing PFA. The overhang of S1 is defined as the horizontal distance between the bicoxo-femoral axis and the midpoint of the sacral plate, and PI has been shown to positively correlate with this overhang(59). The larger the overhang, the greater the horizontal distance between the center of the trunk and the femoral head, which will recruit more hip extension to maintain the body's center of gravity on the femoral head(79).

Furthermore, we found a negative correlation between age and pelvic mobility, but a positive correlation with SS in sitting. Similar findings have been reported in previous studies(133), perhaps because age-related lumbar degeneration limits posterior rotation of the pelvis when changing from a standing to a sitting position.

In this study, we found that preoperative SVA did not affect postoperative standing PFA, but positively affected postoperative sitting PFA. Sagittal compensatory mechanisms may explain this finding. While the body leans forward in the standing position (i.e., SVA increases), the compensatory capacity of the hip joint is exhausted(79), so an increase in standing SVA cannot significantly raise standing PFA. While the trunk tilts forward in the sitting position, less hip flexion is required to achieve an upright posture and a horizontal gaze(79). Therefore, SVA has a positive effect on sitting PFA.

4.2.4. Prediction of postoperative spinopelvic abnormalities using preoperative factors

Previous studies have demonstrated that pelvic stiffness and kyphotic hypermobility increase the risk of postoperative hip instability, and hip hyperextension and over-flexion have also been identified as the primary risk factors for postoperative hip dislocation(38, 115). Prediction of these spinopelvic abnormalities using preoperative parameters can help hip surgeons to select the appropriate prosthesis and optimize the surgical plan, especially the orientation of the acetabular component. Although several studies have attempted to predict spinopelvic abnormalities that influence hip stability(38, 44, 48, 97, 123), no definitive screening protocol has yet addressed what preoperative parameters to use and what thresholds to establish.

Postoperative spinal and pelvic abnormalities can be predicted using the following preoperative parameters according to the multiple linear regression and ROC curve analysis of this study. **For predicting spinal pelvic stiffness**, the optimum threshold of the combined factors was age at surgery ≥74 years old, pre-ΔSS ≤7.5° and KL grade of lumbar spine ≥2, with an 84.2% sensitivity and 75.9% specificity. **For predicting spinopelvic kyphotic hypermobility**, the optimum threshold of pre-SS sitting was ≤9.2°, with an 80.0% sensitivity and 91.3% specificity. **For predicting standing hip hyperextension abnormality**, the optimum threshold of pre-PFA standing was ≥ 192.4°, with an 83.3 % sensitivity and a 91.4 % specificity. **For predicting sitting hip over-**

flexion abnormality, the optimum threshold of pre-PFA sitting was 113.1°, with an 80.0% sensitivity and 66.7% specificity.

The thresholds of preoperative hip motion for predicting postoperative instability found in this study were in line with the findings from Tezuka's study, which demonstrated that an increased preoperative femoral extension (PFA >190°) effectively predicted the risk of anterior dislocation, while an increased preoperative femoral flexion (PFA <120°) predicted the risk of posterior dislocation(38). If the THA candidate is older than 74 years at the time of surgery with a preoperative pelvic mobility of ≤7.5° and KL grade of lumbar spine ≥2, the hip surgeon should be alert to the risk of postoperative hip instability caused by impingement due to excessive hip mobility. Particular attention should be paid when this THA candidate is combined with a standing PFA of ≥192.4° or combined with a sitting PFA of ≤113.1°. In this case, a dual mobility articulation is highly recommended to prevent the risk of dislocation. For patients with a preoperative $SS_{sitting}$ of ≤9.2°, the acetabular anteversion should be appropriately reduced to avoid the risk of 'drop out' dislocation due to possible postoperative pelvic kyphotic hypermobility.

4.2.5. The influence of PI on instability risk following THA

It is currently unknown how PI impacts the instability risk following THA as previous studies hold conflicting views on whether PI is associated with the risk of dislocation(38, 115, 128, 134-138). Tezuka et al.(38) found that PI was the third predictive parameter for predicting the risk of instability after THA. Ike et al.(115) further demonstrated that PI was associated with postoperative spinopelvic imbalance and that specifically a low PI had a predictive value for the risk of postoperative instability. Similar findings were reported by another retrospective investigation, which also showed that a low PI raised the risk of postoperative dislocation(134).

On the other hand, Dagneaux et al.(135) conducted a case-control study and found that patients with unstable THA had a higher PI and PI-LL mismatch than those with stable THA, and Esposito et al.(136) found that there was no significant difference in PI between patients with multilevel degenerative disc disease (DDD) who dislocated, patients with DDD who did not dislocate and patients with a normal spine who did not dislocate (mean 59°, 55° and 56°, respectively; p=0.6). Similar results were also observed by DelSole et al.(137), who investigated 139 THAs and found that no significant difference existed in PI between patients with and without dislocation (mean 64.3 and 52.4, respectively; p=0.121). Vigdorchik et al.(138) reviewed 9,414 THA patients and also found that PI had no significant association with dislocation risk, but excessive standing posterior PT was correlated with instability following THA. Of note, there is a geometrical correlation between PI and PT (PI=PT+SS)(59), and we observed a good correlation between PI and standing PT (pre-op, r=0.546; post-op, r=0.593) in the present study, which makes Vigdorchik's conclusions seem contradictory. The possible reasons for the contradictory conclusions among these studies are as follows. Among the spinopelvic factors, the predictive ability of PI for THA instability is weaker than that of pelvic mobility and femoral position(38). Apart from spinopelvic factors, other crucial factors influencing THA instability include patient factors (such as age, BMI, neuromuscular disorders), implant factors (such as the size of the femoral head component and the design feather of the acetabular liner), and surgeon factors (such as surgical approach, the experience of the surgeon and the components' orientation)(12, 14, 19, 25, 27, 139). Thus, the effect of PI on THA instability may be masked by other factors during the research process. Therefore, different studies regarding the influence of PI on the instability of THA tend to have differing conclusions.

While the results of the present study were in line with Kleeman-Forsthuber’s findings(128), we came to the opposite conclusion. Both of our studies observed that PI was associated with positional parameters of SS, PT, and LL, but not correlated with the lumbar and pelvic mobility. Accordingly, Kleeman-Forsthuber et al. concluded that PI alone was not associated with spinal or pelvic mobility, so it might not be a predictor of THA instability. However, they did not assess the association of PI with the functional safe zone, which would more directly reflect the correlation of PI with dislocation risk. In the present study, we found that PI was moderately correlated with standing CSI (r=0.377) and poorly correlated with sitting CSI (r=0.228). In the comparison between PI groups, we noted that high PI patients had highest CSI $_{standing}$, while low PI patients had lowest CSI $_{sitting}$. The difference in femoral position between PI groups contributed to the difference in CSI rather than the acetabular position. In addition, we found that the distribution of abnormal pelvic motion did not significantly differ between PI groups, while there was a significant difference in the proportion of abnormal hip motion between PI groups, and especially the proportion of over-flexion abnormalities was significantly higher in the low PI group. Therefore, the association of PI with dislocation risk was based on the influence of PI on femoral position rather than pelvic motion.

PI-LL mismatch is a parameter used to assess the presence of a sagittal imbalance in the lumbar spine and is intrinsically correlated with PI(128), and sagittal imbalance could trigger a series of compensatory mechanisms such as pelvic rotation posteriorly and hip hyperextension(50). In the present study, we found that the PFA $_{standing}$ was significantly higher in the imbalanced PI-LL mismatch group, but the pelvic motion did not significantly differ between the two groups. The possible explanations for why imbalanced PI-LL mismatch did not significantly alter pelvic motion are as follows. Patients with imbalanced PI-LL mismatch have a flattened lumbar spine, which may lead to posterior pelvic rotation, while PI-LL positively correlates with SS $_{standing}$ (128). These two factors have opposite effects on pelvic motion and may counteract each other. In addition, we found that the standing CSI was significantly higher in the PI-LL imbalance group, which was attributed to increased hip extension. Therefore, PI-LL mismatch imbalance may lead to hip hyperextension and thus increase the risk of anterior dislocation. Since there is a positive correlation between PI and PI-LL (r=0.418) (128), the larger the PI, the more it is prone to sagittal plane imbalance, and as the severity of spinal degeneration increases, patients with high PI are more prone to standing hip instability.

4.3. Limitations of the study

It should be noted that there were some limitations in the present study. First, due to the COVID-19 pandemic, elective procedures like THA were partially canceled. This resulted in a prolonged recruitment period. EOS assessment was only performed during hospitalization for short-term follow-up, and long-term follow-up is currently in progress. Second, the management policy for COVID-19 resulted in a failure of EOS follow-up. Approximately 55% of patients were excluded due to incomplete EOS imaging, which have led to potential selection bias. Third, some postures, such as flexed-seated or hyperextended, may raise the risk of dislocation or edge loading(140). We only investigated standing or relaxed-seated positions out of safety concerns. Furthermore, we did not investigate actual dislocation rates in our research, but instead used functional safety zones as defined in preceding studies.

4.4. Clinical relevance

When planning THA, hip surgeons need to consider which patients are at potential risk of postoperative THA instability, whether the risk of instability arises from abnormal pelvic mobility or abnormal hip motion, and whether the risk of instability can be reduced or eliminated by adjusted orientation of the acetabular component.

Previous studies have classified preoperative pelvic mobility into five categories and suggested that the orientation of acetabular components should be placed accordingly to reduce the risk of instability(84). However, our study reconfirmed that pelvic mobility may alter after THA. The change in pelvic motion before and after surgery varies between individuals, which may lead to changes in the pelvic mobility category after surgery, and the position of the acetabular component deviates from the preoperative planning orientation, resulting in THA instability. Although sagittal alignment imbalance may affect hip instability, the introduction of PI-LL mismatch combined with preoperative pelvic mobility as a reference index for assessing the risk of postoperative hip dislocation by some studies is insufficient (63, 94). Hip instability caused by abnormal spinopelvic motion is mainly due to the impingement between the acetabular component and the femur(38, 48, 115). Therefore, hip motion cannot be ignored while evaluating the risk of postoperative instability. One of the main mechanisms leading to hip dislocation is hip hyperextension and over-flexion (48, 115). Our study attempted to establish a protocol for predicting postoperative abnormal pelvic and hip motion through preoperative factors, which may benefit the preoperative planning of acetabular component implantation and prosthesis selection. We established ROC models to predict postoperative pelvic stiffness and kyphotic hypermobility, as well as hip hyperextension and over-flexion. This predictive model may help identify patients at risk of dislocation preoperatively and assist in the diagnosis of dislocation risk from pelvic and/or hip motion. However, the accuracy and application value of this predictive model still needs further research. Previous studies have demonstrated that PI is one of the predictors of hip instability(38). We found that the influence of PI on hip motion established a connection between PI and dislocation risk.

4.5. Implications for future research

In the present study, we investigated independent factors affecting postoperative pelvic and hip motion, and developed multiple linear regression models with coefficients of determination ranging from 0.248-0.753, which indicates that these models explain between 24.8% to 75.3% of the variation in postoperative spinopelvic motion. There may be some preoperative independent variables that we did not explore in the present study. Future studies should focus on these variables and establish a more accurate multiple linear regression model to predict postoperative spinopelvic motion. By identifying and studying these factors, future research can improve our understanding of the relationship between preoperative variables and postoperative spinopelvic motion, leading to the development of more accurate predictive models. Accurate predictive models are needed to help surgeons to identify patients at risk of postoperative instability after THA, select the appropriate prosthesis and take preventative measures, such as intraoperative adjustments of the implant position, to minimize the risk of dislocation.

Although we developed ROC models for predicting abnormal postoperative pelvic and hip motion after THA, these models do not establish a direct link with postoperative dislocation. Future studies should focus on analyzing the spinopelvic parameters in patients who experience instability after THA, and develop a more specific ROC model to predict dislocation.

5. Conclusions

Both pelvic and hip motion may improve after THA and vary between individuals. Compared with C7-SVA, PI-LL mismatch may better assess excessive hip extension caused by sagittal imbalance, which may increase the risk of posterior impingement. In addition to preoperative pelvic mobility, other preoperative factors may also affect postoperative pelvic mobility, including age at surgery, lumbar degeneration, and contralateral hip osteoarthritis. Postoperative standing PFA may be influenced by preoperative contralateral osteoarthritis, lumbar degeneration, PI and standing PFA. Besides preoperative sitting PFA, postoperative sitting PFA may be affected by sitting SVA and contralateral hip osteoarthritis.

Using the following preoperative parameters to predict postoperative spinopelvic abnormalities may contribute to identifying the risk of postoperative THA dislocation, namely: age at surgery, pre-ΔSS combined with KL grade of lumbar spine to predict postoperative pelvic stiffness, preoperative sitting SS to diagnose postoperative kyphotic hypermobility, sitting PFA to predict postoperative sitting hip over-flexion abnormality, and preoperative standing PFA to predict standing hip hyperextension abnormality.

Extremely high or low PI may increase the risk of postoperative hip dislocation. The influence of PI on hip motion rather than the acetabular component position may establish a connection between PI and dislocation risk. Individuals with a high PI may be more prone to a sagittal imbalance and thus vulnerable to standing hip instability.

Hip surgeons therefore need to be aware of the implications these parameters have on the postoperative surgical outcome and which patients are at risk of postoperative THA instability in order to adequately plan the procedure. Future studies are needed to correlate the abovementioned parameters with actual dislocation rates and to investigate potential additional relevant factors.

6. References

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7. Statutory declaration

"I, Zhen Wang, by personally signing this document in lieu of an oath, hereby affirm that I prepared the submitted dissertation on the topic “Analysis of predictive factors of hip instability in patients undergoing primary total hip arthroplasty” and in German “Analyse prädiktiver Faktoren der Hüftinstabilität bei Patient:innen, die sich einer primären Hüft-Totalendoprothese unterziehen” independently and without the support of third parties, and that I used no other sources and aids than those stated.

All parts which are based on the publications or presentations of other authors, either in letter or in spirit, are specified as such in accordance with the citing guidelines. The sections on methodology (in particular regarding practical work, laboratory regulations, statistical processing) and results (in particular regarding figures, charts and tables) are exclusively my responsibility.

Furthermore, I declare that I have correctly marked all of the data, the analyses, and the conclusions generated from data obtained in collaboration with other persons, and that I have correctly marked my own contribution and the contributions of other persons (cf. declaration of contribution). I have correctly marked all texts or parts of texts that were generated in collaboration with other persons.

My contributions to any publications to this dissertation correspond to those stated in the below joint declaration made together with the supervisor. All publications created within the scope of the dissertation comply with the guidelines of the ICMJE (International Committee of Medical Journal Editors; www.icmje.org) on authorship. In addition, I declare that I shall comply with the regulations of Charité – Universitätsmedizin Berlin on ensuring good scientific practice.

I declare that I have not yet submitted this dissertation in identical or similar form to another Faculty.

The significance of this statutory declaration and the consequences of a false statutory declaration under criminal law (Sections 156, 161 of the German Criminal Code) are known to me."

Date	Signature

8. Curriculum vitae

My curriculum vitae does not appear in the electronic version of my paper for reasons of data protection.

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10. Confirmation by a statistician

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Bescheinigung

Hiermit bescheinige ich, dass Herr *Zhen Wang* innerhalb der Service Unit Biometrie des Instituts für Biometrie und klinische Epidemiologie (iBikE) bei mir eine statistische Beratung zu einem Promotionsvorhaben wahrgenommen hat. Folgende Beratungstermine wurden wahrgenommen:

- Termin 1: 03.03.2023

Folgende wesentliche Ratschläge hinsichtlich einer sinnvollen Auswertung und Interpretation der Daten wurden während der Beratung erteilt:

- Graphische und Tabelle Darstellung
- ANOVA und Kruskal-Wallis-Test
- Post-hoc-Tests
- T-test
- Korrelation und lineare Regression
- ROC curve

Diese Bescheinigung garantiert nicht die richtige Umsetzung der in der Beratung gemachten Vorschläge, die korrekte Durchführung der empfohlenen statistischen Verfahren und die richtige Darstellung und Interpretation der Ergebnisse. Die Verantwortung hierfür obliegt allein dem Promovierenden. Das Institut für Biometrie und klinische Epidemiologie übernimmt hierfür keine Haftung.

Datum: 09.10.2023

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