■ HIP

A patient-specific algorithm for predicting the standing sagittal pelvic tilt one year after total hip arthroplasty

A PRELIMINARY VALIDATION STUDY

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Aims
The aim of this study was to evaluate the reliability and validity of a patient-specific algorithm which we developed for predicting changes in sagittal pelvic tilt after total hip arthroplasty (THA).

Methods
This retrospective study included 143 patients who underwent 171 THAs between April 2019 and October 2020 and had full-body lateral radiographs preoperatively and at one year postoperatively. We measured the pelvic incidence (PI), the sagittal vertical axis (SVA), pelvic tilt, sacral slope (SS), lumbar lordosis (LL), and thoracic kyphosis to classify patients into types A, B1, B2, B3, and C. The change of pelvic tilt was predicted according to the normal range of SVA (0 mm to 50 mm) for types A, B1, B2, and B3, and based on the absolute value of one-third of the PI-LL mismatch for type C patients. The reliability of the classification of the patients and the prediction of the change of pelvic tilt were assessed using kappa values and intraclass correlation coefficients (ICCs), respectively. Validity was assessed using the overall mean error and mean absolute error (MAE) for the prediction of the change of pelvic tilt.

Results
The kappa values were 0.927 (95% confidence interval (CI) 0.861 to 0.992) and 0.945 (95% CI 0.903 to 0.988) for the inter- and intraobserver reliabilities, respectively, and the ICCs ranged from 0.919 to 0.997. The overall mean error and MAE for the prediction of the change of pelvic tilt were -0.3° (SD 3.6°) and 2.8° (SD 2.4°), respectively. The overall absolute change of pelvic tilt was 5.0° (SD 4.1°). Pre- and postoperative values and changes in pelvic tilt, SVA, SS, and LL varied significantly among the five types of patient.

Conclusion
We found that the proposed algorithm was reliable and valid for predicting the standing pelvic tilt after THA.

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Introduction
Preoperative abnormal spinal pelvic tilt in the sagittal plane is closely related to the rate of complications, such as impingement, dislocation, and polyethene wear, after total hip arthroplasty (THA).[1,2] Several methods of stratifying the risks of these complications and quantitative algorithms have recently been reported for determining the optimal orientation of the acetabular component based on pelvic tilt.[3–9] As a critical component of these methods, the pre- and postoperative standing pelvic tilt vary considerably.[1,10–12] A variation of 5° in the postoperative pelvic tilt may lead to significant alterations to the size of the patient-specific safe zone of the orientation of the acetabular component.[6,8,13]

Although the mean change in pelvic tilt after THA has been reported to be small, the patient-specific change may be considerably larger.[11,12,14–16] Pour et al[17] reported a change in pelvic tilt of > 10° after THA in 34 (14.4%) of 237 primary THAs. Ishida et al[11] found that patients with severely

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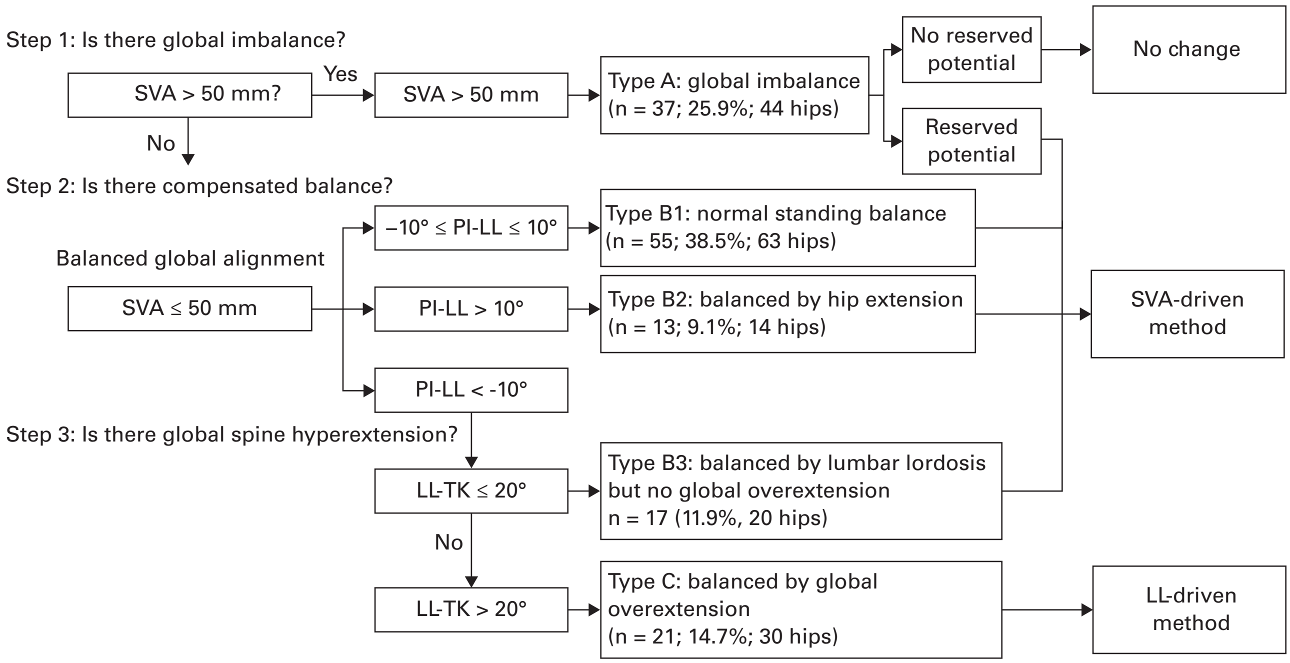

Fig. 1

A flowchart showing the classification of the patients and algorithm for the prediction of the postoperative standing pelvic tilt based on a full-body lateral radiograph. LL, lumbar lordosis; PI, pelvic incidence; SVA, sagittal vertical axis; TK, thoracic kyphosis.

abnormal posture had a large change in pelvic tilt postoperatively.[11] However, to our knowledge, no patient-specific methods of predicting postoperative standing pelvic tilt have been reported.

In order to address this issue, the hypothesis of this study was that the overall sagittal malalignment and spinal hyperextension, indicated by the sagittal vertical axis (SVA), and pelvic incidence and lumbar lordosis mismatch (PI-LL), respectively, would be improved to the normal ranges after THA. The aim was to develop an algorithm that would predict the change in standing pelvic tilt postoperatively.[18] The SVA is an overall measurement of the sagittal balance for the C7 plumb line with a well-established reference range. The PI-LL and LL-TK mismatches are used as tools to analyze the local compensation mechanisms of the hip and pelvic rotation, the lumbar spine, and thoracic spinal curves. Patients were classified into five types based on distinct sagittal rebalancing characteristics after THA (Figure 1).

This was a retrospective cohort study designed to determine the effectiveness of the new prediction algorithm preliminarily. Two main questions were addressed: what is the reliability and validity of the new algorithm for predicting the change in pelvic tilt after THA, and what are the characteristic parameters of the pre- and postoperative standing sagittal posture for each type of patient?

Methods

The study had local ethical approval. A total of 197 THAs in 166 patients who underwent robot-assisted THA (Mako; Stryker, USA) between April 2019 and October 2020 were included in this retrospective study. Patients who had revision THA (n = 8), who could not stand preoperatively (n = 2), who had severe osteoarthritis (OA) of the ipsilateral knee or contralateral hip with a fixed flexion deformity of ≥ 10° (n = 5), or who had incomplete full-body radiographs (n = 8) were excluded. A total of 143 patients (171 THAs), 94 of whom were female (65.7%), with a mean age of 51 years (20 to 87), mean BMI of 24.4 kg/m^2 (17.8 to 32.1), and complete preoperative and a minimum of 12 months follow-up radiographs, were available for analysis. The preoperative diagnosis included primary OA (n = 40), avascular necrosis of the femoral head (n = 46), developmental dysplasia (n = 50), and ankylosing spondylitis (n = 7).

The full-body biplanar radiographs were obtained using the EOS system (EOS Imaging, France), following a local protocol with parameters set as 105 kV and 250 mA for the lateral views. Patients were asked to stand with their feet at the same level, eyes looking forward, and hands held at shoulder level. Full-length lateral views were used for the analyses. The pre- and postoperative standing postures were analyzed using the EOS 3D software on the lateral views. SVA, PI, LL, pelvic tilt, sacral slope (SS), and thoracic kyphosis (TK) were measured (Figure 2a).[18] The PI-LL mismatch was calculated to indicate lumbar spine compatibility with PI, with a normal range of between -10° and 10°.[18] We defined the LL-TK mismatch as an indicator for the compatibility of the lumbar spine with the thoracic curvature with a reference value of < 20°.

The patients were classified into five types (A, B1, B2, B3, and C) (Figure 3) by three steps according to SVA, PI-LL, and LL-TK mismatch measured from the preoperative lateral views (Figure 1). The change in pelvic tilt was defined as the postoperative value minus the preoperative value (Figure 3), and predicted using two different methods according to the patient's type.

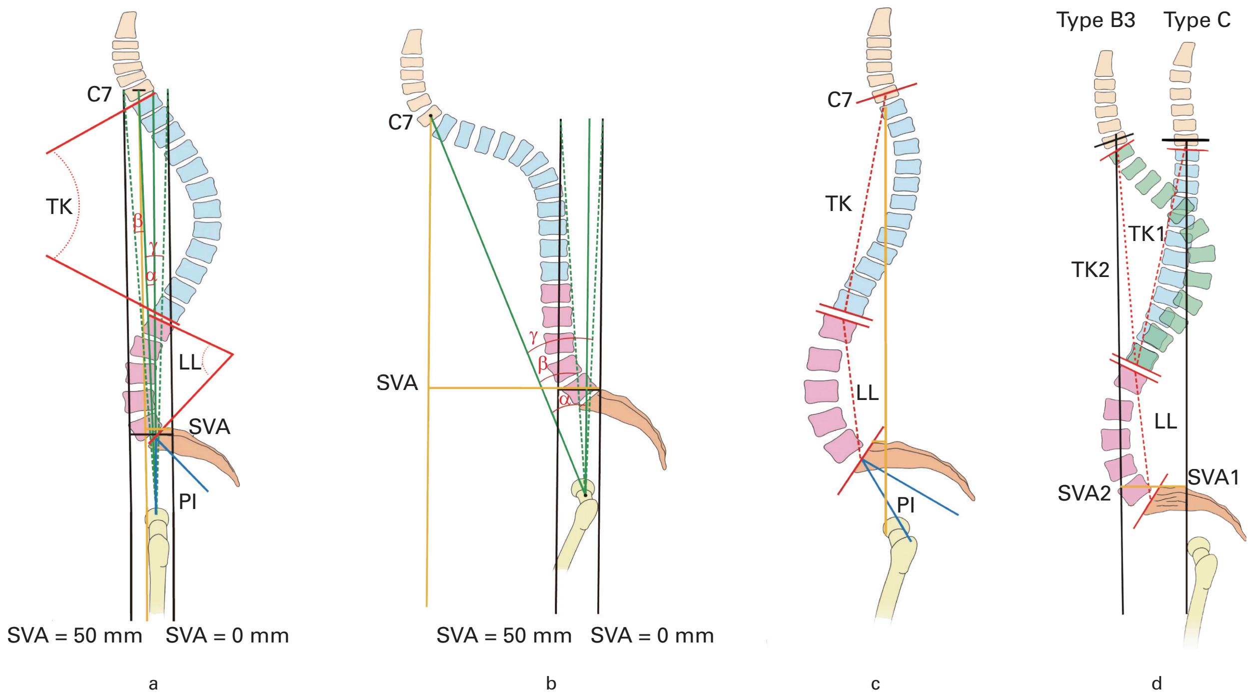

Fig. 2

Schematic drawing of definitions for the classification of the patients and for the parameters of the prediction of the standing pelvic tilt (PT). a) Definitions of the key parameters for the parameters of the classification on the lateral view. The sagittal vertical axis (SVA) was defined as the distance from the upper corner of the S1 endplate to a vertical line from the centre of the body of C7 as the indicator of sagittal balance with a normal range of 0 mm to 50 mm. Pelvic tilt was defined as the angle subtended by a vertical line and the line connecting the centres of both hips and the midpoint of the superior endplate of S1, and PI was defined as the angle subtended by this line and the line perpendicular to the S1 endplate. Lumbar lordosis (LL) was defined as the Cobb angle between the upper endplate of L1 and the upper endplate of S1. Thoracic kyphosis (TK) was defined as the Cobb angle between the upper endplate of T1 and the lower endplate of T12. b) SVA-driven method predicts the change of pelvic tilt by assuming the spine to be a solid body for type A, B1, B2, and B3 patients. This change was predicted as the angle of the centre of C7 shifting from the preoperative C7 plumb line to the vertical line (α angle) over the predicted centre of the hip with SVA = 50 mm and 0 mm vertical lines as the lower (β angle) and upper (γ angle) limits of prediction, respectively. c) LL-driven method for predicting the change for type C patients. d) Effect of the LL-TK mismatch on the sagittal balance, leading to hyperextension of the spine (blue contour) and a negative SVA in type C patients and a balanced spinal curvature (green contour) in type B3 patients.

SVA-driven method. For types A, B1, B2, and B3, the sagittal balance (as indicated by SVA) is the dominant factor determining the postoperative rebalancing; the postoperative C7 plumb line was expected to land at the position passing through the midpoint of the centre of rotation of both hips, with the SVA assumed to return to the normal range of between 0 mm and 50 mm after THA; the change of pelvic tilt was measured as the shifting angle of the centre of the C7 vertebra to the predicted C7 plumb line, and SVA values of 0 mm and 50 mm were used as upper and lower limits of the shift of the C7 plumb, respectively (Figure 2b).[16]

LL-driven method. For type C patients, lumbar spinal overcompensation (PI-LL mismatch accompanied by TK-LL mismatch) is the dominant factor determining the sagittal rebalancing. The postoperative pelvic tilt was predicted using the approximation formula of change of pelvic tilt = 1/3 |PI-LL| (Figure 2c).

We randomly selected 60 patients to assess the reliability of the algorithm. Reliability was defined as an agreement in the type of classification of the patient and the predicted change of pelvic tilt, from preoperative measurements. In order to determine the intraobserver reliability of the radiological method, one examiner (HT) measured all 60 images twice, with a four-week interval between measurements. The interobserver reliability was measured independently by the other two examiners (SG, SW) from the preoperative images of the 60 patients using the same method. The validity of the algorithm was assessed by comparing the predicted and measured values for the change of pelvic tilt.

Statistical analysis. The kappa value was used to assess the inter- and intraobserver reliabilities of the classification system, and the intraclass correlation coefficient (ICC) was calculated for inter- and intraobserver reliabilities for the prediction of the changes of pelvic tilt. For both the kappa values and the ICCs, a value of 1 indicates perfect reliability, and a value of 0 indicates the lowest reliability; a value of between 0.9 and 1 represents near-perfect reliability.[19] For validity, with the change of pelvic tilt as the reference standard, the mean error and the mean absolute error (MAE) for the change that is predicted by the algorithm was calculated. The percentages of the changes of pelvic tilt that fell into the range of those predicted for each type of patient were calculated. A Bland-Altman analysis was performed to calculate the 95% limits of agreement, within which the predicted errors of the estimation of the change of pelvic tilt fell with a 95% probability. Analysis of variance and chi-squared

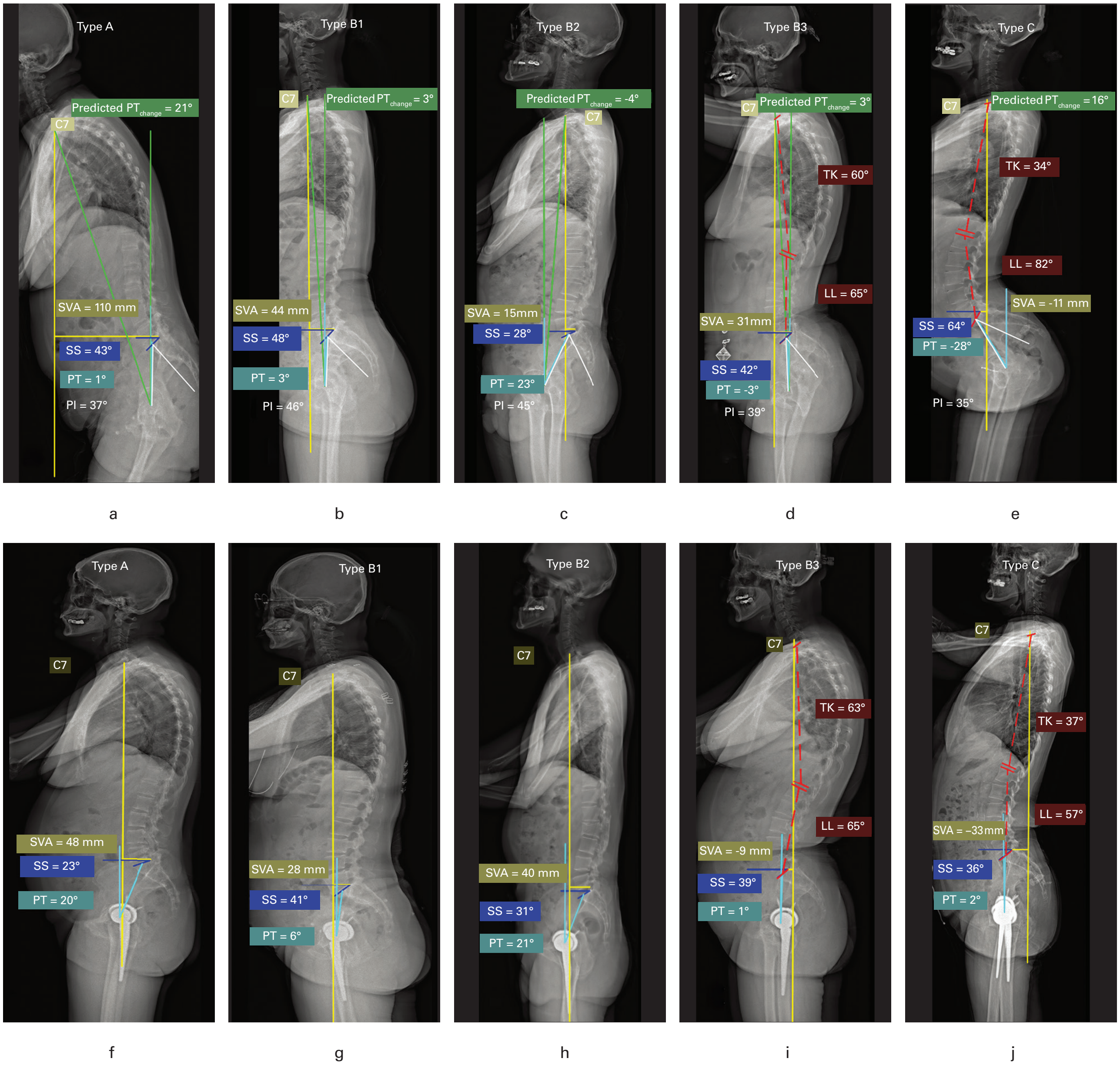

Fig. 3

Pre- and postoperative lateral views of the five types of patient. a) to e) Analysis of preoperative sagittal balance and the predicted change in pelvic tilt (PT). f) to j) Follow-up views of the same patients. LL, lumbar lordosis; PI, pelvic incidence; SS, sacral slope; SVA, sagittal vertical axis; TK, thoracic kyphosis.

tests and subsequent mutiple comparisons were uitilized to detect the differences in the demographic, preoperative, and postoperative sagittal alignment parameters between the five patient groups. Linear regressions were utilized to explore the overall relationship between the standing PT or change in standing PT at follow-up and the preoperative standing PT.

All analyses were performed using SPSS v. 15.0 (SPSS, USA) and Medcalc software (Medcalc, Belgium). Significance was set at $p < 0.05$ for comparisons between two types and $p < 0.01$ for multiple comparisons between the five types, using Bonferroni's correction.

Results

The proposed algorithm had excellent inter- and intraobserver reliability in the both the classification of patients and the prediction of the change of pelvic tilt. The kappa values were 0.927 (95% confidence interval (CI) 0.861 to 0.992) and 0.945 (95% CI 0.903 to 0.988) for inter- and intraobserver reliabilities. The ICC values for the prediction of change of pelvic tilt ranged from 0.919 to 0.997 for the SVA- and LL-driven methods (Table I).

The overall mean errors and MAE for the prediction of change of pelvic tilt using the algorithm were -0.3° (standard

Table I. Intraclass correlation coefficients for the inter- and intraobserver reliability for the algorithm for the change of pelvic tilt.

Reliability	SVA-driven method			LL-driven method
	Anterior threshold	Predicted value	Posterior threshold	
Interobserver, mean (95% CI)	0.985 (0.970 to 0.993)	0.962 (0.925 to 0.981)	0.985 (0.967 to 0.993)	0.946 (0.877 to 0.977)
Intraobserver, mean (95% CI)	0.997 (0.993 to 0.998)	0.995 (0.991 to 0.998)	0.996 (0.992 to 0.998)	0.919 (0.816 to 0.965)

*SVA = 50 mm.
†SVA passing through the midpoint of the centres of both femoral heads.
‡SVA = 0 mm.
CI, confidence interval; LL, lumbar lordosis; SVA, sagittal vertical axis.

Table II. Changes in sagittal pelvic tilt for the five types of patients and accuracy of the sagittal vertical axis-driven method after total hip arthroplasty.

Classification	Mean PT_{change}, ° (SD)	Mean absolute PT_{change}, ° (SD)	Mean predicted PT_{change}, ° (SD)	Mean error of PT_{change} prediction, ° (SD)	Mean absolute error of PT_{change} prediction, ° (SD)	PT_{change} within predicted range, n (%)
A	6.6 (4.1)	6.7 (3.8)	6.5 (4.0)	0.1 (3.5)	2.6 (2.3)	28 (75.7)
B1	-1.2 (3.5)	2.9 (2.3)	-1.3 (3.1)	0.1 (2.5)	2.0 (1.4)	50 (90.9)
B2	-1.4 (3.7)	2.9 (2.6)	-2.3 (2.6)	1.0 (3.9)	3.5 (1.6)	9 (69.2)
B3	-1.5 (5.1)	4.1 (3.2)	-2.1 (2.8)	0.5 (4.6)	3.5 (2.9)	8 (47.1)
C	8.5 (6.8)	9.5 (5.2)	-0.5 (3.3)	9.0 (5.6)	9.5 (4.7)	1 (4.8)
Total	2.2 (6.10	5.0 (4.1)	0.7 (4.8)	1.5 (4.8)	3.6 (3.6)	96 (67.1)

PT, pelvic tilt; PT_{change}, change in sagittal pelvic tilt; SD, standard deviation; SVA, sagittal vertical axis.

Table III. Errors in the prediction of the change of pelvic tilt for type B3 and C patients using the lumbar lordosis-driven method.

Patient type	Target portion of PI-LL mismatch	Mean error of PT_{change} prediction, ° (SD)		p-value*	Mean absolute error of PT_{change} prediction, ° (SD)		p-value*
		LL-driven	SVA-driven		LL-driven	SVA-driven	
B3	1/4	5.9 (5.3)	0.5 (4.6)	0.033	6.5 (4.5)	3.5 (2.9)	0.034
	1/3	7.3 (5.5)		0.010	7.7 (4.9)		0.009
	1/2	10.2 (6.0)		0.001	10.2 (6.0)		0.001
C	1/4	-2.6 (5.7)	9.0 (5.6)	< 0.001	4.6 (4.2)	9.5 (4.7)	< 0.001
	1/3	-0.7 (5.5)		< 0.001	4.0 (3.7)		< 0.001
	1/2	3.2 (5.4)		0.015	5.1 (3.5)		0.004

*Paired *t*-test.
LL, lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; PT_{change}, change in sagittal pelvic tilt; SD, standard deviation; SVA, sagittal vertical axis.

deviation (SD) 3.6°) and 2.8° (SD 2.4°), respectively, for all types of patient, which were significantly smaller than the corresponding errors (1.5° (SD 4.8°) and 3.6° (SD 3.6°), respectively) of applying the SVA-driven method universally for all five types (Table II; $p < 0.010$, independent-samples *t*-test). The prediction of change of pelvic tilt using this method was accurate for types A, B1, B2, and B3, and most of the change fell within the predicted range (Table II). For type C patients, the LL-driven method using one-third of the absolute PI-LL mismatch as the predicted change was significantly more accurate than the SVA-driven method (Table III; $p < 0.001$, paired *t*-test). The Bland-Altman analysis showed evenly and randomly scattered errors with a 95% agreement between -6.9° and 7.5° and a mean difference of 0.3°, indicating no systematic error (Figure 4).

The hypothesis that THA leads to normalizing the sagittal balance was confirmed, as shown by the tendency to normalize SVA (Table IV). Only 55 patients (38.5%) were classified as B1 (normal balance) type. The mean absolute change in pelvic tilt was 5.0° (SD 4.1°) for the whole cohort, with significant differences among the five types (Table V, Figure 5). Type C patients were significantly younger and a higher percentage had hip dysplasia. The pre- and postoperative values and changes in SVA, SS, and LL varied substantially among the five types. No

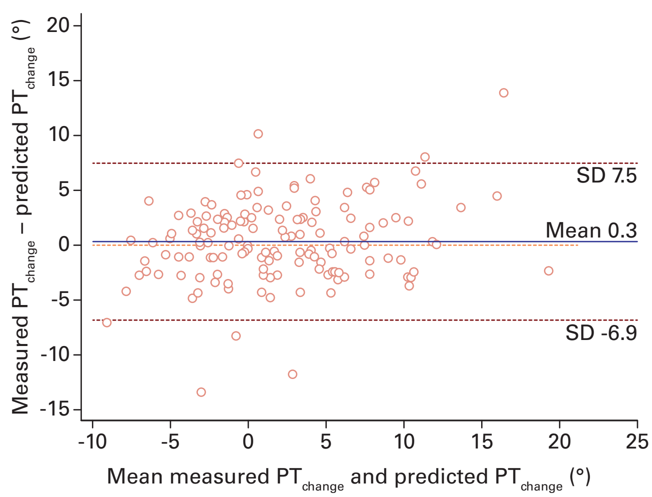

Fig. 4

Bland-Altman analysis for the predicted and measured changes in pelvic tilt (PT_{change}). SD, standard deviation.

Table IV. Comparison of the pre- and postoperative postural parameters of all patients.

Variable	Preoperative mean (SD)	Follow-up mean (SD)	p-value*
SVA, mm	22.6 (42.4)	14.8 (34.7)	0.029
PT, °	4.2 (9.1)	6.5 (7.9)	< 0.001
SS, °	44.5 (10.6)	41.5 (9.7)	0.001
LL, °	50.7 (15.6)	38.7 (10.2)	0.498
TK, °	49.7 (17.3)	37.3 (12.7)	0.309
PI-LL mismatch, °	4.9 (16.7)	2.2 (20.1)	0.269
LL-TK mismatch, °	14.2 (14.8)	12.6 (23.3)	0.573

*Paired *t*-test.
LL, lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SD, standard deviation; SS, sacral slope; SVA, sagittal vertical axis; TK, thoracic kyphosis.

Table V. Demographic pre- and postoperative factors and changes in the standing sagittal alignment of patients after total hip arthroplasty.

Variable	Classification					p-value
	A	B1	B2	B3	C	
Mean age, yrs (SD)	56.9 (4.9)[a]	48.7 (3.3)[b]	56.8 (8.3)[a,b]	49.4 (7.7)[a,b]	42.9 (5.2)[b]	0.006
Mean BMI, kg/m^2 (SD)	24.3 (1.1)	24.9 (0.9)	23.5 (2.2)	24.0 (1.7)	23.6 (2.7)	0.966
Female, n (%)	17 (45.9)	34 (61.8)	7 (53.8)	10 (58.8)	18 (85.7)	0.065
Hip dysplasia, n (%)	8 (21.6)[a]	23 (41.8)[a,b]	5 (38.5)[a,b]	7 (41.2)[a,b]	16 (76.2)[b]	0.002
Mean preoperative values (SD)						
SVA, mm	80.7 (31.6)[a]	12.2 (25.6)[b]	14.9 (23.1)[b]	2.5 (26.7)[b]	-7.2 (21.2)[b]	< 0.001
PI, °	48.5 (9.4)	47.7 (8.9)	49.6 (8.7)	41.4 (7.1)	46.1 (9.5)	0.107
SS	45.6 (10.6)[a]	39.6 (7.4)[b]	34.0 (10.1)[b]	41.0 (9.9)[a,b]	49.8 (8.6)[c]	< 0.001
PT, °	2.6 (8.5)[a]	7.4 (6.1)[b]	14.4 (5.7)[c]	0.7 (9.6)[a,b]	-2.7 (8.8)[d]	< 0.001
LL, °	42.8 (15.4)[a]	50.3 (8.8)[b]	31.8 (12.7)[c]	61.0 (8.4)[d]	65.7 (8.4)[d]	< 0.001
TK, °	36.3 (14.2)[a]	37.9 (8.1)[a]	30.8 (9.6)[a]	48.9 (6.7)[b]	38.0 (8.2)[a]	< 0.001
PI-LL mismatch, °	5.7 (13.6)[a]	-2.6 (4.8)[b]	17.8 (7.6)[c]	-19.7 (7.1)[d]	-19.6 (10.0)[d]	< 0.001
LL-TK mismatch, °	6.2 (14.0)[a]	12.2 (11.3)[b]	0.9 (14.1)[a]	12.2 (8.2)[a,b]	27.0 (9.0)[c]	< 0.001
Mean postoperative values (SD)						
SVA, mm	38.2 (34.2)[a]	12.5 (27.7)[b]	13.6 (27.4)[a,b]	14.1 (45.8)[b]	-10.8 (29.1)[b]	< 0.001
PI, °	44.0 (8.3)	46.6 (8.6)	52.8 (4.0)	45.5 (10.7)	44.5 (14.9)	0.620
SS	37.7 (11.0)[a]	39.7 (7.4)[a]	41.8 (1.6)[a]	47.1 (10.6)[a]	46.2 (9.1)[a]	0.013
PT, °	9.7 (7.9)[a]	6.1 (6.3)[a]	13.1 (7.1)[a]	0.8 (8.6)[b]	2.2 (6.9)[b]	< 0.001
LL, °	46.1 (15.8)[a]	48.4 (20.1)[a]	40.6 (11.0)[a]	55.0 (9.9)[a,b]	57.7 (15.4)[b]	0.024
TK, °	35.7 (8.6)	36.8 (13.3)	37.3 (25.7)	43.8 (14.5)	36.3 (9.5)	0.645
PI-LL mismatch, °	-1.2 (14.5)[a]	4.8 (24.3)[a]	13.7 (7.4)[a]	-10.5 (16.5)[a,b]	-13.1 (14.7)[b]	0.026
LL-TK mismatch, °	15.1 (8.1)	5.6 (30.9)	8.5 (19.5)	12.2 (12.6)	21.0 (21.8)	0.320
Mean change (SD)						
SVA, mm	-39.9 (38.8)[a]	3.7 (26.4)[b]	1.3 (22.7)[b]	7.4 (49.0)[b]	-0.1 (27.3)[b]	< 0.001
PI, °	2.1 (5.6)	1.9 (4.9)	-1.0 (1.0)	-1.7 (13.8)	0.9 (8.2)	0.714
SS	-7.4 (6.7)[a]	0.1 (5.1)[b]	3.1 (6.6)[a,b]	2.7 (10.1)[b]	-5.5 (8.9)[a]	< 0.001
PT, °	6.9 (3.7)[a]	-1.1 (3.6)[b]	-1.4 (3.7)[b]	0.7 (9.3)[b]	5.0 (7.1)[a]	0.001
LL, °	6.0 (12.3)	-2.9 (19.6)	9.6 (9.4)	-6.7 (5.4)	-8.2 (13.7)	0.482
TK, °	0.8 (10.2)[a]	-0.9 (10.7)[a]	4.8 (13.1)[a]	-4.4 (14.2)[a]	-4.0 (9.2)[a]	0.016
PI-LL mismatch, °	-11.6 (14.2)	7.4 (24.6)	-5.1 (4.3)	9.0 (14.2)	7.8 (12.6)	0.125
LL-TK mismatch, °	11.4 (13.5)[a]	-8.0 (31.4)[b]	4.5 (12.9[a,b]	-2.9 (15.0)[a,b]	-5.6 (18.1)[b]	< 0.001

[a, b, c, d]The post-hoc multiple comparisons were conducted with Bonferroni correction for items with overall p < 0.05. Different labels between any two groups indicate a significant difference (p < 0.005).
LL, lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SD, standard deviation; SS, sacral slope; SVA, sagittal vertical axis; TK, thoracic kyphosis;

significant differences in PI, postoperative TK, postoperative LL, and the change in PI-LL mismatch values were seen in the five types of patients (Table V).

Discussion

This study established a new algorithm for predicting changes in pelvic tilt after THA, which accurately predicted the postoperative standing pelvic tilt when planning functional orientation of the acetabular component. Although there was a general trend towards normalization of the sagittal alignment, the five types of patients showed considerable differences in the changes of pelvic tilt and spinal curvatures after THA. This algorithm may also help plan hip and spinal surgery for patients with severe combined hip and spinal pathology.

Previous authors have described heterogeneous results when reporting the effects of THA on pelvic posture.[11,20,21] This variation is due to the diversity in the five different rebalancing models, as we found. The overall change in pelvic tilt is similar

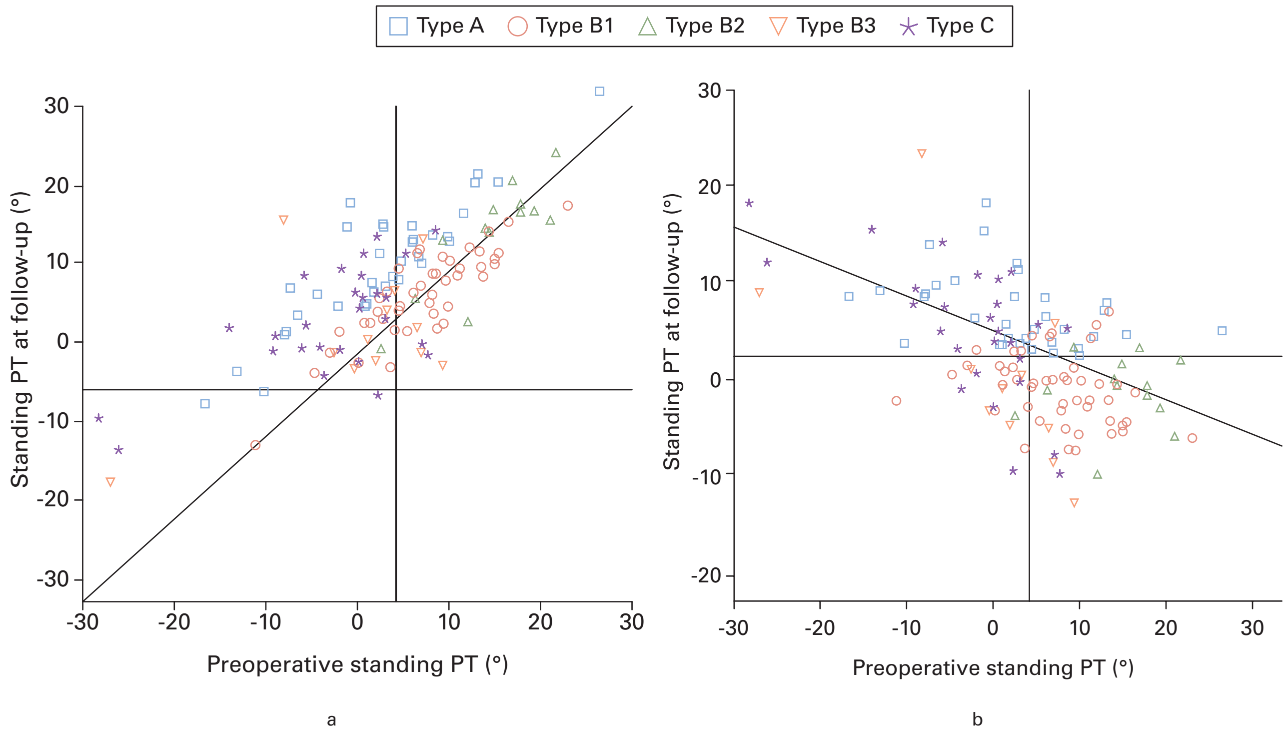

Fig. 5

Scatter plots for the pre- and postoperative pelvic tilt (PT) showing a) the five types of patients distributed unevenly around the reference line (y = x) and b) a negative slope of the regression line between the preoperative standing PT and change in PT at follow-up (y = 3.79-0.36 × x; R_2 = 0.269).

to that reported by Ishida et al.[11] The major difference is that we classified patients according to the overall parameters of sagittal balance enabling a patient-specific prediction of the change of pelvic tilt. Interestingly, we found that PI was not related to this change, whereas Kim et al[22] reported that patients with a low PI had a significantly larger change in pelvic tilt than those with a high PI. This difference might be because our cohort contained more patients with severe dysplasia at a younger age (51 vs 65.3 years) than Kim et al.[22]

The excellent inter- and intraobserver reliability indicates that the classification system and the algorithm for the prediction of the change of pelvic tilt are easy and consistent to apply. The MAE of between 2° and 3° of the change of pelvic tilt had high validity for predicting postoperative pelvic tilt by the SVA-driven method, particularly for types A, B1, B2, and B3. For type C patients, the LL-driven method was significantly more accurate than the SVA-driven method.

The current classification system uses biomechanical indexes to predict the change in pelvic-spinal sagittal posture after THA. Patients were classified into three types and five subgroups for surgeons to understand how the spine is working to maintain the sagittal balance. We found that the SVA is a useful indicator for predicting rebalancing after THA, especially for type A patients, and the flat thoracic deformity also contributes to the sagittal balancing for patients with severe hip dysplasia.

The differences in the sagittal posture in the five types of patient reflect different compensation mechanisms for sagittal imbalance.

In type A patients, SVA abnormality can be from the spine, hip, or both. We simplified the prediction process by assuming that the spine had exhausted its reserve of compensation such that the thoracic and lumbar spine could be analyzed as a rigid body. With this assumption, the pelvis-hip-femur complex becomes the major mobile arch of rebalancing after THA, with the hip regaining extension. We found that the mean error and MAE of the predicted change of pelvic tilt for these patients was as good as that of those with normal balance (type B1), suggesting that simplifying the prediction of pelvic tilt worked for patients with severe imbalance. There was a mean increase of 6.6° in pelvic tilt after THA, which is clinically significant.[1,7]

Remarkably, only 55 patients (38.5%) were classified as type B1. The change of pelvic tilt in type B1 patients was the smallest, as THA caused no alterations in the overall sagittal balance. However, the predicted change of pelvic tilt was still more accurate than when using the preoperative pelvic tilt when planning THA, as the mean error and MAE of the predicted change were smaller than the actual changes. With the smallest change of pelvic tilt, these patients still had a mean change of SVA after THA of 3.7 mm (SD 26.4).

Type B2 patients achieved global balance as compensated by extension of the hip. Patients usually had a flatback deformity, evidenced by significantly smaller LL, SS, and larger pelvic tilt preoperatively than the other four types. Type A and B2 might be two sides of the same coin of the hip-spine syndrome, as indicated by the difference in preoperative PI-LL mismatch and pelvic tilt. Type A patients were likely to develop OA of the hip first, exceeding the ability of the spine to compensate, whereas type B2 patients were more likely to have OA of the spine instead, activating the compensation mechanisms of the hip, leading to OA.

The PI-LL of $\leq$ -10° indicated that balance was achieved by LL hyperextension in type B3 patients. Unlike type C patients, LL was comparable to TK, and there was no overcompensation (LL-TK $\leq$ 20°). Thus, there was no momentum for the LL to decrease after THA, as this would result in overall imbalance in type B3 patients. As the error of the LL-driven method was significantly greater than that of the SVA-driven method, we recommend using the latter to predict the change of pelvic tilt in type B3 patients.

In contrast to type B3, the coexistence of PI-LL and LL-TK mismatches in type C patients indicated overcompensation of LL, which was excessively large for both PI and TK. A classical type C patient had severe bilateral hip dysplasia with a spinal curvature that had formed as compensation for severe pelvic anteversion. The adaptive decrease in LL after THA leads to relief of the lumbar symptoms.[14] Based on the spine's solid-body assumption, the SVA-driven method was ineffective for this type, as two mobile arches (the hip and lumbar spine) participate in the rebalancing process. Thus, we recommend using the approximation equation of the change of pelvic tilt = 1/3|PI-LL for type C patients.

We found that the LL-TK mismatch effectively differentiated type B3 from type C patients. Interestingly, previous authors have reported a decrease in LL and an increase in standing pelvic tilt, but without a statistically significant difference after THA for patients with high dislocation dysplasia.[14,15] However, we found a mixture of types B1 (n = 8; 40%), B2 (n = 1; 5%), B3 (n = 2; 10%), and C (n = 9; 45%) among the 20 patients reported by Calgar et al,[14] explaining the absence of statistical significance in their data. In particular, they stated that some patients had a compensatory decrease of the excessive pelvic tilt and lordosis after THA, which is consistent with type C patients as evidenced by their data and radiographs.

'Hip first or spine first' is always a question in the surgical management of patients with both hip and spinal symptoms, requiring a stable THA and the restoration of sagittal balance.[23] It is a challenge to evaluate the effects of THA on spinal curvatures, and vice versa, quantitatively. The current method enables surgeons to plan THA according to the spinal-pelvic kinematics and also to plan the impact of THA on the global sagittal alignment quantitatively, which is the residual sagittal deformity after THA that necessitates further spinal correction. As an extreme example, if a type A patient has exhausted all compensation reserves (SS $\leq$ 10°) preoperatively, THA has little power to correct the imbalance, and spinal surgery should be considered to address it.

This study had limitations. First, it was retrospective and performed in a single centre. Further larger multicentre prospective studies are required to validate the findings and clinical effectiveness. Second, axial rotation and coronal tilting, which might affect sagittal balance, were not considered. Third, the current criterion of the LL-TK mismatch is arbitrary and requires further biomechanical research into the cut-off value.

In summary, we propose a reliable and valid algorithm for predicting the rebalancing of spinal and pelvic posture after THA. This can improve the accuracy of preoperative planning of the functional orientation of the acetabular component at THA, and may help with the quantitative surgical planning for the patients who have a combination of severe symptoms from the hip and spine. Further prospective studies on the application of this method are necessary to evaluate its influence on the preoperative planning for patients undergoing THA.

Take home message

- The standing spinal and pelvic postures after total hip arthroplasty (THA) can be predicted based on a new, patient-specific algorithm.
- This can improve the accuracy of preoperative planning of the functional orientation of the acetabular component after THA.
- The classification may also help with the quantitative surgical planning for the patients who have a combined severe hip and spine deformity.

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