The Influence of Knee Osteoarthritis on Spinopelvic Alignment and Global Sagittal Balance

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J Knee Surg 2023;36:917–924.

Abstract

Osteoarthritis (OA) of the knee is thought to lead to a loss of lumbar lordosis (LL) as a compensation for knee flexion contracture. Changes in sagittal alignment are not limited to the lumbar spine and involve a complex interplay of alignment of the hip, pelvis, and spine. While spine–hip interactions have been previously explored, the influence of knee OA sagittal alignment parameters on spinopelvic alignment and global sagittal balance remains unexplored. Standing radiological examination using EOS biplanar radiography was examined in 108 patients with knee OA. Whole-body sagittal alignment parameters (thoracic kyphosis, LL, pelvic incidence, pelvic tilt [PT], femoropelvic angle [FPA], femoral tilt angle [FTA], tibial tilt angle, and knee flexion angle [KFA]) and global balance parameters (sagittal vertical axis [SVA] and odontoid hip axis [OD-HA] angle) were measured three dimensionally (3D). The correlation coefficients among all parameters were assessed. A multiple stepwise linear regression model was built to investigate the direct association between SVA or OD-HA angle (dependent variables) and sagittal alignment parameters and demographic data (independent variables). Significant correlations between KFA, FPA, FTA, SVA, and OD-HA angle were found. FTA was correlated with LL and FPA. The FTA was the most influential predictor of both global sagittal balance parameters ($p < 0.001$). Knee OA leads to changes in global sagittal balance with effects at the hip, knee, pelvis, and spine. FTA (forward flexion of the femur vs. the vertical plane) is the largest driver of global sagittal plane balance in patients with knee OA.

Keywords

- ► knee–spine syndrome
- ► lumbar lordosis
- ► knee flexion contracture
- ► knee osteoarthritis
- ► spinal deformity
- ► sagittal alignment

The knee and spine interact in terms of global sagittal balance and alignment.[1] Abnormal spinal balance may lead to knee contracture and vice versa, contracture of the knee may affect spinal balance. Knee osteoarthritis (OA) is a common cause of knee flexion contracture due to a combination of pain, degenerative changes, and an inflammatory reaction of the surrounding tissues.[2] Patients with knee flexion contractures have been found to have significantly reduced lumbar lordosis (LL) and low back pain may also be caused by knee OA, a phenomenon described as the "knee–spine syndrome."[3] Simulated knee flexion leads to decreased LL and increased hip flexion in healthy young adults without significant change in pelvic alignment.[4] However, few studies have focused on the effects of knee OA on the hip, pelvis, and spine, as well as patient's global sagittal alignment due to the challenge of obtaining whole-body standing lateral radiographs.[3,4]

received
November 3, 2021
accepted after revision
February 25, 2022
article published online
May 23, 2022

Thieme Medical Publishers, Inc.,
333 Seventh Avenue, 18th Floor,
New York, NY 10001, USA

DOI https://doi.org/10.1055/s-0042-1747947.
ISSN 1538-8506.

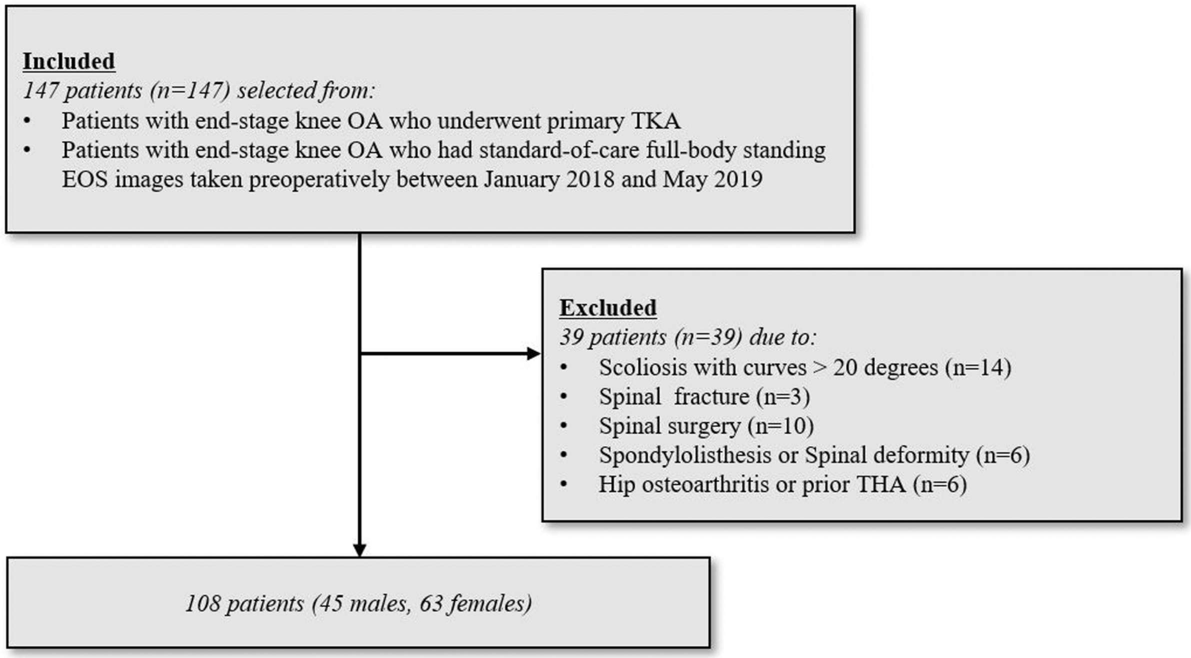

Fig. 1 Flow chart showing subjects from eligibility to inclusion in the present study. OA, osteoarthritis; THA, total hip arthroplasty; TKA, total knee arthroplasty.

Previous work has shown the importance of considering the hip–spine alignment when undertaking total hip arthroplasty (THA). The alignment and mobility of the spine can lead to functional changes in the position of the acetabulum based on pelvic accommodation.[5] If these relationships are not understood, arthroplasty components can be malpositioned during the index surgery, leading to a greater risk of impingement and dislocation of the hip prosthesis).[6,7] It is believed that 10 to 20% of patients have adverse spinopelvic mobility, which likely can affect the rest of the lower extremity as well.[8] While the functional and long-term hip arthroplasty outcomes related to sagittal evaluation of spinopelvic mobility and adjustments made for hip arthroplasty have been increasingly studied,[9] the relative importance of sagittal spinal alignment parameters in knee arthroplasty is not well known.

The objectives of our study were (1) to assess the sagittal alignment and global sagittal balance parameters of patients with end-stage knee OA, (2) to clarify the correlation between sagittal alignment of the OA knee and spinopelvic alignment and global sagittal balance, and (3) to investigate the direct association between sagittal alignment of the whole-body and global sagittal balance in patients with knee OA. We hypothesized that sagittal alignment of the knee would have a correlation with loss of lumber lordosis, hip flexion, and global sagittal balance parameters without significant change of pelvic alignment in patients with knee OA.

Materials and Methods

Participants and Data Selection

A retrospective case–control study was conducted in accordance with the protocol approved by our Institutional Review Board. Patients with end-stage knee OA who underwent primary total knee arthroplasty (TKA) and had full-body standing EOS images (model number 3.3 and serial number 3.1507.337, EOS Imaging Paris, France) taken preoperatively between January 2018 and May 2019 were screened for study inclusion. EOS full-body biplanar images are a standard part of the presurgical planning and templating process for TKA in our practice. Of the 147 subjects reviewed, 39 were excluded due to previous spinal fracture or fusions, evidence of spondylolistheses, or presence of a known spinal deformity such as cervical or lumbar kyphosis, scoliosis with curves >20 degrees, advanced hip OA, or prior THA. In our practice, patients with both hip and knee OA are treated with THA prior to TKA. After exclusions, 108 patients (45 males and 63 females) were included as the final study population (►**Fig. 1**). We collected data including sex, age, weight, height, and body mass index (BMI) for baseline demographics (►**Table 1**).

Biplanar Radiographic Acquisition

All included patients underwent routine biplanar full-body standing stereographs with the EOS system (EOS Imaging Paris, France), a low-dose system acquiring simultaneous stereographs in the sagittal (105 kVp/250 mA) and coronal (90 kVp/200 mA) planes of the patient (with two sources at 90 degrees) from head to toe. Per protocol, images were acquired with the patient standing in the EOS suite in a relaxed position with hands gripping the bar to prevent falling as per manufacturer's guidelines.

Studied Parameters

From biplanar stereographs, a 3D patient-specific model including the full spine, the pelvis, and the lower limbs

Table 1 Demographic parameters and measured variables

	Mean	SD	Range
Age (y)	66.2	10.7	30–88
Height (cm)	170.7	10.3	150–193
Weight (kg)	95.9	19.5	42–135
BMI	31.3	4.8	13.1–39.9
TK (deg)	41.3	13.9	11.8–74.7
LL (deg)	54.2	12.1	20.6–81.3
PI (deg)	52.9	11.1	30.2–81.2
PT (deg)	15.1	9.3	−5.7 to 44.0
FPA (deg)	12.7	10.5	−17.4 to 39.9
FTA (deg)	3.0	5.0	−8.3 to 16.7
TTA (deg)	6.2	4.4	−7.1 to 22.1
KFA (deg)	9.3	7.8	−11.6 to 38.2
SVA (mm)	29.6	38.3	−58.4 to 137.8
OD-HA angle (deg)	1.3	4.6	−9.1 to 12.8

Abbreviations: BMI, body mass index; FPA, femoropelvic angle; FTA, femoral tilt angle; KFA, knee flexion angle; LL, lumbar lordosis; OD-HA, odontoid-hip axis; PI, pelvic incidence; PT, pelvic tilt; SD, standard deviation; SVA, sagittal vertical axis; TK, thoracic kyphosis; TTA, tibial tilt angle.

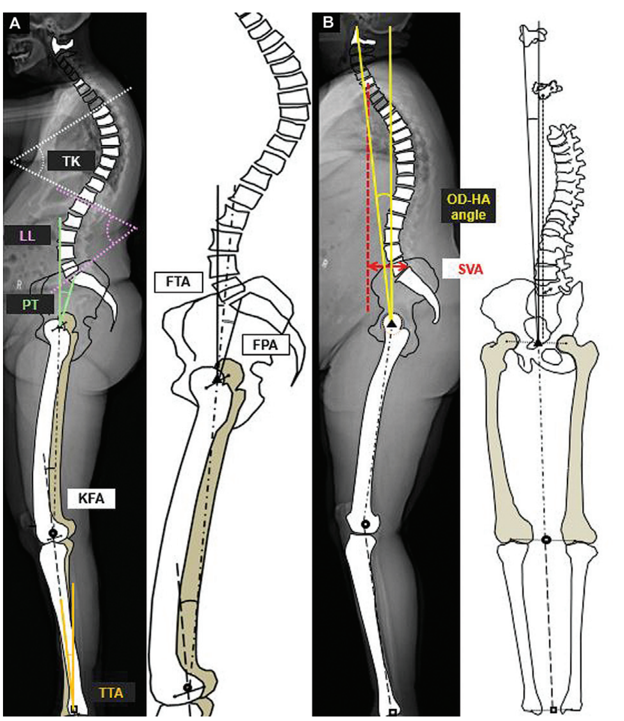

Fig. 2 (**A**) Schematic illustrations of the sagittal alignment parameters of the whole body; (**B**) schematic illustration of the global sagittal alignment parameter. The SVA corresponds to the horizontal distance between C7 plumb line and the posterior–superior S1 corner. The OD-HA angle is the angle between the vertical and the highest point of the odontoid process (dens) connecting to the center of the bicoxofemoral axis. FPA, femoropelvic angle; FTA, femoral tilt angle; KFA, knee flexion angle; LL, lumbar lordosis; OD-HA, odontoid-hip axis; PT, pelvic tilt; SVA, sagittal vertical axis; TK, thoracic kyphosis; TTA, tibial tilt angle.

was created with sterEOS 3D software version 1.6.4 (EOS Imaging, Paris, France) using validated reconstruction techniques.[10] All parameters were measured in the patient frame where the frontal plane is the vertical plane containing the bicoxofemoral axis connecting both femoral head centers and the sagittal plane defined as the orthogonal to the frontal plane. The origin of the frame was the center of the bicoxofemoral axis.

Sagittal alignment parameters (►**Fig. 2A**) included: (1) thoracic kyphosis (TK), (2) LL, (3) pelvic incidence (PI), (4) pelvic tilt (PT), (5) femoropelvic angle (FPA), (6) femoral tilt angle (FTA), (7) tibial tilt angle (TTA), and (8) knee flexion angle (KFA). Global sagittal balance parameters (►**Fig. 2B**) included: (1) sagittal vertical axis (SVA) and (2) odontoid hip axis (OD-HA) angle (a measurement of coronal imbalance). Details of each measurement are outlined in ►**Table 2** and have previously been described.[11]

PI and PT were measured according to previously documented methods.[12] The FPA and FTA were used to describe the relationship between the femur and pelvis.[3] The FPA was defined as the angle between the sagittal femoral axis and a line joining the middle of the cranial S1 endplate to the center of the bicoxofemoral axis. The FTA was defined as the angle between the hip axis and the femoral mechanical axis to represent femoral inclination caused by knee flexion. The FPA includes the relationship to the sacrum, while FTA only shows the angle of the femur in relationship to the vertical. Both a knee flexion contracture and a hip flexion contracture may lead to increased FTA. The TTA was defined as the angle between the vertical axis and the tibial mechanical axis to represent tibial inclination caused by knee flexion.

Table 2 Descriptive analysis of the measured variables

Term and abbreviation	Definition
Bicoxofemoral axis	The line connecting to bilateral center of the femoral head
Origin	The center of the bicoxofemoral axis
Hip axis	The vertical line from the origin
Femoral mechanical axis	The line connecting the origin and the midpoint of the line between bilateral knee centers, which is the center of intercondylar fossa
Tibial mechanical axis	The line connecting the midpoint of the line between bilateral knee centers to the midpoint of the line between the bilateral ankle centers, which is the center of the distal tibial joint surface
Thoracic kyphosis (TK) (deg)	The angle between the superior endplate of T4 and the inferior endplate of T12. Larger angle indicates thoracic spine with more kyphosis
Lumbar lordosis (LL) (deg)	The angle between the superior endplate of L1 and the superior endplate of S1 Larger angle indicates lumbar spine with more lordosis
Pelvic incidence (PI) (deg)	The angle between the perpendicular to the sacral plate at its midpoint and the line connecting this point to origin. Larger angle indicates a broad pelvis
Pelvic tilt (PT) (deg)	The angle between the hip axis and the line through the midpoint of the sacral plate to the origin. Larger angle indicates retroversion of the pelvis
Femoropelvic angle (FPA) (deg)	The angle between the femoral mechanical axis and a line connecting the midpoint of the sacral plate to the origin. Larger angle indicates extension of the hip joint
Femoral tilt angle (FTA) (deg)	The angle between the hip axis and the femoral mechanical axis. Larger angle indicates a backward femur tilt
Tibial tilt angle (TTA) (deg)	The angle between tibial mechanical axis and vertical. Larger angle indicates a forward tibial tilt
Knee flexion angle (KFA) (deg)	The angle between the femoral mechanical axis and the tibial mechanical axis. Larger angle indicates the flexion of the knee
Sagittal vertical axis (SVA) (mm)	The horizontal distance between C7 plumb line and the posterior–superior S1 corner. Larger values indicate anterior sagittal balance
Odontoid-hip axis (OD-HA) angle (deg)	The angle between the hip axis and the highest point of the odontoid process (dens) connecting to the origin. Larger angle indicates anterior sagittal balance

Statistical Analysis

A post hoc power analysis was performed using software G*Power 3.1 (Institut fur Experimentelle Psychologie, Dusseldorf, Germany) to determine the power of the study considering the current sample size. Using an α of 0.05 and a medium effect size ($f^2 = 0.15$), a total sample size of 108 provided a study power of 0.979. All parameters including demographic data were checked for normal distribution using the Shapiro–Wilk's test. Intraclass correlation coefficient (ICC) was determined from data obtained by one author (R.K.) who measured each parameter twice for 20 participants in a blinded manner on different days. To determine interobserver reproducibility of each parameter, the ICC was obtained by measuring the parameters in a blinded manner in 20 patients by two authors (R.K. and G.B.). Correlation coefficients among all parameters, including demographic data, were subsequently calculated. Demographic data were added to the regression analysis, as they were considered clinically important variables that may have influence on sagittal or balance parameters. Spearman's rank-order correlation coefficients (R_s) were calculated when the parameters were not normally distributed, and Pearson's product-moment correlation coefficients (R_p) were calculated when the parameters were normally distributed.

To investigate the direct association between SVA and OD-HA angle (dependent variables) and sagittal alignment parameters and demographic data (independent variables), a multiple, stepwise linear regression model was built. Sagittal alignment parameters that did not have statistically significant correlation with the SVA or OD-HA angle were excluded as independent variables. If a significant correlation was evident between two variables (R_p or $R_s > 0.7$), a variable that had lower correlation coefficient with SVA or OD-HA angle was excluded. The probability level accepted for statistical significance was set at $p < 0.05$ (SPSS version 24; SPSS, Inc., Chicago, IL).

Results

Reliability of Measurements

The mean value, standard deviation, and range of each parameter are shown in ►**Table 1**. The overall KFA was

Table 3 Correlation between all parameters

	SVA	OD-HA angle	TK	LL	PI	PT	FPA	FTA	TTA	KFA	Age	Weight	Height	BMI
SVA	1.000	0.838[a,b]	−0.013[b]	−0.267[a,b]	0.189[b]	0.096[b]	−0.103[b]	0.460[a,b]	0.110[b]	0.315[a,b]	0.055[b]	−0.131[b]	0.117[b]	−0.193[a,b]
OD-HA angle		1.000	0.045	−0.161[a]	−0.016	−0.192[a]	−0.396[a]	0.487[a]	0.102[b]	0.314[a,b]	0.023	−0.183[a]	0.023[b]	−0.208[a,b]
TK			1.000	0.591[a]	0.009	0.013	0.063	−0.035	0.221[a,b]	0.113[b]	0.033	−0.149	−0.051[b]	0.102[b]
LL				1.000	0.335[a]	−0.126	0.003	−0.245[a]	0.062[b]	−0.095[b]	−0.029	0.214[a]	0.086[b]	0.141[b]
PI					1.000	0.722[a]	0.606[a]	−0.003	0.007[b]	−0.006[b]	0.046	0.075	0.030[b]	0.009[b]
PT						1.000	0.861[a]	0.073	0.049[b]	0.042[b]	−0.018	0.076	0.034[b]	0.038[b]
FPA							1.000	−0.302[a]	−0.101[b]	−0.261[a,b]	−0.024	0.109	0.036[a,b]	0.077[b]
FTA								1.000	0.314[a,b]	0.782[a,b]	−0.070	−0.132	−0.025[b]	−0.070[b]
TTA									1.000[b]	0.792[a,b]	−0.047[b]	−0.117[b]	0.078[b]	−0.215[a,b]
KFA										1.000	−0.088[b]	−0.127[b]	0.054[b]	−0.177[b]
Age											1.000	−0.187[a]	−0.088[b]	−0.241[a,b]
Weight												1.000	0.547[a,b]	0.759[a,b]
Height													1.000	−0.110[b]
BMI														1.000

Abbreviations: BMI, body mass index; FPA, femoropelvic angle; FTA, femoral tilt angle; KFA, knee flexion angle; LL, lumbar lordosis; OD-HA, odontoid-hip axis; PI, pelvic incidence; PT, pelvic tilt; SVA, sagittal vertical axis; TK, thoracic kyphosis; TTA, tibial tilt angle.
[a]Significant difference = $p < 0.05$; correlation coefficient (R value) after Pearson's product-moment correlation test (R_p).
[b]Spearman's rank correlation test (R_s).

consistent with knee flexion contracture (mean 9.3 ± 7.8 degrees). Global sagittal balance showed overall normal balance parameters (SVA 29.6 ± 38.3 mm; OD-HA angle 1.3 ± 4.6 degrees). The intra- and interobserver reproducibilities via ICC were all above 0.800, with an average intrarater ICC of 0.955 and an average interrater ICC of 0.961.

Correlations between All Parameters

There was a negative correlation between KFA and FPA ($R_s = -0.261$), and a strong positive correlation between KFA and FTA ($R_s = 0.782$), and TTA ($R_s = 0.792$). KFA was not correlated with either PI ($R_s = -0.006$) or PT ($R_s = 0.042$). There were negative correlations between FTA and LL ($R_p = -0.245$), and FPA ($R_p = -0.2302$) (►**Table 3**).

In regard to sagittal balance, we found a negative correlation between the SVA and LL ($R_s = -0.267$), and positive correlations between the SVA and FTA ($R_s = 0.460$), KFA ($R_s = 0.315$), and BMI ($R_s = -0.193$). There were negative correlations between OD-HA angle and LL ($R_p = -0.161$), PT ($R_p = -0.192$), and FPA ($R_p = -0.396$), and positive correlations between OD-HA angle and KFA ($R_s = 0.314$), and FTA ($R_p = 0.487$) (►**Table 3**).

Multiple Regression Analysis between Global Sagittal Alignment Parameters and Sagittal Balance Parameters

LL, FTA, and BMI were selected as predictors among sagittal alignment parameters that had statistically significant correlation with the SVA ($p < 0.05$). The multiple stepwise linear regression found that FTA (standardized partial regression coefficient: $\beta = 0.467$, $p < 0.001$) and LL ($\beta = -0.179$, $p = 0.037$) were predictors of SVA. The coefficient of determination (R^2) of the regression model is 0.291 (►**Table 4**).

LL, FPA, FTA, and BMI were selected as independent variables among sagittal alignment parameters that had statistically significant correlations with OD-HA angle ($p < 0.05$). Multiple stepwise linear regression found that FTA ($\beta = 0.404$, $p < 0.001$) and FPA ($\beta = -0.274$, $p = 0.002$) were identified as independent variables of OD-HA angle. The coefficient of determination (R^2) of the regression model is 0.305 (►**Table 4**).

Discussion

Our data support the hypothesis that sagittal alignment of the knee is correlated with loss of LL, increased hip flexion, and loss of global sagittal balance parameters in patients with knee OA. These findings indicate a complex interplay between the knee, hip, and spine. Furthermore, our findings suggest that FTA, which measures the angle of the femur in relation to the vertical plane, is a major factor in driving sagittal balance. The correlation between KFA and FTA was strong ($R_s = 0.782$) in patients with knee OA. Our findings also demonstrate that the more the FTA increases, the larger the loss of LL and the more anterior the sagittal balance becomes. This anatomic relationship, first described by Murata et al, compared plain radiographs to joint range of motion and found that patients with a knee flexion contracture of more than 5 degrees had significantly reduced spinal lordosis.[3] In two separate experimental studies, LL was significantly reduced in patients with an experimental flexion contracture produced by wearing a knee brace.[3,4] The studies suggested a relationship between the knee and spine, but could not reveal the amount of influence a knee flexion contracture had on the global sagittal balance, nor whether the knee flexion contracture resulted in lumbar spinal symptoms.[3]

Our study found a significant correlation between the SVA and OD-HA angle with sagittal alignment of the lumbar spine, hip, and knee joints. Multiple stepwise linear regression analysis found that the FTA was the most influential predictor associated with both the SVA and OD-HA angle. LL was the second most significant predictor associated with the SVA, while the FPA was the second predictive parameter associated with the OD-HA angle. From these findings, we can surmise that in cases where the primary driver is knee flexion contracture due to OA and backward femur tilt, the trunk tends to move posteriorly. Therefore, the lumbar spine or hip joint must respond to maintain balance. The lumbar spine achieves this compensation by reducing the lordosis, while the hip joint flexes to shift the center of mass forward.[3] These results are similar to other studies that have evaluated lateral radiographs of the spine.[13] By using EOS whole-body imaging, our study has the unique advantage of visualization of the knee as well as the entire spine in one view. By linking the anteroposterior (AP) and lateral views, subtle differences in radiographs can also be standardized.

While our results showed a relationship of KFA with global sagittal balance, KFA did not correlate with PT or PI. This agrees with previous literature that knee flexion, both experimentally[4] and from knee OA,[13] does not seem to alter pelvic alignment. Instead, the compensation involves flexion

Table 4 Multiple linear regression analysis with stepwise procedure and dependent variable of global sagittal balance parameters

Dependent variable	Selective variables by stepwise procedure	Beta	*t* value	*p*-Value	R^2 value
SVA	FTA	0.467	5.503	< 0.001	
	LL	−0.179	−2.114	0.037	0.291
OD-HA angle	FTA	0.404	4.730	< 0.001	
	FPA	−0.274	−3.209	0.002	0.305

Abbreviations: FPA, femoropelvic angle; FTA, femoral tilt angle; LL, lumbar lordosis; OD-HA, odontoid-hip axis; SVA, sagittal vertical axis.

of the hip and knee resulting in a significant correlation with FPA and FTA. Flexion contracture of the knee due to knee joint disease leads to a decrease in FPA and an increase in FTA, resulting in the lumbar spine and hips shifting forward to maintain balance.

Similarly, OA of the hip and hip flexion contracture have also been shown to affect global sagittal balance. Flexion contracture of the hip leads to change in pelvic alignment with retroversion of the pelvis and decrease lordosis of the spine.[14] Total hip replacement is able to improve hip contracture and alter spinal alignment.[13] The interaction between the hip and the spine is particularly important when positioning the acetabular component in hip arthroplasty. If there is both severe lumbar deformity and hip deformity, the position of the acetabular component may have to be altered to allow for hip stability.[6,15] In the future, further work is needed to elucidate the precise interaction between knee and spine. Perhaps subtle differences in positioning of femoral and/or tibial prosthesis could allow for more knee extension in these cases that may help overall sagittal alignment.

Total knee replacement can decrease knee flexion contracture with subsequent normalization of spinal balance.[7] Correction of the flexion contracture by knee surgery, such as TKA, might decrease the FTA and therefore prevent the loss of LL and anterior sagittal imbalance. If the standing posture with knee flexion does not change despite the correction by TKA, there might be compensatory mechanisms to anterior sagittal balance caused by a rigid spinal deformity, which the primary pathology may then be considered the loss of LL. If both spine deformity and knee deformity from OA are present, it is unknown whether it is better to first address the spine or the knee. It is generally thought that if there is severe deformity or windswept coronal deformity from valgus knee arthritis that the knee should be corrected first.[16] These patients are especially challenging and results of spine correction[4,17] and knee replacement[18] have been found to be inferior when both conditions are present. No prospective studies have been performed to examine outcomes of patients with both spine and knee arthritis.

This study has several limitations. First, it is difficult to know the relative contributions of the hip and knee to sagittal imbalance and spinal deformity. We removed any patients with a documented history of previous spinal fracture and surgeries, spondylolistheses, and severe coronal deformities of the spine to focus on the effects of knee OA and flexion contracture on spinal alignment and balance. However, there may have been patients who had unreported knee or spine pathology not visualized on radiographs and potentially confounding our measured anatomic relationships. Second, there are limitations to the method in which a subject must stand in the EOS system. Patients stood with hands gripping the bar equipped on the EOS station platform, which may artificially affect one's global balance by not truly simulating a natural standing posture. Standing position with the hands resting on the clavicle has been recommended to obtain a functional radiograph of the lateral spine.[19] However, all our patients had severe knee OA and were at risk of falling, so they were instructed to grip the bar lightly in a relaxed position. This could have further led to increased knee flexion that was not solely due to the contracted joint. Neither dynamic knee function nor hamstring function was part of this study, though we realize these factors may influence knee flexion. Third, cervical alignment was not assessed via EOS imaging, which may affect the OD-HA angle. C7 slope, which is reported as the key parameter to assess the cervical alignment,[20] could not be identified clearly because the humerus and ribs were superimposed in some cases. Although the center of the C7 vertebral body was difficult to identify in some instances, the reproducibility of the measurements was high and accepted as confirmation of measurement reliability. Finally, it is possible that changes in coronal plane alignment of the knee also could affect sagittal balance. As our imaging acquisition protocol utilized both AP and lateral EOS images to calculate our radiological parameters, we believe this effect to be muted.

Conclusion

Knee OA leads to changes in global sagittal balance with effects at the hip, knee, pelvis, and spine. FTA, which measures the angle of the femur in relationship to the vertical plane, had a strong association with loss of LL and anterior sagittal balance.

Conflict of Interest
None declared.

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