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Lower limb compensation mechanisms influencing sagittal balance after lumbar fusion

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Abstract

Background The adoption of whole-body imaging in routine practice has allowed radiographic analysis of the lower limbs, even in degenerative pathologies. This work aims to characterize the occurrence of knee flexion in relation to global and regional sagittal parameters of the spine in lumbar degenerative pathologies.

Methods This work is a single-center retrospective analysis including patients who underwent lumbar spine fusion for degenerative pathology. All included patients had biplanar whole-body imaging before and after surgery with a minimum of 6 months of follow-up. Exclusion criteria were patients with prior spine surgery and total knee replacement before lumbar spine fusion. Patients were grouped based on preoperative knee flexion threshold (10°) and postoperative changes in knee flexion (Δ KF).

Results Postural parameters of 108 patients (65 M; 43 F) with an average age of 63.02 years were studied. Patients with greater preoperative knee flexion ($n=68$) had significantly greater PI-LL mismatch ($9.88 \pm 10.48^\circ$ vs. $0.57 \pm 12.19^\circ$) and SVA (5.7 ± 4.2 cm vs. 2.1 ± 3.9 cm) than the group with less knee flexion ($n=44$). Patients with exacerbated knee flexion postoperatively ($n=57$) had significantly greater PI-LL mismatch ($p=0.01$) as well as loss of lordosis ($p=0.04$) after surgery compared to the group with less flexion ($n=51$) without any impact on SVA.

Conclusion Knee flexion angle can help quantify lower limb compensation in relation to spinopelvic misalignment in patients operated on for degenerative pathologies. Nevertheless, further work is needed to fully understand the complex interplay of compensation mechanisms in the face of sagittal imbalance and spinopelvic malalignment.

Keywords Spine surgery, Knee flexion, Compensatory mechanisms, Degenerative spine disease

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Introduction

Sagittal balance loss is a consequence of various spinal deformities, affecting almost 32% of the population over 50, and 68% over 70. It is the factor that causes the most significant impact on various tests measuring daily pain and the inability to perform certain everyday activities [1–5]. In response to this imbalance, the whole body implements compensatory mechanisms aimed at bringing the torso back and adopting the most upright position possible [6, 7]. These compensatory mechanisms are diverse and their consideration is essential in understanding this sagittal balance and in preoperative planning when vertebral fusion is required. Previous studies have described compensatory mechanisms involving pelvic retroversion and thoracic adjustments to maintain sagittal balance [6, 8, 9].

While spinal and pelvic compensatory mechanisms have been widely described, lower limb adaptations, particularly knee flexion, remain comparatively underexplored in the literature [10, 11]. This gap in the literature is partly due to the limited access to whole-body X-rays, which allow us to visualize the relationships of all postural parameters in a natural position. This is made possible by EOS® Imaging. Biplanar imaging system (EOS®) can acquire clinical parameters of the entire skeleton in all three planes of space with less radiation [12, 13]. Unlike conventional radiographs, EOS® imaging enables simultaneous acquisition of full-body images in a weight-bearing position, allowing accurate assessment of global alignment and compensatory mechanisms across the entire kinetic chain [12, 13].

The aim of this work is therefore to fill the gap in the literature by describing the involvement of compensation mechanisms in the lower limbs in maintaining sagittal balance. To this end, the relationships between these mechanisms and all postural parameters are analyzed. We hypothesize that increased knee flexion is associated with greater spinopelvic mismatch and may persist or worsen postoperatively in patients with insufficient restoration of lumbar lordosis.

Material and methods

Population

This is a retrospective single center study approved by the institutional ethics committee. The need for informed consent to participate was waived by the institutional ethics committee (University of Montreal). The study was conducted according to the declaration of Helsinki. Patients were included if they underwent lumbar or lumbosacral fusion surgery between 2015 and 2020 for various degenerative spinal pathologies. All patients included underwent pre- and postoperative standing whole-body radiological examinations at least 6 months after surgery. This minimum duration of 6 months, classically found in

the literature [14], is necessary to overcome most postoperative pain and thus adopt a more natural position. Exclusion criteria consisted of patients who have already undergone spinal surgery, patients with knee prostheses, patients adopting a position that is not very representative of a natural position on X-rays, who need to hold themselves in place, or non-compliant radiographs (incomplete field of acquisition, in two images, or too much movement during imaging).

Data collection

All parameters used in this study are available from the software SterEOS® (EOS Imaging, Paris) that allows to reconstruct, in three dimensions, the thoracic and lumbar spine and the pelvis. The 3D reconstruction from the biplanar radiographs used parametric models based on transversal and longitudinal inferences, as described by Humbert et al. [13] and Pomero et al. [15]. The intra- and inter-operator reliability of 3D angular parameters of spinal curvatures, 3D angular or distance parameters of the pelvis, 3D distance parameters involving plumb lines, and the measurement of each vertebral and intervertebral axial, sagittal, and coronal rotation, available after using this same semiautomatic method, have been previously reported in some studies. All these studies confirmed the good or excellent intra-rater and inter-rater reliability of 3D parameter measurements in patients with adolescent idiopathic scoliosis [16, 17], with severe scoliosis or on postoperative images [18] and with adult spinal deformity [19]. They thus justify the current clinical use of this method in the proposed study.

The parameters extracted from the radiographs was done using the commercial version of SterEOS® (1.8.99.23R), the EOS image processing software and consisted of pelvic incidence (PI); sacral slope (SS); pelvic tilt (PT); cervical lordosis (C2-C7); occipito-cervical angle (O-C2); thoracic kyphosis T1-T12, T4-T12 and total thoracic kyphosis at inflection point (TK); lumbar lordosis L1-L5, L1-S1 and total lumbar lordosis at inflection point (LL); sagittal vertical axis (SVA); lead line through auditory canals (CAM); spino-sacral angle (SSA); T1 and T9 tilt; T1 pelvic angle (TPA); Full-body balance index (FBI); Ondotoïd hip axis (ODHA); sacrofemoral distance (SFD) and sacrofemoral angle (SFA); global sagittal angle (GSA); number of fused levels; maximum knee flexion (KF) and maximum ankle dorsiflexion (AA). All parameters were measured by one observer using validated SterEOS® software according to standardized definitions previously described in the literature [20, 21].

Grouping

In order to highlight what differentiates populations according to the presence or absence of excessive compensation mechanisms in the lower limbs, a critical

Table 1 Characteristics of the included patients

	Population (n = 108) n (%)	Mean
Gender		
Male	65 (60.2%)	
Female	43 (39.8%)	
Age		63.02
20–39	8 (7.4%)	
40–59	22 (20.4%)	
60–79	75 (69.4%)	
> 80	3 (2.8%)	
Pathologies		
Lumbar scoliosis	33 (30.6%)	
Spondylolisthesis	31 (28.7%)	
Disc disease and stenosis	89 (82.4%)	
Loss of lordosis	21 (19.4%)	
Fracture	2 (1.8%)	
Metastasis	2 (1.8%)	

threshold for the degree of knee flexion of 10° was chosen as described in the literature [10, 11]. Knee flexion will be judged to be significantly greater postoperatively if: Flexion_{post op} > Flexion_{pre op} + 2 RMSsd (root mean square of successive differences).

Thus, when we seek to compare sagittal parameters according to the evolution of knee flexion (Δ KF). Δ KF represents the postoperative change in knee flexion, adjusted for measurement variability, with positive values indicating a clinically meaningful increase in knee flexion after surgery. We will separate the database into two groups:

- Group A: Patients with less knee flexion after lumbar fusion (Δ KF $\leq$ 0)
- Group B: Patients with greater knee flexion after lumbar fusion (Δ KF > 0)

With

$$\Delta\text{KF} = \text{Flexion}_{\text{post op}} - \text{Flexion}_{\text{pre op}} + 2 \text{RMSsd}$$

The addition of 2 RMSsd to the Δ KF threshold was used to minimize the influence of measurement variability and to identify clinically meaningful changes in knee flexion beyond expected fluctuations.

Statistical analysis

All statistical tests are carried out using XLSTAT-R 2022 in Excel and GraphPad Prism 9 at a significance level of 95%. First, a normality test (Shapiro-Wilk) is performed to verify the normality of all parameters. For those meeting this criterion, a Grubbs test is performed to detect any outliers. Differences between clinical parameters, are analyzed by Student's t-tests (paired or unpaired as appropriate) for data following a normal distribution,

Table 2 Spinopelvic parameters for the 2 different groups separated based on knee flexion angle

Parameters	KF < 10° (n = 44)	KF > 10° (n = 68)	P-value
	Mean $\pm$ sd	Mean $\pm$ sd	
PI (°)	54.42 $\pm$ 14.39	54.07 $\pm$ 11.42	0.8898
SS (°)	37.24 $\pm$ 13.27	33.85 $\pm$ 10.52	0.1419
PT (°)	17.17 $\pm$ 7.80	20.23 $\pm$ 6.55	0.0299
C2–C7 (°)	9.93 $\pm$ 12.14	15.03 $\pm$ 16.94	0.0893
TK (°)	48.13 $\pm$ 14.35	43.90 $\pm$ 12.94	0.1132
LL (°)	53.85 $\pm$ 15.34	44.20 $\pm$ 14.79	0.0039
PI–LL	0.57 $\pm$ 12.19	9.88 $\pm$ 10.48	< 0.0001
TPA (°)	13.73 $\pm$ 8.219	20.18 $\pm$ 7.85	< 0.0001
SVA (mm)	20.79 $\pm$ 38.35	57.37 $\pm$ 42.26	< 0.0001
KF (°)	5.00 $\pm$ 3.21	16.84 $\pm$ 5.15	< 0.0001
AA (°)	5.615 $\pm$ 2.86	9.80 $\pm$ 3.44	< 0.0001

Bold values denotes statistical significance

otherwise a Wilcoxon signed ranks test was performed. Differences between several groups are also analyzed using an ANOVA test. As this was a retrospective study including all eligible patients during the study period, no a priori sample size calculation was performed.

Results

Baseline characteristics

One hundred and eight subjects (65 men, 43 women, mean age: 63.02 years [25–89]) were included with spinal stenosis being the most common pathology. However, it is important to note that 42.5% are associated with other pathologies such as scoliosis or spondylolisthesis. They all required surgical treatment by spinal fusion (Table 1).

Preoperative parameters according to knee flexion

When separating the population into two distinct groups according to the threshold of knee flexion (Table 2), TPA, SVA and PI–LL, and to a lesser extent PT, were significantly higher for the group with more than 10° of flexion, while LL was significantly lower.

Evolution of knee flexion

52.78% ($n=57$) of the patients who underwent lumbar fusion surgery had greater knee flexion six months post-operatively. Moreover, 66% ($n=29$) of patients initially below the critical threshold of 10° had greater flexion after lumbar fusion, and 23% ($n=10$) exceeded the threshold. Conversely, for patients with significant pre-operative flexion, 56% ($n=36$) experienced a reduction in knee flexion, with 14% ($n=9$) even falling below the 10° threshold.

Postural parameters according to evolution of knee flexion

There were no significant changes in postural parameters in patients with less knee flexion six months after lumbar fusion (Table 3). Only thoracic kyphosis (TK) was

Table 3 Spinopelvic parameters before, and 6 months after spinal fusion for patients who had less knee flexion post-operatively

$\Delta KF \leq 0$	Pre-operative	Post-operative	
Parameters	Mean $\pm$ sd	Mean $\pm$ sd	P-value
PI ($^{\circ}$)	53.87 $\pm$ 12.07	54.09 $\pm$ 12.11	0.8491
SS ($^{\circ}$)	34.49 $\pm$ 11.73	35.43 $\pm$ 11.33	0.4418
PT ($^{\circ}$)	19.38 $\pm$ 7.31	18.66 $\pm$ 7.72	0.2177
C2-C7 ($^{\circ}$)	15.13 $\pm$ 14.60	13.74 $\pm$ 15.22	0.3897
TK ($^{\circ}$)	46.16 $\pm$ 15.15	49.22 $\pm$ 13.89	0.0334
LL ($^{\circ}$)	47.47 $\pm$ 17.12	48.72 $\pm$ 17.23	0.4297
PI-LL ($^{\circ}$)	6.40 $\pm$ 11.45	5.37 $\pm$ 11.83	0.3563
TPA ($^{\circ}$)	18.01 $\pm$ 8.35	17.51 $\pm$ 8.43	0.5336
SVA (mm)	44.23 $\pm$ 40.29	45.54 $\pm$ 45.37	0.8069
KF ($^{\circ}$)	14.28 $\pm$ 7.14	8.02 $\pm$ 6.36	<0.0001
AA ($^{\circ}$)	9.00 $\pm$ 3.52	2.89 $\pm$ 22.90	0.0191

Bold values denotes statistical significance

Table 4 Spinopelvic parameters before, and 6 months after spinal fusion for patients who had more knee flexion post-operatively

$\Delta KF > 0$	Pre-operative	Post-operative	
Parameters	Mean $\pm$ sd	Mean $\pm$ sd	P-value
PI ($^{\circ}$)	54.74 $\pm$ 13.19	54.75 $\pm$ 13.36	0.9971
SS ($^{\circ}$)	35.57 $\pm$ 11.95	33.06 $\pm$ 10.8	0.0369
PT ($^{\circ}$)	19.17 $\pm$ 7.73	21.69 $\pm$ 7.87	<0.0001
C2-C7 ($^{\circ}$)	10.79 $\pm$ 15.62	11.88 $\pm$ 17.68	0.4608
TK ($^{\circ}$)	44.88 $\pm$ 12.52	46.55 $\pm$ 13.61	0.142
LL ($^{\circ}$)	48.62 $\pm$ 14.40	45.61 $\pm$ 12.58	0.0439
PI-LL ($^{\circ}$)	6.13 $\pm$ 12.90	8.806 $\pm$ 11.5	0.0154
TPA ($^{\circ}$)	17.51 $\pm$ 9.41	19.76 $\pm$ 9.13	0.0039
SVA (mm)	40.91 $\pm$ 48.24	43.65 $\pm$ 40.66	0.5733
KF ($^{\circ}$)	10.19 $\pm$ 7.31	14.66 $\pm$ 7.43	<0.0001
AA ($^{\circ}$)	7.301 $\pm$ 3.93	9.684 $\pm$ 4.08	<0.0001

Bold values denotes statistical significance

significantly greater, and ankle dorsiflexion lower after surgery. These results are quite different in patients with more knee flexion after surgery for SS, PT, LL, TPA and PI-LL (Table 4). Comparing the evolution of parameters between these two groups, the group with greater knee flexion gains significantly more PT, PI-LL and TPA and loses SS and LL than the group with less knee flexion after spinal fusion.

Discussion

The recent implementation of whole-body imaging in the daily practice of spine surgeons practice allowed access to the radiographic analysis of the lower limbs, even in degenerative pathologies. In fact, our findings corroborate the logic in the literature according to which compensatory mechanisms, including knee flexion, come into play in response to a deterioration in sagittal balance as the lack of lumbar lordosis becomes significant [6, 8].

The literature explains that compensatory mechanisms in the lower limbs are initiated only after the spine and pelvis have reached its limit of retroversion transcribed by a PTmax [6, 8, 9]. Yet, our results show that the difference in PT between flexion groups below and above 10° was the smallest of all the parameters. These findings are also addressed in the study by Lee et al. [22], which evaluates in 30 participants the extent to which spinopelvic parameters change during simulated knee flexion in healthy patients. The results of their study show a significant reduction in lordosis beyond 15° of flexion, however no significant change could be found for pelvic parameters, including PT.

When investigating the evolution of knee flexion after surgery in patients with flexion less than or greater than 10°, 52.78% ($n = 57$) of patients experienced a significant increase in flexion after surgery. This percentage rises to 66% ($n = 29$) in patients who had no excessive flexion pre-operatively, with almost a quarter (23%; $n = 10$) exceeding the critical threshold of 10°. At the same time, 56% of patients initially above 10° flexed less postoperatively, even falling back below the 10° threshold for 9 of them (14%). In fact, in patients whose knee flexion increased, there was a significant drop in LL, leading to an increase in PT, PI-LL and TPA. Importantly, TPA appears to increase significantly ($p = 0.013$), while SVA remains unchanged ($p = 0.92$). This suggests that the additional knee flexion in place is sufficient to compensate for the greater anterior imbalance caused by the loss of lumbar lordosis. The average LL loss of 3.0° can be explained by the fact that vertebral fusions are mostly performed in the lower lumbar region, where degenerative changes are most common [23]. This loss of lumbar lordosis after fusion has already been described in the literature [24, 25]. For patients with less or identical flexion, we find the opposite phenomenon, where they gain on average 1.3° of lordosis. This results in a lower need for PT retroversion (-0.72 ± 4.14) and a lower TPA (-0.50 ± 5.73). This rebalancing of the sagittal balance results in less knee flexion and ankle dorsiflexion (-3.71 ± 2.82 and -0.98 ± 2.88). As shown in the literature, a decrease in PT is indeed correlated with a better perception of the benefits of the operation on the part of the patient, with notably less lumbar and leg pain [14, 26]. Nevertheless, while an association between loss of lumbar lordosis and increased postoperative knee flexion was observed, causal relationships cannot be definitively established from this analysis and should be interpreted with caution.

From a clinical perspective, the assessment of knee flexion using whole-body imaging may help identify compensatory mechanisms masking sagittal imbalance. Persistent or increased knee flexion after lumbar fusion may reflect insufficient restoration of lumbar lordosis and should be considered when evaluating postoperative

alignment. Therefore, incorporating lower limb parameters into the global assessment of sagittal balance may improve surgical planning and postoperative interpretation. Persistent knee flexion may also increase mechanical loading across the knee joint and could potentially contribute to the progression of degenerative changes such as osteoarthritis. This highlights the importance of restoring optimal sagittal alignment to minimize long-term compensatory strain. Nevertheless, although several parameters demonstrated statistically significant differences, the magnitude of these changes should be interpreted with caution. Small radiographic variations may not translate into clinically meaningful differences, highlighting the need to correlate these findings with patient-reported outcomes in future studies.

Strengths and limitations

There is currently a great lack of studies assessing the impact of lumbar fusion on the lower limbs, and our study appears to be the first to address this, with the use of a large database. However, this study is not without limitations with the main one being the heterogeneity of our database. All types of sagittal scales or pathologies requiring various therapeutic approaches made up our study. This may well have erased some of the relationships between different parameters that might prove more relevant with homogeneous groups. However, this heterogeneity is also a strength that has enabled us to gather a fairly large database in comparison with the literature, and which above all gives results that can be transposed to a general population and not specific to a category of patients or precise surgical techniques. In addition, there are still many factors that can influence sagittal balance and the implementation of compensation mechanisms such as hip and knee osteoarthritis [7, 27], which are not taken into account here, and which demonstrate the complexity of the subject. Moreover, Lower limb compensation mechanisms involve coordinated adaptations at the hip, knee, and ankle levels. While ankle dorsiflexion was included in the present analysis, a comprehensive evaluation of hip-related compensatory mechanisms was not performed. Such an analysis would require a larger cohort and dedicated investigation. The statistical analysis was primarily based on pairwise comparisons. While this approach allowed identification of significant associations, it does not account for potential confounding interactions between variables. Future studies using multivariable models are needed to identify independent predictors of lower limb compensation. As for the follow-up period, it was limited to a minimum of six months, reflecting early postoperative alignment. However, sagittal balance and compensatory mechanisms may continue to evolve over longer periods, and longer-term follow-up studies are needed to assess the

persistence or progression of these adaptations. Finally, it is important to note that there is sometimes asymmetry in knee flexion in both lower limbs. This issue has not been raised in all the literature studied, which only considers maximum flexion on perfectly aligned bone structures in profile view. In our study, when there is significant asymmetry between the two lower limbs, only the limb with the greatest flexion is then considered, to reflect the maximum compensation in place.

Conclusion

The results of this study show knee flexion angle can help quantify lower limb compensation in relation to spinopelvic malalignment induced by a lack of lordosis in patients undergoing surgery for degenerative pathologies. However, while compensation mechanisms are often described in the literature as appearing in cascade, a great variability in the implementation of knee flexion with all parameters was highlighted. Moreover, knee flexion does not seem to be so dependent on PT, and does not occur solely in response to a retroversion limit, as theorized in the literature. Furthermore, more than half of patients undergoing lumbar fusion had greater flexion after surgery which could be partly explained by a loss of lumbar lordosis during fusion.

Abbreviations

PI	Pelvic incidence
SS	Sacral slope
PT	Pelvic tilt
C2-C7	Cervical lordosis
O-C2	Occipito-cervical angle
TK	Thoracic kyphosis
LL	Lumbar lordosis
SVA	Sagittal vertical axis
CAM	Lead line through auditory canals
SSA	Spino-sacral angle
TPA	T1 pelvic angle
FBI	Full-body balance index
ODHA	Ondotoïd hip axis
SFD	Sacrofemoral distance
SFA	Sacrofemoral angle
GSA	Global sagittal angle
KF	Maximum knee flexion
AA	Maximum ankle dorsiflexion
ΔKF	Evolution of knee flexion

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s12893-026-03760-z>.

Supplementary Material 1.

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Authors' contributions

MD, AS, VB: writing original draft. JG, CV, TC, JS: Collecting data. ZW: Writing review and editing.

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Data availability

Data is available upon reasonable request from the corresponding author.

Declarations

Ethics approval and consent to participate

The need for informed consent to participate was waived by the institutional ethics committee (University of Montreal). The study was conducted according to the declaration of Helsinki.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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