European Spine Journal
https://doi.org/10.1007/s00586-025-09063-w

RESEARCH

Abdominal wall tension after spinal deformity correction compromises postoperative biomechanics and may contribute to proximal junctional kyphosis

Elisa Jolas[1] · Fabio Galbusera[2] · Tamas F. Fekete[3] · Daniel Haschtmann[3] · Dezsö Jeszenszky[3] · Sarah Richner-Wunderlin[2] · Ferran Pellisé[4] · Ibrahim Obeid[5] · Javier Pizones[6] · Ahmet Alanay[7] · Frank Kleinstück[3] · Caglar Yilgor[7] · Stephen J. Ferguson[1] · Markus Loibl[3] · Dominika Ignasiak[1]

Received: 14 October 2024 / Revised: 4 June 2025 / Accepted: 12 June 2025

Abstract

Purpose Proximal junctional kyphosis (PJK) is a common complication after fusion surgery for adult spinal deformity (ASD). Tissue adaptation to deformity may cause abdominal wall shortening/stiffening. This study evaluated, using musculoskeletal modeling, the effect of these adaptations and sarcopenia on trunk muscle effort required to maintain postoperative alignment in PJK patients versus controls.

Methods ASD patient data was grouped by mechanical complication status: PJK (N=44), other (N=56), none (N=260). Spinopelvic landmarks were annotated in pre-op, post-op, and follow-up X-ray images. Patient-specific musculoskeletal models of corresponding alignments were built. Forces due to stretching of the abdominal wall beyond pre-op length (assumed slack) were applied, representing abdominal wall stiffness. Sarcopenia was implemented by reducing paraspinal muscle strength based on patient age and gender. Inverse-static simulations predicted overall muscle effort by summing muscle activities.

Results Postoperatively, the abdominal wall was more elongated in the PJK group (+8.4%[-0.3;20.0]) versus the no-complication group (+2.4%[-4.9;10.2], $p<0.01$) due to larger preoperative deformities and greater surgical correction. This elongation correlated more with pelvic tilt change ($r=-0.53$) than lumbar lordosis correction ($r=0.16$). Greater muscle effort was estimated for post-op alignment in the PJK group (12.40[6.42;28.6]) versus the no-complication group (8.42[4.34;13.3], $p<0.05$). Muscle effort was reduced at follow-up in groups with mechanical complications.

Conclusion Alignment restoration tensions abdominal structures, requiring increased extensor muscle forces to maintain postoperative alignment. Patients might develop PJK to reduce unsustainable muscle effort or due to spinal structure failure. More attention should be given to pelvic reciprocal changes to improve surgical planning and perioperative rehabilitation.

Keywords Adult spinal deformity · Proximal junctional kyphosis · Fusion surgery · Musculoskeletal model · Abdominal wall stiffness

Introduction

Multilevel spinal fusion is a common surgical treatment for adult spinal deformity (ASD), a condition expected to affect an increasing number of patients as the population ages [1]. One frequent complication is proximal junctional kyphosis and failure (PJK), with an incidence ranging from 17 to 46% [2]. Patients with PJK often experience heightened symptomatic pain and functional impairment [3–5]. The etiology of proximal junctional complications is multi-factorial and remains poorly understood. From a biomechanical perspective, increased spinal loads due to sagittal malalignment [6], lower thoracolumbar muscularity and higher fatty degeneration [7, 8] have been speculated to play a role, but what seems to be neglected is that the postoperative spine biomechanics might be compromised by the prior adaptation of tissues to spinal deformity, which can hinder surgical outcomes.

Extended author information available on the last page of the article

Published online: 26 June 2025

The deformity that develops and progresses for years before surgery [9] influences the functional length of the connective tissue structures and muscles responsible for stabilizing the spine in an upright standing posture. Animal studies have shown that the muscle bellies adapt to their functional lengths [10–12] and the prolonged muscle shortening leads to connective tissue accumulation [13, 14] and remodeling (fiber re-arrangement) [14] and a reduction in the number of sarcomeres in series [15–17]. These changes result in muscle shortening, loss of muscle mass and strength, and increased passive resistance (stiffening) [13, 17]. In scoliosis, paravertebral muscle stiffness at the apex of the thoracic curve has been reported to be significantly greater on the concave side (where the muscles are shortened) compared to the convex side [18]. While it is not definitely proven that these adaptations result from muscle shortening, it is believed that scoliotic deformities alter the mechanical environment of the paravertebral muscles, leading to adaptive changes [18, 19]. Similar adaptations of muscle shortening and stiffening might affect abdominal wall in patients with sagittal plane deformity. In fact, patients with degenerative kyphoscoliosis have been found to exhibit significantly smaller longitudinal diameters and volumes of the abdominal cavity compared to age-matched controls [20].

The altered properties of the abdominal muscles due to long-term deformity-induced shortening could play a role in the development of PJK, by applying forces resisting the surgically restored alignment and– either alone or exacerbated by age-related weakness (sarcopenia) of the extensor muscles– increasing the muscular effort needed to sustain the postoperative posture. While previous musculoskeletal modelling studies have investigated spinal loads in the context of spinal fusion [6, 21–25] and the general effects of sarcopenia on the muscular effort needed to maintain posture [26], to our knowledge, abdominal muscle adaptation to long-term spinal deformities as a potential factor in the etiology of PJK has not been yet explored.

The aim of this study was to evaluate the effect of adaptation of the abdominal wall passive properties to spinal deformities on the trunk muscle effort required to maintain postoperative alignment in patients who developed PJK during follow-up, compared to controls. A secondary objective of the study was to analyze the individual and combined effects of abdominal muscle adaptation and sarcopenia of spine extensors on the trunk muscle effort, aiming to better understand their relative roles and interaction.

We hypothesized that surgical restoration of sagittal alignment is related to postoperative elongation of abdominal structures in patients who later develop PJK. The resulting tension in the abdominal wall would create unfavorable bending moment on the spine, requiring increased extensor muscle forces to support the posture. We also hypothesized that postoperative muscle effort is the greatest when both the effects of abdominal tissue adaptations and sarcopenia are considered.

Methods

The effect of adaptation of the abdominal wall passive properties to spinal deformities on the trunk muscle effort required to maintain postoperative alignment were investigated using an established musculoskeletal model of the spine, personalized to represent spinal alignment of 360 patients surgically treated for adult spinal deformity.

Study sample

Radiographic and clinical data of patients with ASD were retrospectively retrieved from a prospective multi-center database. The inclusion criteria for this database were age ≥ 18 years and at least one of the following conditions confirming spinal deformity: coronal Cobb angle ≥ 20°, sagittal vertical axis ≥ 5 cm, pelvic tilt ≥ 25°, or thoracic kyphosis ≥ 60°. The specific inclusion criteria for this study were instrumentation with upper instrumented vertebrae (UIV) ≤ T2, available sagittal and coronal annotations of standing X-ray images including landmarks from T1 to S1 and femoral heads at three time points (pre-operation, post-operation < 100 days before complication development, and follow-up with the most recent X-ray before potential re-operation).

After exclusions from the 1294 patients with X-ray data in the database (Fig. 1), a final study cohort consisted of 360 patients, grouped by mechanical complication status: PJK (N = 44), other (N = 56), or none (N = 260). The PJK group consisted of patients with two characteristics: (1) a proximal junctional sagittal Cobb angle ≥ 10°, and (2) at least 10° greater than the preoperative measurement. The "Other mechanical complication" group included rod breakage, distal junctional kyphosis, sagittal malalignment, screw breakage, screw pull-out, screw/rod/hook dislodgement, adjacent segment degeneration, pseudarthrosis, coronal malalignment (> 3 cm), and shoulder imbalance (> 2 cm).

Musculoskeletal modeling

A validated thoracolumbar spine model established in AnyBody Modeling System (AnyBody Technology A/S, Aalborg, Denmark, version 7.4.0) [31–35] was used with few modifications to perform static upright-standing simulations of patient alignments at preoperative, postoperative and follow-up time points. In this model, intervertebral joints were

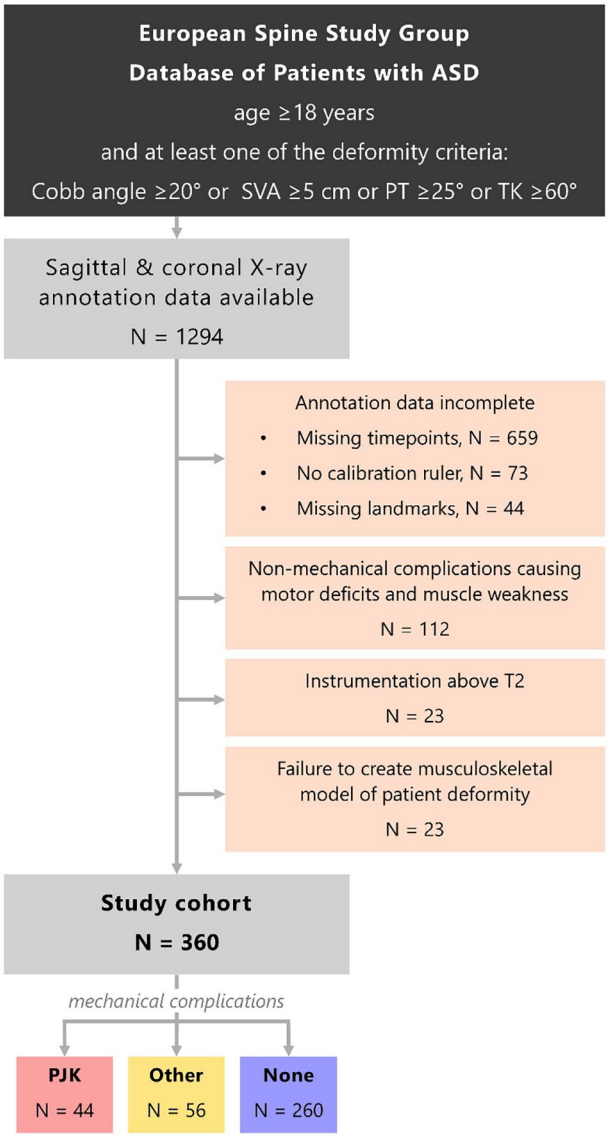

Fig. 1 Flow diagram of patient inclusion and exclusion criteria. (Non-mechanical complications that could cause motor deficits and muscle weakness– one of the exclusion criteria - were e.g., radiculopathy, screw malposition, paraparesis, and dural tear [27–30]

modeled as spherical joints with a traveling center of rotation by implementing reaction forces in translational directions. This allowed relative translation between vertebrae, assuming that the joint transfers forces in these directions, which reflects constraints imposed by stabilizing structures and joint anatomy (such as facet impaction [36]). Assuming neutral positions of intervertebral joints in each posture, segmental stiffness was not included. As in the original model, the ribcage was represented by passive stiffness elements from ex-vivo measurements [37, 38] and an intra-abdominal pressure model was included in the lumbar region [39, 40]. Rotations between ribs and vertebrae were estimated using the force-dependent kinematics method [41], which allows to compute unknown displacements under given load conditions. The sternum position was delimited by the first rib, with its rotation averaging those of the 10 pairs of non-floating ribs. All major trunk muscles were represented by over 600 fascicles, based on anatomical descriptions (details provided in the Supplementary material 2– Model muscle description). Each fascicle was modeled as a force element transmitting force along the muscle path—either directly for short muscles, or via intermediate nodes to account for muscle wrapping in longer muscles. Tendon properties, force-length, and force-velocity relationships of the muscle function were not considered.

Model individualization with subject-specific inputs

Generic spine model was adjusted to represent relevant patient characteristics. Subject-specific parameters: body weight and height [42] were used to scale the model mass and geometry. Patient-specific alignment was represented by adjusting pelvic parameters as well as vertebral positions and orientations according to the radiographic data, and assuming horizontal gaze. Information about upper and lower instrumented vertebrae were used to model spinal fusion location accordingly. Spinal fusion was modeled by applying external moments compensating for 90% of the gravity-related moment of each fused vertebra to represent non-rigid instrumentation behavior, with assumption of small (10%) contribution of posterior muscles to balancing gravity loads. Muscle strength, i.e. maximum force generating capacity, proportional to muscle PCSA, was scaled using a strength factor non-linearly related to patient body weight [42]. The models individualized in this way were simulated for all patients in 3 configurations: (1) muscle loss modeled based on patient age and gender (Sarcopenia), (2) abdominal wall tension modeled based on the postoperative changes to spinal alignment (Abdominal stiffness), and (3) both (Sarcopenia + Abdominal stiffness).

Sarcopenia

Muscle degeneration modelling was implemented to reflect the deteriorated contractile capacity of the lumbar erector spinae and multifidus in the model based on age, gender and spinal level-specific data [43, 44]. As sarcopenia is manifested by fat infiltration and muscle atrophy, PCSA was reduced depending on %fat infiltration and a %loss in PCSA: $PCSA_{reduced} = PCSA_{normal} * (100\% - Fat[\%]) * (100\% - PCSA\ loss[\%])$, similarly to previous work by Ignasiak et al. [26].

Estimation of abdominal wall elongation

Abdominal wall length was estimated from kinematic (position) analysis of patient-specific models, due to the challenges of assessing the abdominal landmarks from radiographic images (outside the field of view or difficult to identify). The patient-specific models reflected positions and orientations of individual lumbar and thoracic vertebrae (T1 to L5) derived from endplate coordinates in the sagittal and coronal X-rays of patients in an upright position. To account for uncertainties in X-ray data annotation [45], sagittal plane coordinates were linearly rescaled for each patient across the three time points to match the average endplate length, which varies negligibly over time [46]. Coronal coordinates were similarly rescaled by minimizing their longitudinal axis differences with sagittal data (see Supplementary Material 1 for details). Vertebral centroid (i.e., center of four vertebral endplate landmarks), vertebral angle (i.e., average inclination of inferior and superior endplates relative to the horizontal line), and spinopelvic parameters (i.e., pelvic incidence, sacral slope, pelvic tilt, and pelvic obliquity) in the sagittal and coronal planes were incorporated into the model for the three time points. The distance between the xiphoid process and pubic symphysis in 3D space was found as a measure of abdominal wall length (Fig. 2, left). Its changes in postoperative and follow-up alignment (L_f) from preoperative length (L_0, assumed slack) were considered as abdominal strain ($\lambda = L_f/L_0$).

Passive muscle adaptations

Forces due to abdominal wall stretching beyond pre-op length were applied in post-op and follow-up models. The constitutive law used to estimate the passive force based on abdominal wall elongation f(λ) was derived from Kriener et al. [47], who measured the tensile properties of a composite specimen including the linea alba, rectus abdominis, rectus sheath, and peritoneum (Fig. 2, middle). The stress in MPa was multiplied by the total physiological cross-sectional area (PCSA) of these soft tissues, estimated from laser scanning microscopy and cadaver studies: 20 mm^2 for the linea alba [48] and 600mm^2 for the rectus abdominis [49]. The PCSA of the rectus sheath, 80mm^2 was estimated using the dimensions of the rectus abdominis as well as the thickness of the rectus sheath [48, 50]. For the inverse-static analysis using sagittal model, the estimated tension force produced by the abdominal wall was projected onto the sagittal plane (Fig. 2, right).

Inverse static simulations

Inverse-static simulations were performed to predict muscle activities (exerted muscle force divided by a maximum force it could generate), and the sum of all muscle activities served to estimate overall muscle effort. By solving Newtonian equations of motion with the known gravity moments, the unknown muscle forces are calculated. A polynomial optimization method minimizing the sum of cubed muscle activities (i.e., muscle active state as a fraction of maximum voluntary contraction) as an objective function, was used to solve the problem of muscle recruitment caused by

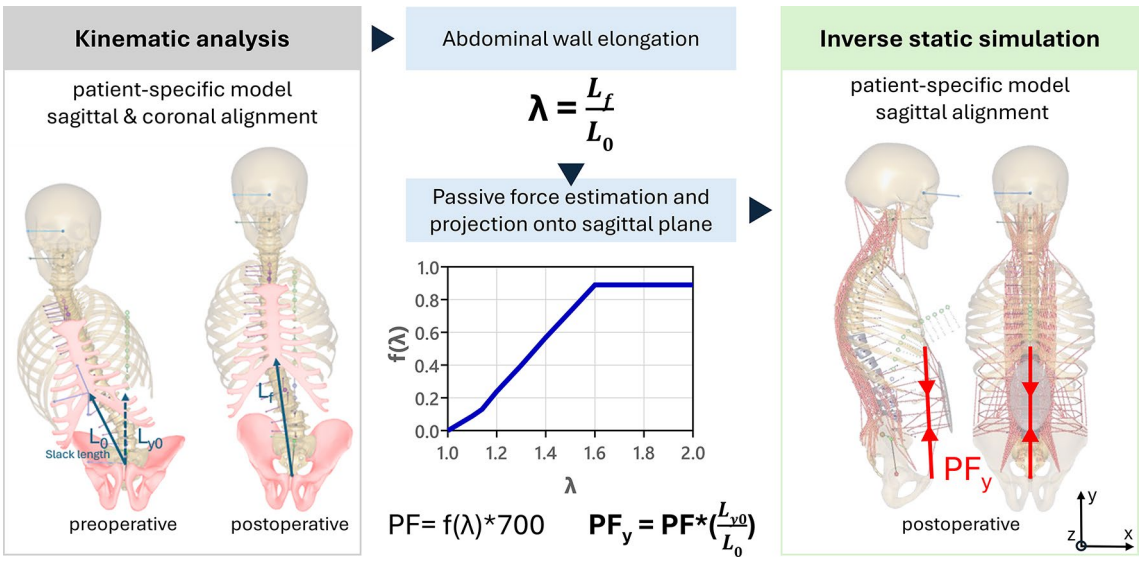

Fig. 2 Calculation of abdominal wall elongation and related passive force applied during inverse-static analysis. λ: strain/abdominal wall elongation, L_f: abdominal wall length in the post-operation or follow-up posture, L_0: slack length/abdominal wall length in the pre-operation posture, PF: passive force

muscle redundancy [51] (Supplementary material 2– Muscle recruitment equation). This method mimics physiological muscle recruitment by favoring muscle synergy while reducing energy expenditure [52].

The simulations were performed for all patients across three patient groups: PJK, other mechanical complications, and no complications. Each patient case was simulated with three model conditions: sarcopenia, abdominal wall stiffness, and their combination to predict muscle effort. In this way, the respective roles of abdominal wall adaptation to deformity and age-related muscle degeneration could be discerned.

Statistical analysis

Muscle effort, abdominal wall elongation, and spinopelvic parameters were compared between patient groups using the Kruskal-Wallis test and Dunn's test with Bonferroni correction for non-normally distributed data, and analysis of variance with Tukey's HSD for normally distributed data. Since muscle effort data were not normally distributed, comparisons across postures and modeled conditions (i.e., sarcopenia, abdominal wall stiffness, both) within each patient group were made using the Friedman test and pairwise comparisons [53]. For each test, the r-type effect size [54] was calculated: small ($0.1<r\leq0.3$), medium ($0.3<r\leq0.5$), and large ($r>0.5$; [55]). Pearson's correlations (R) between the amount of correction of spinopelvic parameters and abdominal wall elongation, and Spearman's correlations (ρ) between the elongation and muscle effort were assessed.

Results

Patient sample

A sample of 360 patients with ASD was analyzed, grouped by a mechanical complication status: PJK ($N=44$), other ($N=56$), or none ($N=260$). The two groups with mechanical complications were statistically older and had higher body weight compared to the No Complication group ($p<0.01$, Table 1). Additionally, their preoperative deformities and the magnitude of postural correction during surgery (changes in spinopelvic parameters) were greater for these two groups compared to the No Complication group for SVA, GT, SS, PT, and LL ($p<0.05$, Table 1). ~85% of patients had fusion to the pelvis in the two groups with mechanical complications vs. 39% in the No Complication group.

Abdominal wall elongation and relationship with spinopelvic parameters

In the PJK group, the postoperative abdominal wall elongation was found significantly greater compared to the no-complication group (median[Q1;Q3] = +8.4%[-0.3; 20.0] vs. median = +2.4%[-4.9; 10.2]; $r=0.17$, $p<0.01$; Fig. 3). During follow-up (i.e., 859 ± 596 days, min. 9 weeks, max. 121 months), it was significantly shortened relative to preoperative length in both other mechanical complication and PJK groups compared to the group without complications (median[Q1;Q3] = -3.6%[-15.8; 3.3], $r=0.15$ and median = -5.7%[-14.1; 2.7], $r=0.14$ vs. median = -0.6%[-7.1; 6.2], $p<0.05$; Fig. 3). All three groups showed a significant shortening of the abdominal wall from postoperative alignment to follow-up, with a smaller effect size observed in the no-complication group ($r=0.32$ vs. $r=0.70$ and $r=0.80$). The change in abdominal wall length was most strongly correlated with ΔPT and ΔGT (R = -0.53, Table 2).

Muscle effort

Postoperatively, simulations with abdominal wall stiffness modelled in combination with sarcopenia (Abd + Sarc) predicted greater muscle effort in all three groups compared to the sarcopenia condition alone (r ranging from 0.45 to 1.14, $p<0.001$; Fig. 4). This effect between the Sarc and Abd + Sarc conditions was the greatest in the PJK group.

In the simulated Abd + Sarc condition, greater muscle effort was estimated for post-op alignment in PJK group vs. no-complications group (median[Q1;Q3] = 12.40[6.42; 28.6] vs. median = 8.42[4.34; 13.3], $p<0.05$; Fig. 5), but not anymore at follow-up posture. For this condition, both groups with mechanical complications reduced their muscle effort at the follow-up alignment (-4.74 i.e., -42% and −8.14 i.e., -65%; $p<0.05$), which was not the case for the no-complication group, for whom muscle effort remained statistically similar (Fig. 5). A strong polynomial relationship was found between postoperative muscle effort and the modification of abdominal wall length for the conditions where passive forces were added (Spearman's ρ = 0.65, $p<0.001$; Fig. 6).

Discussion

Findings

Our study aimed to evaluate the effect of the abdominal wall adaptation to spinal deformity on trunk muscle effort required to maintain postoperative alignment. We compared estimated abdominal wall elongation and muscle effort at

Table 1 Anthropometric and clinical data of the three investigated groups. PJK: proximal junctional kyphosis, BM: body mass, BH: body height, SVA: sagittal vertical axis, GT: global tilt, PI: pelvic incidence, SS: sacral slope, PT: pelvic tilt, LL: lumbar lordosis, *: $p<0.05$, **: $p<0.01$, ***: $p<0.001$

	Whole sample	1. PJK	2. Other mechanical complications	3. No complications	*p*-value (test if groups 1-2-3 are different)
N	362	44	56	260	
N Males	77	6	15	55	
N Females	285	38	41	205	
Age	54.3 ± 18.2	67.9 ± 7.9	61.0 ± 12.8	50.5 ± 19.0	* * * 1–3 2–3
BM [kg]	66.3 ± 13.0	69.7 ± 10.4	70.2 ± 13.5	64.9 ± 13.1	* * 1–3 2–3
BH [cm]	162.9 ± 8.6	160.2 ± 7.3	162.5 ± 9.7	163.4 ± 8.5	n.s
Surgical details					
UIV	T2-L5	T2-L2	T2-L5	T2-L3	
LIV	T10-Iliac	T10-Iliac	T12-Iliac	T11-Iliac	
Fused to pelvis	186 (51%)	38 (86%)	45 (80%)	103 (39%)	
Radiographic parameters Pre-operation					
SVA [mm]	40.2 61.2	75.3 ± 63.2	67.8 ± 59.5	28.3 ± 57.1	* * * 1–3 2–3
GT [°]	29.3 18.7	39.1 ± 16.9	39.1 ± 16.9	25.0 ± 17.6	* * * 1–3 2–3
PI [°]	57.9 14.0	62.5 ± 16.0	61.2 ± 16.2	56.4 ± 12.8	n.s
SS [°]	32.7 11.4	28.8 ± 12.0	29.9 ± 10.4	33.9 ± 11.3	* * 1–3
PT [°]	25.2 13.1	33.7 ± 11.5	31.3 ± 12.1	22.5 ± 12.5	* * * 1–3 2–3
LL [°]	41.6 20.6	33.3 ± 18.8	34.2 ± 16.4	44.6 ± 20.9	* * * 1–3 2–3
L4-S1 [°]	30.7 14.8	29.6 ± 15.1	25.9 ± 15.0	31.9 ± 14.5	* 2–3
T2-T12 [°]	41.2 18.6	43.3 ± 18.1	39.3 ± 14.4	41.2 ± 19.5	n.s
T2-T5 [°]	9.7 8.5	10.2 ± 8.0	8.2 ± 7.5	9.9 ± 8.8	n.s
T10-L2 [°]	12.3 19.2	15.7 ± 20.1	11.5 ± 20.3	11.8 ± 18.8	n.s
Change from pre-op to post-op					
ΔSVA [mm]	-31.1 ± 55.0	-54.6 ± 55.0	-39.4 ± 58.0	-25.4 ± 53.3	* * * 1–3
ΔGT [°]	-7.4 ± 15.0	-15.2 ± 14.1	-11.9 ± 15.0	-5.2 ± 14.5	* * * 1–3 2–3
ΔSS [°]	2.3 ± 9.2	4.5 ± 9.7	4.0 ± 11.5	1.4 ± 8.5	* * 2–3
ΔPT [°]	-3.31 ± 10.3	-8.1 ± 10.1	-6.5 ± 10.8	-1.8 ± 9.9	* * * 1–3 2–3
ΔLL [°]	9.8 ± 18.8	18.3 ± 18.3	14.2 ± 19.3	7.4 ± 18.2	* * * 1–3 2–3
ΔL4-S1 [°]	0.4 ± 14.0	2.1 ± 13.0	2.6 ± 16.2	-0.4 ± 13.6	n.s
ΔT2-T12 [°]	7.9 ± 13.4	12.2 ± 14.3	10.3 ± 11.6	6.7 ± 13.4	* 1–3
ΔT2-T5 [°]	3.2 ± 8.8	3.6 ± 9.2	2.2 ± 6.6	3.3 ± 9.1	n.s
ΔT10-L2 [°]	-3.1 ± 17.5	-2.5 ± 17.6	-2.8 ± 18.5	-3.3 ± 17.4	n.s
X-ray date with respect to surgery date [days]					
Pre-operation	-106 ± 134	-168 ± 174	-98 ± 102	-98 ± 131	* 1–3
Post-operation	51 ± 28	34 ± 28	50 ± 30	54 ± 26	* * * 1–2 1–3
Follow-up	859 ± 596	953 ± 628	1070 ± 601	797 ± 579	* * 2–3

postoperative and follow-up time-points between patients who develop: PJK vs. other mechanical complications or no mechanical complications. Our results indicate that greater postoperative elongation of abdominal wall (due to deformity correction) together with age-related sarcopenia is related to significantly higher muscular effort in patients who develop PJK. This increased effort is primarily due to abdominal elongation, as indicated by our regression analyses (Fig. 6). Since the passive forces applied in the model are determined by abdominal wall elongation (Fig. 2), they need to be counterbalanced by increased extensors muscle activity, driving the overall muscle effort. Consequently, PJK might be developed as an energy-conserving posture or due to structural failure under increased muscular and segmental loads. While increased muscle activity in the lumbar region has been observed post-fusion in scoliosis patients [56], no prior studies, to our knowledge, have explored its correlation with surrounding tissue stiffness.

The greater abdominal wall elongation in the PJK and other mechanical complication groups is related to greater preoperative deformities, necessitating more correction during surgery. As a result, the abdominal wall is shorter preoperatively and significantly more stretched postoperatively when alignment is restored, leading to increased muscle effort. These findings are consistent with studies showing that preoperative sagittal malalignment [57, 58] and the magnitude of correction [59–61] are risk factors for PJK and other mechanical complications [62]. Correlations between abdominal elongation and several sagittal alignment parameters found in the current work suggest that careful surgical planning might limit tension on stabilizing tissues and minimize PJK risk.

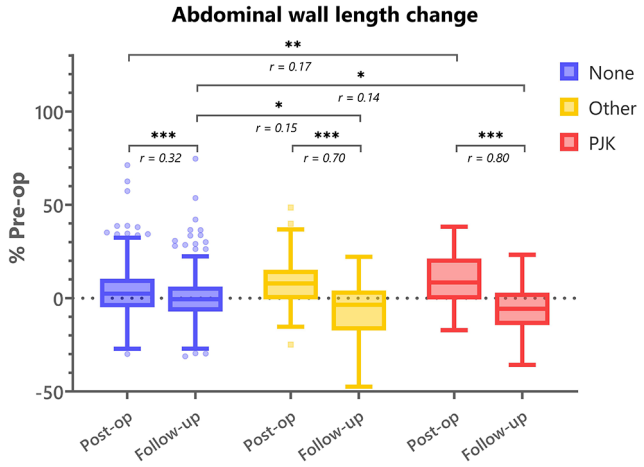

Fig. 3 Change in abdominal wall length (as % of pre-op) in postoperative (post-op) and follow-up alignments. The no complication group is marked in blue, the group with other mechanical complication in yellow and the PJK group in red. PJK: Proximal Junctional Kyphosis, r: r-type effect size, *: $p<0.05$, **: $p<0.01$, ***: $p<0.001$

Table 2 Correlation coefficients (R) between change in sagittal alignment parameters and change in abdominal wall length, data combined for postoperative and follow-up timepoints and all patients. SVA: sagittal vertical axis, GT: global tilt, PI: pelvic incidence, SS: sacral slope, PT: pelvic tilt, LL: lumbar lordosis, ***: $p<0.001$

	R
ΔSVA [mm]	-0.33***
ΔGT [°]	-0.53***
ΔPI [°]	-0.26***
ΔSS [°]	0.39***
ΔPT [°]	-0.53***
ΔLL [°]	0.16***
ΔL4-S1 [°]	n.s
ΔT2-T12 [°]	-0.21***
ΔT2-T5 [°]	0.13***
ΔT10-L2 [°]	-0.34***

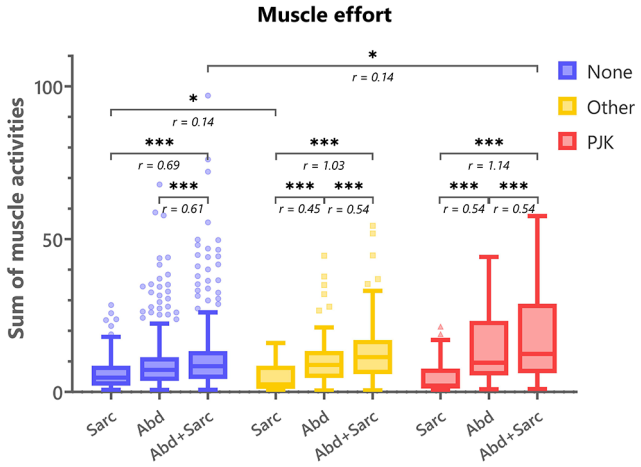

Fig. 4 Postoperative muscle effort across the three simulated conditions: Sarc–sarcopenia, Abd– abdominal wall stiffness, Abd+Sarc - both. The no complication group is marked in blue, the group with other mechanical complication in yellow and the PJK group in red. PJK: Proximal Junctional Kyphosis, r: r-type effect size, *: $p<0.05$, **: $p<0.01$, ***: $p<0.001$

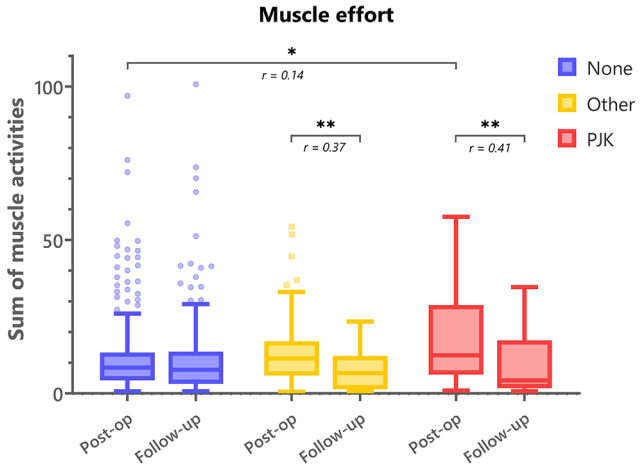

Fig. 5 Change in muscle effort in postoperative (post-op) and follow-up alignments, when both abdominal stiffness and sarcopenia are considered (Abd+Sarc). The no-complication group is marked in blue, the group with other mechanical complication in yellow and the PJK group in red. PJK: Proximal Junctional Kyphosis, r: r-type effect size, *: $p<0.05$, **: $p<0.01$, ***: $p<0.001$

However, abdominal elongation was only very weakly influenced by lumbar lordosis correction ($R=0.16$), slightly more by T10-L2 change ($R=0.34$), and not at all by L4-S1 correction. Thus, the greater postoperative change in LL seen in patients with PJK does not affect abdominal length directly. Instead, it is driven by a reduction in pelvic tilt and global tilt, as they are more strongly correlated with abdominal elongation ($R=-0.53$). This is expected, as the rectus abdominis muscle runs vertically from the pubic crest to the costal cartilages [63]. This is consistent with previous studies showing that PJK patients have a higher PT change ratio (31% vs. 16%) postoperatively compared to no-PJK patients, despite similar global sagittal alignment [64].

While reciprocal change of pelvic compensation may seem clinically favorable by reducing hip flexor effort, our findings indicate that it increases abdominal tension, demanding more effort from trunk extensors. As hip muscles may have adapted to prolonged pelvic compensation (shortened hamstrings and lengthened, weaker hip flexors), it could still be more ergonomic for patients to return to pelvic retroversion. Considering the majority (87% in our study) has been fused to pelvis, they might then develop PJK to maintain trunk balance over the hips. Indeed, studies show that patients with PJK return to their preoperative pelvic tilt with an increase in PJA [64]. This highlights the need for further research into spine-hip biomechanics, its adaptation to deformity and then disruption by surgical correction.

Simulations of abdominal wall stiffness alone, without modeling age-related muscle degeneration, did not show

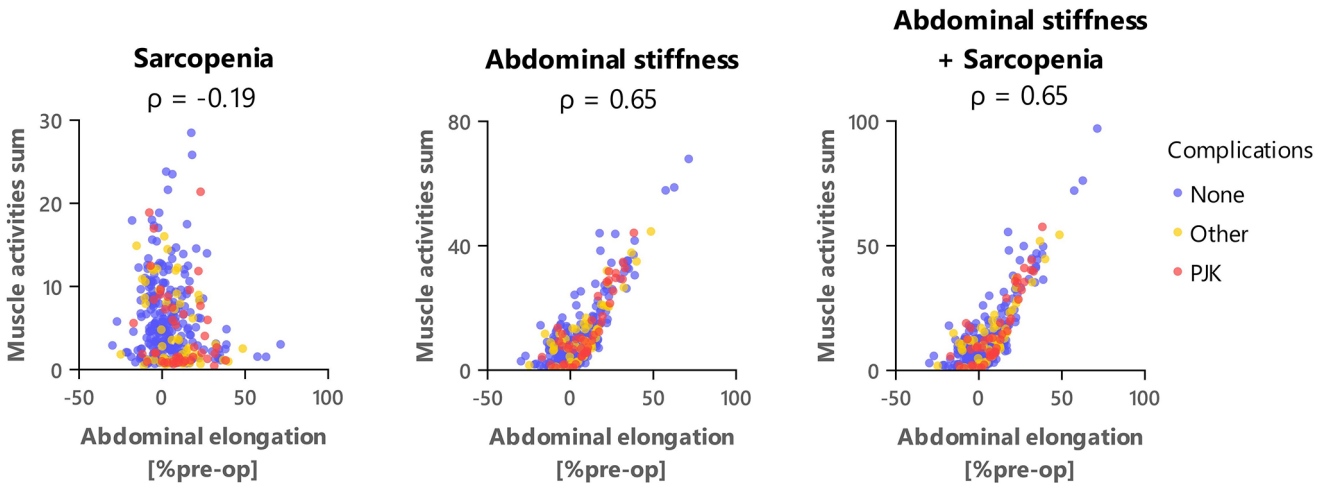

Fig. 6 Spearman's correlation analysis between muscle effort and postoperative abdominal wall elongation for the three tested conditions. The no-complication group is marked in blue, the group with other mechanical complication in yellow and the PJK group in red. PJK: Proximal Junctional Kyphosis, ρ: Spearman's correlation coefficient. All correlations were significant at $p<0.001$

differences in postoperative muscle effort between groups, suggesting that stronger muscles might have a preventive effect, and indicating that PJK might result from multiple muscular factors. Psoas CSA [65], fatty infiltration ratio, and CSA of paraspinal muscles at the UIV [66, 67] are in fact significant independent predictors of PJK. Weak trunk extensors are associated with sagittal malalignment in static position [68] and increase mechanical stress on vertebrae due to anterior upper torso shift above the UIV, potentially leading to fractures [66]. During follow-up, the abdominal wall in the PJK group shortened to below the preoperative value, and muscle effort reduced, becoming similar to the no-complication group. This suggests postural collapse of PJK may develop to reduce unsustainable metabolic effort and/or from structural failure, as the abdominal tension on the ribcage could increase compression forces and potentially lead to fractures at the adjacent segment [69]. In the no-complication group, despite a significant reduction in abdominal wall length during follow-up (possibly due to postural adjustments to the new load distribution on the spine), muscle effort did not decrease. At low elongation, tissues are in the "toe" region where stiffness is low due to crimped fibers gradually straightening [70], thus length modifications have minimal effect on muscle effort.

Novelty in the context of previous works

While studies have primarily focused on the active component of muscle force, passive biomechanical properties of skeletal muscles can significantly impact age-related diseases, particularly the balance of the spine in the sagittal plane. Previous musculoskeletal models have incorporated passive muscle forces to study spinal alignment using the Hill-type model [71, 72], which includes passive properties of the tendon and muscle itself [73–79]. However, the effect of passive muscle properties in the context of spinal fusion and postoperative complications have not been yet investigated. Our model, which represents passive properties of the abdominal wall, as adapted to deformity, showed a substantial impact on spine biomechanics, which can have clinical implications. Clinical studies often focus on muscle elasticity, stiffness, and asymmetry in scoliosis e.g [18, 80]. This study should prompt further investigation into the effects of muscle stiffness and its postoperative evolution in other contexts, particularly complications following spinal fusion.

Additionally, a study demonstrated that following spinal fusion or bracing in scoliosis patients, muscle stiffness changes within six months [80]. Specifically, paraspinal muscle stiffness decreased significantly on both concave and convex sides, with a more pronounced reduction on the concave side (-5.9 kPa, $p=0.025$), likely due to surgical stretching. Passive stretch studies report muscle length growth [81], reductions in muscle stiffness and increased flexibility with daily passive stretching [82–84]. Therefore, while rehabilitation is typically performed postoperatively, our study suggests that prehabilitation involving abdominal wall stretching and spine extensor strengthening could be beneficial. Although this approach is not commonly implemented, it has demonstrated positive effects on patient pain, disability, self-efficacy, psychological behaviors, and satisfaction [85].

Limitations and outlook

The present study had the following limitations:

This study involved a small number of patients in the PJK and other mechanical complication groups, with differing

patient characteristics, including anthropometric features and the aggregated analysis of various fusion constructs. Studies have shown that instrumentation type and the number of fused levels can affect spinopelvic parameters and clinical outcomes [86], as well as muscle effort [3, 87].

Since the abdominal wall was not visible in the radiographs, its length was estimated using a musculoskeletal model, from the rib cage to the pelvis, without further personalization. Its stiffness was then derived from the estimated elongation and data from a mechanical testing study, which may introduce inaccuracies. We assumed that the tissues fully adapt to preoperative deformity, which might be an overestimation. However, only abdominal wall shortening was considered, not the stiffening observed in previous studies on long-term muscle shortening [17, 88]. Thus, our study may have underestimated the stiffness and passive forces linked to muscle fibrosis, already observed in patients with degenerative lumbar disease (i.e., 22% of 171 fiber bundles showing elastic moduli up to 20 times greater than normal [89]). Future studies should measure abdominal wall stiffness and length pre- and post-surgery for more faithful patient modeling.

This study only accounted for the stiffness of the abdominal wall. However, in a static standing position, patients with ASD and high PT exhibit significantly shorter hamstring lengths compared to controls: biceps femoris at 52% vs. 56% of lower limb length, semitendinosus at 61% vs. 64%, and semimembranosus at 52% vs. 55% [90]. Future studies should model the adaptations of other stabilizing structures of the spine and pelvis (e.g., spine extensors and hamstrings) to evaluate their effects.

We modeled sarcopenia only as a function of age and gender. As the severity of sarcopenia can be influenced by other factors, in the future muscle properties should be personalized based on patient imaging data. Additionally, muscle-skeleton interactions were simplified by assuming active force transmission along the muscle path, neglecting more complex factors such as anisotropic passive properties [91] and the force-length relationship [92]. Due to lack of data, body morphology was not individualized in the model, although variations in body shape and tissue composition can influence mass distribution and spine biomechanics [93].

Finally, it needs to be emphasized this study analyzed biomechanical consequences of certain patient factors as one possible mechanism involved in PJK development, which does not elucidate the causes of PJK. The relevance of abdominal wall adaptations for PJK development remains to be investigated, as it is possible that other factors and mechanisms are more important. In the future, the role of abdominal elongation among other known risk factors should be explored, employing a multivariable logistic regression or a mediation analysis with confounders, respecting many interdependencies between predictors (e.g. age, deformity severity, fusion site, muscle quality), mediating factors (e.g. abdominal tension, loading of adjacent segment), and outcomes. This would allow to untangle complex causal relationships between patient and radiographic factors, biomechanics and complication risk.

In conclusion, differences in abdominal wall elongation following ASD correction were identified between patients who develop PJK and those who did not. Associated differences in muscle effort might affect a patient's ability to maintain postoperative alignment in the long term. Because abdominal wall elongation and muscle effort were estimated from biomechanical analyses of patient inputs, such as alignment, the results suggest a potential mechanism underlying known PJK risk factors, including preoperative deformity severity and the magnitude of correction. However, given the multifactorial nature of PJK as well as modeling limitations, these findings do not imply causality between abdominal muscle adaptation and PJK risk. Future work should further investigate this relationship, with particular focus on pelvic reciprocal changes, as it might have implications for surgical planning and perioperative rehabilitation aimed at preventing PJK.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00586-025-09063-w.

Acknowledgements We would like to acknowledge the contribution of Martina Nussbaumer, the leader of Spine Physiotherapy Unit at Schulthess Clinic, for her inputs regarding rehabilitation of spine surgery patients.

Author contributions Study conception and design: E. Jolas, F. Galbusera, J. Pizones, S. J. Ferguson, M. Loibl, D. Ignasiak; Data collection: T. F. Fekete, D. Haschtmann, D. Jeszenszky, S. Richner-Wunderlin, F. Pellisé, I. Obeid, J. Pizones, A. Alanay, F. Kleinstück, C. Yilgor, M. Loibl; Model development: E. Jolas, D. Ignasiak; Simulations: E. Jolas; Data analysis: E. Jolas; Manuscript preparation: E. Jolas, D. Ignasiak; Critical review of manuscript: all; Supervision: S. J. Ferguson, M. Loibl, D. Ignasiak.

Funding Open access funding provided by Swiss Federal Institute of Technology Zurich. Open access funding provided by Swiss Federal Institute of Technology Zurich.

Data availability Our clinical data come from a prospective multicenter database and cannot be shared openly in order to protect patient privacy.

Declarations

Competing interests The authors declare no competing interests.

References

1. Katz JN (1995) Lumbar spinal fusion. Surgical rates, costs, and complications. Spine 20:78S–83S
2. Sardar ZM, Kim Y, Lafage V et al (2021) State of the art: proximal junctional kyphosis—diagnosis, management and prevention. Spine Deform 9:635–644. https://doi.org/10.1007/s43390-020-00278-z
3. Hassanzadeh H, Gupta S, Jain A et al (2013) Type of anchor at the proximal fusion level has a significant effect on the incidence of proximal junctional kyphosis and outcome in adults after long posterior spinal fusion. Spine Deform 1:299–305. https://doi.org/10.1016/j.jspd.2013.05.008
4. Kim HJ, Bridwell KH, Lenke LG et al (2013) Proximal junctional kyphosis results in inferior SRS pain subscores in adult deformity patients. Spine 38:896–901. https://doi.org/10.1097/BRS.0b013e3182815b42
5. Pellisé F, Vila-Casademunt A, Ferrer M et al (2015) Impact on health related quality of life of adult spinal deformity (ASD) compared with other chronic conditions. Eur Spine J 24:3–11. https://doi.org/10.1007/s00586-014-3542-1
6. Ignasiak D, Behm P, Mannion AF et al (2023) Association between sagittal alignment and loads at the adjacent segment in the fused spine: a combined clinical and musculoskeletal modeling study of 205 patients with adult spinal deformity. Eur Spine J 32:571–583. https://doi.org/10.1007/s00586-022-07477-4
7. Hyun S-J, Kim YJ, Rhim S-C (2016) Patients with proximal junctional kyphosis after stopping at thoracolumbar junction have lower muscularity, fatty degeneration at the thoracolumbar area. Spine J 16:1095–1101. https://doi.org/10.1016/j.spinee.2016.05.008
8. Yagi M, Hosogane N, Watanabe K et al (2016) The paravertebral muscle and Psoas for the maintenance of global spinal alignment in patient with degenerative lumbar scoliosis. Spine J 16:451–458. https://doi.org/10.1016/j.spinee.2015.07.001
9. Barrey C, Roussouly P, Perrin G, Le Huec J-C (2011) Sagittal balance disorders in severe degenerative spine. Can we identify the compensatory mechanisms? Eur Spine J 20:626–633. https://doi.org/10.1007/s00586-011-1930-3
10. Gajdosik RL (2001) Passive extensibility of skeletal muscle: review of the literature with clinical implications. Clin Biomech 16:87–101. https://doi.org/10.1016/S0268-0033(00)00061-9
11. Kruse A, Rivares C, Weide G et al (2021) Stimuli for adaptations in muscle length and the length range of active force Exertion—A narrative review. Front Physiol 12:742034. https://doi.org/10.3389/fphys.2021.742034
12. Riley DA, Van Dyke JM (2012) The effects of active and passive stretching on muscle length. Phys Med Rehabil Clin N Am 23:51–57. https://doi.org/10.1016/j.pmr.2011.11.006
13. Tabary JC, Tabary C, Tardieu C et al (1972) Physiological and structural changes in the cat's soleus muscle due to immobilization at different lengths by plaster casts*. J Physiol 224:231–244. https://doi.org/10.1113/jphysiol.1972.sp009891
14. Williams PE, Goldspink G (1984) Connective tissue changes in immobilised muscle. J Anat 138(Pt 2):343–350
15. Goldspink G, Tabary C, Tabary JC et al (1974) Effect of denervation on the adaptation of sarcomere number and muscle extensibility to the functional length of the muscle*. J Physiol 236:733–742. https://doi.org/10.1113/jphysiol.1974.sp010463
16. Williams PE (1988) Effect of intermittent stretch on immobilised muscle. Ann Rheum Dis 47:1014–1016. https://doi.org/10.1136/ard.47.12.1014
17. Williams PE, Goldspink G (1978) Changes in sarcomere length and physiological properties in immobilized muscle. J Anat 127:459–468
18. Liu Y, Pan A, Hai Y et al (2019) Asymmetric Biomechanical characteristics of the paravertebral muscle in adolescent idiopathic scoliosis. Clin Biomech 65:81–86. https://doi.org/10.1016/j.clinbiomech.2019.03.013
19. Kennelly KP, Stokes MJ (1993) Pattern of asymmetry of paraspinal muscle size in adolescent idiopathic scoliosis examined by Real-Time ultrasound imaging: A preliminary study. Spine 18:913–917. https://doi.org/10.1097/00007632-199306000-00017
20. Guo C, Xu S, Liang Y et al (2021) Abdominal changes in patients with degenerative spinal deformity: A comparative study. Med (Baltim) 100:e26851. https://doi.org/10.1097/MD.0000000000026851
21. Benditz A, Auer S, Spörrer JF et al (2018) Regarding loads after spinal fusion, every level should be seen separately: a musculoskeletal analysis. Eur Spine J 27:1905–1910. https://doi.org/10.1007/s00586-018-5476-5
22. Ebrahimkhani M, Arjmand N, Shirazi-Adl A (2021) Biomechanical effects of lumbar fusion surgery on adjacent segments using musculoskeletal models of the intact, degenerated and fused spine. Sci Rep 11:17892. https://doi.org/10.1038/s41598-021-97288-2
23. Farshad M, Furrer PR, Wanivenhaus F et al (2021) Musculoskeletal biomechanics of patients with or without adjacent segment degeneration after spinal fusion. BMC Musculoskelet Disord 22:1038. https://doi.org/10.1186/s12891-021-04916-z
24. Rasmussen J, Iversen K, Engelund BK, Rasmussen S (2021) Biomechanical evaluation of the effect of minimally invasive spine surgery compared with traditional approaches in lifting tasks. Front Bioeng Biotechnol 9:724854. https://doi.org/10.3389/fbioe.2021.724854
25. Senteler M, Weisse B, Rothenfluh DA et al (2017) Fusion angle affects intervertebral adjacent spinal segment joint forces-Model-based analysis of patient specific alignment: predicted intervertebral joint forces after fusion. J Orthop Res 35:131–139. https://doi.org/10.1002/jor.23357
26. Ignasiak D, Valenzuela W, Reyes M, Ferguson SJ (2018) The effect of muscle ageing and sarcopenia on spinal segmental loads. Eur Spine J 27:2650–2659. https://doi.org/10.1007/s00586-018-5729-3
27. Berry JA, Elia C, Saini HS, Miulli DE (2019) A Review of Lumbar Radiculopathy, Diagnosis, and Treatment. Cureus. https://doi.org/10.7759/cureus.5934
28. Dong R-P, Zhang Q, Yang L-L et al (2023) Clinical management of dural defects: A review. World J Clin Cases 11:2903–2915. https://doi.org/10.12998/wjcc.v11.i13.2903
29. Dydyk AM, Khan MZ, Singh P (2024) Radicular back pain. In: StatPearls. StatPearls Publishing, Treasure Island (FL)
30. Gautschi OP, Schatlo B, Schaller K, Tessitore E (2011) Clinically relevant complications related to pedicle screw placement in thoracolumbar surgery and their management: a literature review of 35,630 pedicle screws. Neurosurg Focus 31:E8. https://doi.org/10.3171/2011.7.FOCUS11168

31. de Zee M, Falla D, Farina D, Rasmussen J (2007) A detailed rigid-body cervical spine model based on inverse dynamics. J Biomech 40:S284. https://doi.org/10.1016/S0021-9290(07)70280-4
32. de Zee M, Hansen L, Wong C et al (2007) A generic detailed rigid-body lumbar spine model. J Biomech 40:1219–1227. https://doi.org/10.1016/j.jbiomech.2006.05.030
33. Ignasiak D, Dendorfer S, Ferguson SJ (2016) Thoracolumbar spine model with articulated ribcage for the prediction of dynamic spinal loading. J Biomech 49:959–966. https://doi.org/10.1016/j.jbiomech.2015.10.010
34. Ignasiak D, Ferguson SJ, Arjmand N (2016) A rigid thorax assumption affects model loading predictions at the upper but not lower lumbar levels. J Biomech 49:3074–3078. https://doi.org/10.1016/j.jbiomech.2016.07.006
35. Ignasiak D, Rüeger A, Sperr R, Ferguson SJ (2018) Thoracolumbar spine loading associated with kinematics of the young and the elderly during activities of daily living. J Biomech 70:175–184. https://doi.org/10.1016/j.jbiomech.2017.11.033
36. Norris CM (1995) Spinal stabilisation. Physiotherapy 81:64–72. https://doi.org/10.1016/S0031-9406(05)67047-2
37. Andriacchi T, Schultz A, Belytschko T, Galante J (1974) A model for studies of mechanical interactions between the human spine and rib cage. J Biomech 7:497–507. https://doi.org/10.1016/0021-9290(74)90084-0
38. Schultz AB, Benson DR, Hirsch C (1974) Force-deformation properties of human costo-sternal and costo-vertebral articulations. J Biomech 7:311–318. https://doi.org/10.1016/0021-9290(74)90024-4
39. Arshad R, Zander T, Dreischarf M, Schmidt H (2016) Influence of lumbar spine rhythms and intra-abdominal pressure on spinal loads and trunk muscle forces during upper body inclination. Med Eng Phys 38:333–338. https://doi.org/10.1016/j.medengphy.2016.01.013
40. Han K-S, Zander T, Taylor WR, Rohlmann A (2012) An enhanced and validated generic thoraco-lumbar spine model for prediction of muscle forces. Med Eng Phys 34:709–716. https://doi.org/10.1016/j.medengphy.2011.09.014
41. Skipper Andersen M, de Zee M, Damsgaard M et al (2017) Introduction to Force-Dependent kinematics: theory and application to mandible modeling. J Biomech Eng 139:091001. https://doi.org/10.1115/1.4037100
42. Rasmussen J, de Zee M, Damsgaard M et al (2005) A general method for scaling Musculo-Skeletalmodels. 2005 Int Symp Comput Simul Biomech Clevel Ohio USA
43. Crawford RJ, Filli L, Elliott JM et al (2016) Age- and Level-Dependence of fatty infiltration in lumbar paravertebral muscles of healthy volunteers. Am J Neuroradiol 37:742–748. https://doi.org/10.3174/ajnr.A4596
44. Huang R, Pan F, Kong C, Lu S (2022) Age- and sex-dependent differences in the morphology and composition of paraspinal muscles between subjects with and without lumbar degenerative diseases. BMC Musculoskelet Disord 23:734. https://doi.org/10.1186/s12891-022-05692-0
45. Wu W, Liang J, Du Y et al (2014) Reliability and reproducibility analysis of the Cobb angle and assessing sagittal plane by computer-assisted and manual measurement tools. BMC Musculoskelet Disord 15:33. https://doi.org/10.1186/1471-2474-15-33
46. Junno J, Paananen M, Karppinen J et al (2015) Age-related trends in vertebral dimensions. J Anat 226:434–439. https://doi.org/10.1111/joa.12295
47. Kriener K, Lala R, Homes RAP et al (2023) Mechanical characterization of the human abdominal wall using uniaxial tensile testing. Bioengineering 10:1213. https://doi.org/10.3390/bioengineering10101213
48. Axer H, Keyserlingk DG v., Prescher A (2001) Collagen fibers in linea Alba and rectus sheaths. J Surg Res 96:127–134. https://doi.org/10.1006/jsre.2000.6070
49. Delp SL, Suryanarayanan S, Murray WM et al (2001) Architecture of the rectus abdominis, quadratus lumborum, and erector spinae. J Biomech 34:371–375. https://doi.org/10.1016/S0021-9290(00)00202-5
50. Kim J, Lim H, Lee SI, Kim YJ (2012) Thickness of rectus abdominis muscle and abdominal subcutaneous fat tissue in adult women: correlation with age, pregnancy, laparotomy, and body mass index. Arch Plast Surg 39:528–533. https://doi.org/10.5999/aps.2012.39.5.528
51. Damsgaard M, Rasmussen J, Christensen ST et al (2006) Analysis of musculoskeletal systems in the anybody modeling system. Simul Model Pract Theory 14:1100–1111. https://doi.org/10.1016/j.simpat.2006.09.001
52. Erdemir A, McLean S, Herzog W, van den Bogert AJ (2007) Model-based Estimation of muscle forces exerted during movements. Clin Biomech 22:131–154. https://doi.org/10.1016/j.clinbiomech.2006.09.005
53. Eisinga R, Heskes T, Pelzer B, Te Grotenhuis M (2017) Exact p-values for pairwise comparison of Friedman rank sums, with application to comparing classifiers. BMC Bioinformatics 18:68. https://doi.org/10.1186/s12859-017-1486-2
54. Rosnow RL, Rosenthal R, Rubin DB (2000) Contrasts and correlations in Effect-Size Estimation. Psychol Sci 11:446–453. https://doi.org/10.1111/1467-9280.00287
55. Cohen J (1992) A power primer. Psychol Bull 112:155–159. https://doi.org/10.1037/0033-2909.112.1.155
56. Lu WW, Hu Y, Luk KDK et al (2002) Paraspinal muscle activities of patients with scoliosis after spine fusion: an electromyographic study. Spine 27:1180–1185. https://doi.org/10.1097/00007632-200206010-00009
57. Annis P, Lawrence B, Spiker W et al (2014) Predictive factors for acute proximal junctional failure after adult deformity surgery with upper instrumented vertebrae in the thoracolumbar spine. Evid-Based Spine-Care J 05:160–162. https://doi.org/10.1055/s-0034-1386755
58. Smith M, Annis P, Lawrence B et al (2013) Early proximal junctional failure in patients with preoperative sagittal imbalance. Evid-Based Spine-Care J 04:163–164. https://doi.org/10.1055/s-0033-1357366
59. Mendoza-Lattes S, Ries Z, Gao Y, Weinstein SL (2011) Proximal junctional kyphosis in adult reconstructive spine surgery results from incomplete restoration of the lumbar lordosis relative to the magnitude of the thoracic kyphosis. Iowa Orthop J 31:199–206
60. Kim HJ, Bridwell KH, Lenke LG et al (2014) Patients with proximal junctional kyphosis requiring revision surgery have higher postoperative lumbar lordosis and larger sagittal balance corrections. Spine 39:E576–E580. https://doi.org/10.1097/BRS.0000000000000246
61. Maruo K, Ha Y, Inoue S et al (2013) Predictive factors for proximal junctional kyphosis in long fusions to the sacrum in adult spinal deformity. Spine 38:E1469–E1476. https://doi.org/10.1097/BRS.0b013e3182a51d43
62. Marie-Hardy L, Pascal-Moussellard H, Barnaba A et al (2020) Screw loosening in posterior spine fusion: prevalence and risk factors. Glob Spine J 10:598–602. https://doi.org/10.1177/2192568219864341
63. Flynn W, Vickerton P (2024) Anatomy, abdomen and pelvis: abdominal wall. In: StatPearls. StatPearls Publishing, Treasure Island (FL)
64. Ponchelet L, Khalife M, Finoco M et al (2024) Influence of pelvic Tilt correction on PJK occurrence after adult spinal deformity surgery. Eur Spine J 33:1796–1806. https://doi.org/10.1007/s00586-024-08180-2

65. Eleswarapu A, O'Connor D, Rowan FA et al (2022) Sarcopenia is an independent risk factor for proximal junctional disease following adult spinal deformity surgery. Glob Spine J 12:102–109. https://doi.org/10.1177/2192568220947050
66. Tsutsui S, Hashizume H, Iwasaki H et al (2023) Sarcopenia at the upper instrumented vertebra is more significantly associated with proximal junctional kyphosis after long fusion for adult spinal deformity surgery than osteopenia. J Clin Neurosci 116:13–19. https://doi.org/10.1016/j.jocn.2023.08.012
67. Pennington Z, Cottrill E, Ahmed AK et al (2019) Paraspinal muscle size as an independent risk factor for proximal junctional kyphosis in patients undergoing thoracolumbar fusion: presented at the 2019 AANS/CNS joint section on disorders of the spine and peripheral nerves. J Neurosurg Spine 31:380–388. https://doi.org/10.3171/2019.3.SPINE19108
68. Saadé M, Rachkidi R, Rteil A et al (2025) Weak trunk extensors in adult spinal deformity patients are related to sagittal malalignment and kinematic limitations. Gait Posture 117:292–299. https://doi.org/10.1016/j.gaitpost.2025.01.018
69. Nishida N, Ohgi J, Jiang F et al (2019) Finite element method analysis of compression fractures on Whole-Spine models including the rib cage. Comput Math Methods Med 2019:1–10. https://doi.org/10.1155/2019/8348631
70. Galbusera F, Innocenti B (2022) Ligament and tendon biomechanics. Human orthopaedic biomechanics. Elsevier, pp 137–149
71. Hill AV (1938) The heat of shortening and the dynamic constants of muscle. Proc R Soc Lond Ser B - Biol Sci 126:136–195. https://doi.org/10.1098/rspb.1938.0050
72. Zajac FE (1989) Muscle and tendon: properties, models, scaling, and application to biomechanics and motor control. Crit Rev Biomed Eng 17:359–411
73. Bruno AG, Bouxsein ML, Anderson DE (2015) Development and validation of a musculoskeletal model of the fully articulated thoracolumbar spine and rib cage. J Biomech Eng 137:081003. https://doi.org/10.1115/1.4030408
74. Malakoutian M, Street J, Wilke H-J et al (2016) Role of muscle damage on loading at the level adjacent to a lumbar spine fusion: a Biomechanical analysis. Eur Spine J 25:2929–2937. https://doi.org/10.1007/s00586-016-4686-y
75. Christophy M, Faruk Senan NA, Lotz JC, O'Reilly OM (2012) A musculoskeletal model for the lumbar spine. Biomech Model Mechanobiol 11:19–34. https://doi.org/10.1007/s10237-011-0290-6
76. Guo J, Guo W, Ren G (2021) Embodiment of intra-abdominal pressure in a flexible multibody model of the trunk and the spinal unloading effects during static lifting tasks. Biomech Model Mechanobiol 20:1599–1626. https://doi.org/10.1007/s10237-021-01465-1
77. Rupp TK, Ehlers W, Karajan N et al (2015) A forward dynamics simulation of human lumbar spine flexion predicting the load sharing of intervertebral discs, ligaments, and muscles. Biomech Model Mechanobiol 14:1081–1105. https://doi.org/10.1007/s10237-015-0656-2
78. Fasser M-R, Jokeit M, Kalthoff M et al (2021) Subject-Specific alignment and mass distribution in musculoskeletal models of the lumbar spine. Front Bioeng Biotechnol 9:721042. https://doi.org/10.3389/fbioe.2021.721042
79. Favier CD, Finnegan ME, Quest RA et al (2021) An open-source musculoskeletal model of the lumbar spine and lower limbs: a validation for movements of the lumbar spine. Comput Methods Biomech Biomed Engin 24:1310–1325. https://doi.org/10.1080/10255842.2021.1886284
80. Lim HJ, Yoon H, Kim J et al (2024) Comparison of elasticity changes in the paraspinal muscles of adolescent patients with scoliosis treated with surgery and bracing. Sci Rep 14:5623. https://doi.org/10.1038/s41598-024-56189-w
81. Gajdosik RL (1991) Effects of static stretching on the maximal length and resistance to passive stretch of short hamstring muscles. J Orthop Sports Phys Ther 14:250–255. https://doi.org/10.2519/jospt.1991.14.6.250
82. Bandy WD, Irion JM, Briggler M (1998) The effect of static stretch and dynamic range of motion training on the flexibility of the hamstring muscles. J Orthop Sports Phys Ther 27:295–300. https://doi.org/10.2519/jospt.1998.27.4.295
83. Nordez A, Cornu C, McNair P (2006) Acute effects of static stretching on passive stiffness of the hamstring muscles calculated using different mathematical models. Clin Biomech 21:755–760. https://doi.org/10.1016/j.clinbiomech.2006.03.005
84. Guissard N, Duchateau J (2004) Effect of static stretch training on neural and mechanical properties of the human plantar-flexor muscles. Muscle Nerve 29:248–255. https://doi.org/10.1002/mus.10549
85. Eubanks JE, Carlesso C, Sundaram M et al (2023) Prehabilitation for spine surgery: A scoping review. PM&R 15:1335–1350. https://doi.org/10.1002/pmrj.12956
86. Park S-J, Lee C-S, Park J-S et al (2023) Does the amount of correction of sagittal deformity really promote proximal junctional kyphosis?? Multivariate analyses according to uppermost instrumented vertebra levels. World Neurosurg 177:e554–e562. https://doi.org/10.1016/j.wneu.2023.06.095
87. Harada GK, Khan JM, Vetter C et al (2021) Does the number of levels fused affect spinopelvic parameters and clinical outcomes following posterolateral lumbar fusion for Low-Grade spondylolisthesis?? Glob Spine J 11:116–121. https://doi.org/10.1177/2192568220901527
88. Herbert RD, Balnave RJ (1993) The effect of position of immobilisation on resting length, resting stiffness, and weight of the soleus muscle of the rabbit. J Orthop Res 11:358–366. https://doi.org/10.1002/jor.1100110307
89. Malakoutian M, Noonan AM, Dehghan-Hamani I et al (2022) Dysfunctional paraspinal muscles in adult spinal deformity patients lead to increased spinal loading. Eur Spine J 31:2383–2398. https://doi.org/10.1007/s00586-022-07292-x
90. Rebeyrat G, Skalli W, El Rachkidi R et al (2023) Effect of pelvic retroversion on hamstring lengths in adult spinal deformity patients in standing position and during gait. Gait Posture 106:S169–S170. https://doi.org/10.1016/j.gaitpost.2023.07.204
91. Kubo K, Ikebukuro T, Yata H (2022) Mechanical properties of muscles and tendon structures in middle-aged and young men. Sci Rep 12:1702. https://doi.org/10.1038/s41598-022-05795-7
92. Rassier DE, MacIntosh BR, Herzog W (1999) Length dependence of active force production in skeletal muscle. J Appl Physiol 86:1445–1457. https://doi.org/10.1152/jappl.1999.86.5.1445
93. Liu T, Hulleck AA, El-Rich M (2023) Sensitivity of subject-specific upper body musculoskeletal model predictions to mass scaling methods. Comput Biol Med 165:107376. https://doi.org/10.1016/j.compbiomed.2023.107376

Authors and Affiliations

Elisa Jolas[1] · Fabio Galbusera[2] · Tamas F. Fekete[3] · Daniel Haschtmann[3] · Dezsö Jeszenszky[3] · Sarah Richner-Wunderlin[2] · Ferran Pellisé[4] · Ibrahim Obeid[5] · Javier Pizones[6] · Ahmet Alanay[7] · Frank Kleinstück[3] · Caglar Yilgor[7] · Stephen J. Ferguson[1] · Markus Loibl[3] · Dominika Ignasiak[1]

✉ Elisa Jolas
jolaselisa@gmail.com

✉ Dominika Ignasiak
dominika.ignasiak@hest.ethz.ch

Fabio Galbusera
fabio.galbusera@kws.ch

Tamas F. Fekete
tamas.fekete@kws.ch

Daniel Haschtmann
daniel.haschtmann@kws.ch

Dezsö Jeszenszky
dezsoe.jeszenszky@kws.ch

Sarah Richner-Wunderlin
sarah.richner-wunderlin@kws.ch

Ferran Pellisé
24361fpu@gmail.com

Ibrahim Obeid
ibrahim.obeid@gmail.com

Javier Pizones
javierpizones@gmail.com

Ahmet Alanay
aalanay@gmail.com

Frank Kleinstück
frank.kleinstueck@kws.ch

Caglar Yilgor
caglaryilgor@gmail.com

Stephen J. Ferguson
sferguson@ethz.ch

Markus Loibl
markus.loibl@kws.ch

[1] Institute for Biomechanics, ETH Zürich, Zürich, Switzerland

[2] Department of Teaching, Research and Development, Schulthess Klinik, Zürich, Switzerland

[3] Department of Spine Surgery, Schulthess Klinik, Zürich, Switzerland

[4] Spine Surgery Unit, Hospital Vall D'Hebron, Barcelona, Spain

[5] Spine Unit Orthopaedic Department, Hôpital Pellegrin Bordeaux, Bordeaux, France

[6] Spine Unit Orthopaedic Department, La Paz University Hospital, Madrid, Spain

[7] Department of Orthopedics and Traumatology, Acibadem University School of Medicine, İstanbul, Turkey