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CT based bone mineral density as a predictor of proximal junctional fractures

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ABSTRACT

Background: Proximal junctional fractures (PJFr) can be a catastrophic complication associated with adult spinal deformity surgery. Osteoporosis can be a major risk factor for the cause of PJFr. Recent studies suggest using surrogate computed tomography (CT) scans in place of spinal dual-energy x-ray absorptiometry (DEXA) scores for bone mineral density (BMD). Investigate the feasibility of using preoperative CT based bone mineral density at upper instrumented vertebrae (UIV) and one level proximally (UIV+1) and distally (UIV-1) to predict the possibility of PJFr risk.
Methods: Retrospective two-academic center case-controlled study, reviewed consecutive adult spinal deformity surgeries; included constructs encompassing at least five fusion levels and fusions to pelvis. Examined demographic, surgical, and radiographic data preoperatively, postoperatively, and final follow-up. Formed groups based on type of proximal junctional deformity (PJD): Control (no PJD), proximal junctional kyphosis (PJK) and PJFr. Preoperative CT BMD values measured in Hounsfield units (HU) for sagittal and axial planes at UIV, UIV+1, and UIV-1 and compared between groups.
Results: N=92 patients. Preoperative CT scan BMD values were significantly lower in PJFr vs. control at: UIV+1 in sagittal ($p=0.007$), axial ($p=0.02$) planes; UIV sagittal ($p=0.04$) and axial ($p=0.03$) planes; and UIV-1 sagittal ($p=0.05$) plane. Similarly, lower CT scan BMD values noted in PJFr vs. PJK at: UIV+1 in sagittal ($p=0.04$) and axial ($p=0.03$) planes. Trend seen with lower CT scan BMD values at UIV+1 level in PJFr vs. PJK in sagittal ($p=0.12$) and axial ($p=0.10$) planes. Preoperative global sagittal imbalance measurements significantly lower in control, but comparable between PJK and PJFr.
Conclusions: Higher preoperative global sagittal imbalance with lower preoperative CT BMD values at UIV and UIV+1 vertebral body may increase the risk of proximal junctional fractures after adult spine deformity surgery. Proximal junctional hooks may supplement the pathogenesis. Readers should note the small sample size.
Level of Evidence: 3

Background

Proximal junctional fractures (PJFr) are prominent adult spine deformity surgery associated complications [1]. This type of fracture can cause a catastrophic impact on the patient resulting in significant kyphosis, pain, or new neurological deficits with or without associated hardware failure at the end of the construct or adjacent to it [2,3].

Presence of osteoporosis has been shown to be a potential risk factor for proximal junctional failure and compression fractures [4]. Osteoporosis is a most concerning problem which is often prevalent in the elderly population especially since the necessity for spine surgery has steadily increased within this demographic [5]. Research study findings have observed a potential correlation between osteoporosis and adult spinal deformity.

In a study conducted by Pappou et al, they observed scoliosis was common among the osteoporotic population in adult lumbar scoliosis patients [6]. Diagnosis of osteoporosis is important because surgery in this specific subset can have notable complications [5]. Dural-Energy

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X-Ray Absorptiometry (DEXA) scans have been utilized as a standard screening tool for osteoporosis. However, spinal DEXA scores have been reported to be flawed with regional sclerosis associated with spinal degeneration stated as a possible confounder [7]. Recently, investigators have reported on the use of computed tomography (CT) scans surrogate studies in place of spinal DEXA scans [8,9].

Determination of the upper end vertebrae for instrumentation is crucial in the surgical treatment of adult degenerative spine deformities especially when constructs are extended to the pelvis. More importantly, in patients with osteoporosis, is minimizing the incidence of complication rates utilizing optimal surgical aids. Several factors are involved in the determination of the upper instrumented end vertebrae (UIV). Bone mineralization is one factor which estimates the healthiness of a vertebrae [10]. Flaws in spinal DEXA scans often miss osteoporosis which may impact surgical decisions and the prediction of proximal junctional fractures. The intention of our study was to investigate if decreased bone mineralization at the upper instrumented end vertebrae (UIV) or adjacent segments play any role in predicting proximal junctional fractures prior to surgery; thereby, surgeons could analyse bone minerals at the upper end levels, plan surgery and counsel patients about associated risks. Because CT scans can estimate bone mineral density (BMD) in Hounsfield units (HU), these scans can be utilized to measure the BMD of UIVs and their adjacent segments preoperatively.

The purpose of our study was to investigate the feasibility of using preoperative CT based assessments of BMD values in HUs at the UIV, one level proximal (UIV +1) and one level distal (UIV-1) to predict the risk of a possible proximal junctional fracture (PJFr) in adult spinal deformity surgery.

Materials and methods

After Institutional Review Board (IRB) approval, this case-controlled retrospective study from two academic centers included consecutive patients who underwent adult spinal deformity surgery for various generative spinal pathologies such degenerative scoliosis, lumbar stenosis, kyphosis, flat back syndrome, and radiculopathy. Spinal deformities associated with infections, trauma, or multilevel fractures were excluded from the study. Only patients who had multilevel posterior spinal fusions to the pelvis that encompassed at least five or more levels were included in this study sample.

Data collected

A total of 92 consecutive patients met the inclusion criteria. The patients' preoperative, intraoperative, and postoperative records were retrospectively reviewed for: age, gender, Charlson Comorbidity Index (CCI) scores, American Society of Anesthesiologists (ASA) scores, history of osteoporosis, DEXA scan T-scores, surgery indications, type of construct anchors at UIV and one level caudal to UIV, number of levels instrumented, total anchor saturation and proximal three-level anchor saturation. These variables were collected for investigational purposes.

Additionally, follow-up charts (up to 2 years) of outpatient visits, radiological charts and hospital admissions were documented for any vertebral fractures at the UIV, UIV+1 and UIV-1. Vertebral fractures, confirmed by the primary physician, based on evidence from the CT scans were documented. Preoperative, postoperative, and final follow-up radiographs were analyzed for coronal major Cobb angles, thoracic kyphosis (TK) (T5-T12), lumbar lordosis (LL) (L1-S1), global coronal balance (CB) and global sagittal balance (SB) also known as sagittal vertical axis (SVA).

CT measurement of BMD

Preoperative CT scans were utilized to measure the BMD of the cortical bone of vertebral body in Hounsfield units (HU). The BMD HU values were measured at the mid-sagittal and axial cross sections of the vertebrae in the sagittal and axial planes by drawing an elliptical region of interest (ROI) with the aid of image tools. (Fig. 1) These measurements were documented at the UIV, UIV+1 (one level proximal) and UIV-1 (one level distal). In addition, the acquired routine preoperative and all follow-up radiographs were analysed to measure the proximal kyphotic angle.

Proximal junctional kyphosis (Fig. 2) was defined as a postoperative or follow-up proximal junctional sagittal Cobb angle at least ≥ 10° than the preoperative angle measured between the inferior end plate of the

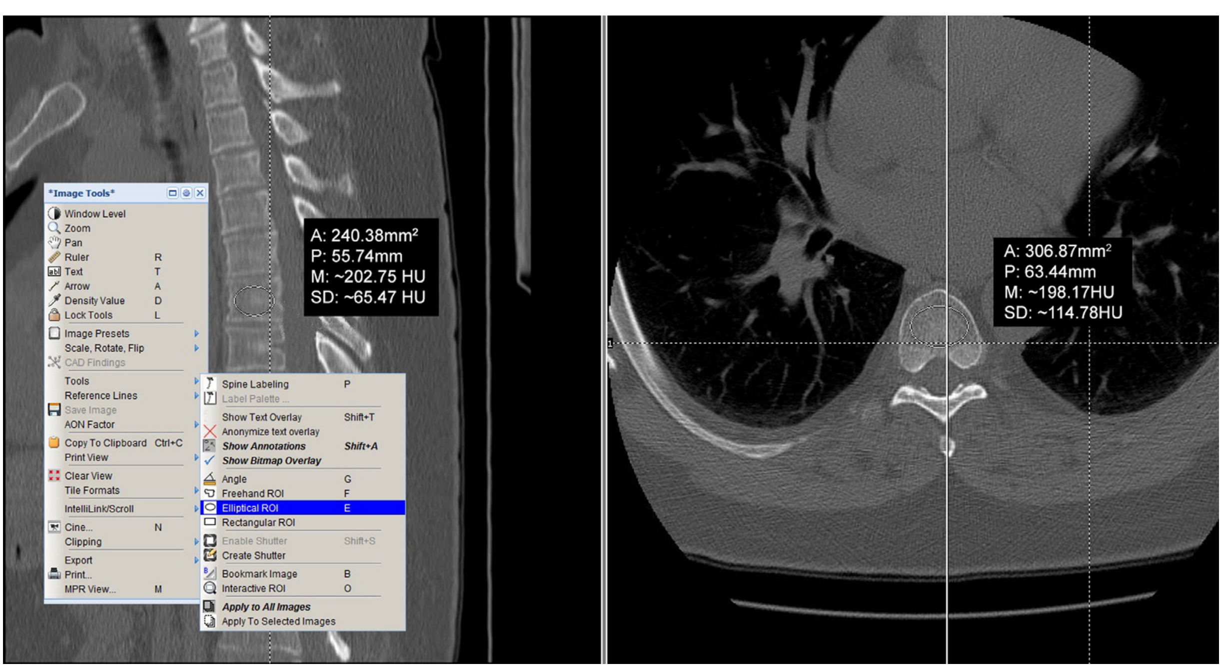

Fig. 1. In preoperative CT scans, BMD values (HUs) were measured at mid-sagittal and axial cross sections of the vertebrae by drawing an elliptical region of interest (ROI) with the aid of image tools.

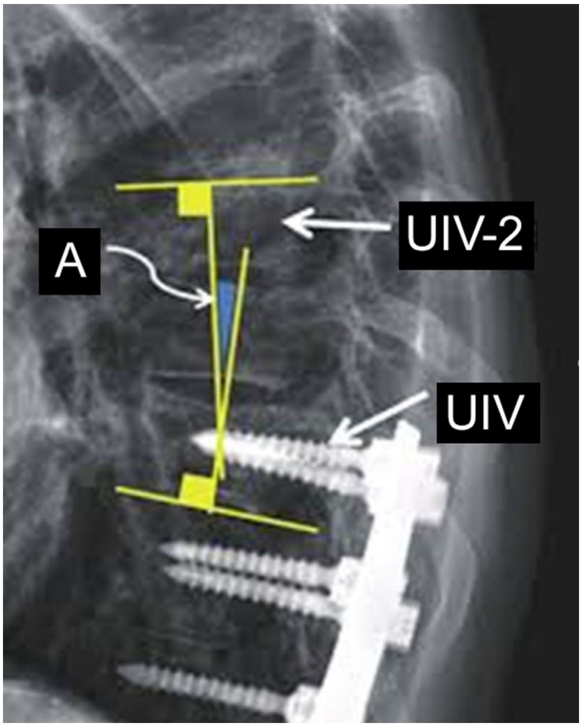

Fig. 2. Illustration of measuring the proximal junctional kyphotic angle.

UIV and the superior end plate of UIV+2 (two levels proximal to UIV) [11].

Patients were categorized into three groups: control (no proximal junctional deformity (NoPJD)); proximal junctional kyphosis (PJK) (Fig. 3); and proximal junctional fracture (PJFr) which excluded patients with PJK (Fig. 4).

Statistical analysis

Statistical comparisons were made between the control (No PJD) and PJK groups, control and PJFr groups, and PJK and PJFr groups separately. An analysis of variance (ANOVA) test for continuous variables and Chi square tests for categorical variables were used. IBM SPSS v.22 (IBM Corp., Armonk, NY) was utilized for the analyses. $P \leq 0.05$ was considered as statistically significant.

Results

Overall results

Of the 92 patients, 59 patients had no proximal junctional disease (control group) and 33 patients (PJK =22, PJFr =11) demonstrated proximal junctional pathologies (33.8%). The overall patient demographic data demonstrated an average age = 64 years (range: 42 - 81); gender distribution (male = 43, female = 49); mean CCI score = 0.9 (range: 0 - 10); mean ASA score = 2.7 (range: 0 - 4); average preoperative major Cobb angle = 19.7° (range: 0°- 59°), mean thoracic kyphosis (TK) = 31° (range: 1°- 70°), mean lumbar lordosis (LL) = 31° (range: 14°- 62°), mean coronal balance (CB) = 5.1mm (range: -45mm - 48.4mm); mean sagittal balance (SB) = 27.4mm (range: -1mm - 190mm); average length of follow-up =1.5 years (range: 0.2 - 4 years); and average levels of fusion = 10.7 (range: 5 -17).

For most patients (n=82, 89%), pedicle screws were proximal level rod anchors. Proximal anchors were placed in 22 patients (24%) at or below T11 and in 70 patients (76%) above T11. The average total anchor saturation was 96% and proximal 3-level anchor saturation was 97.4%.

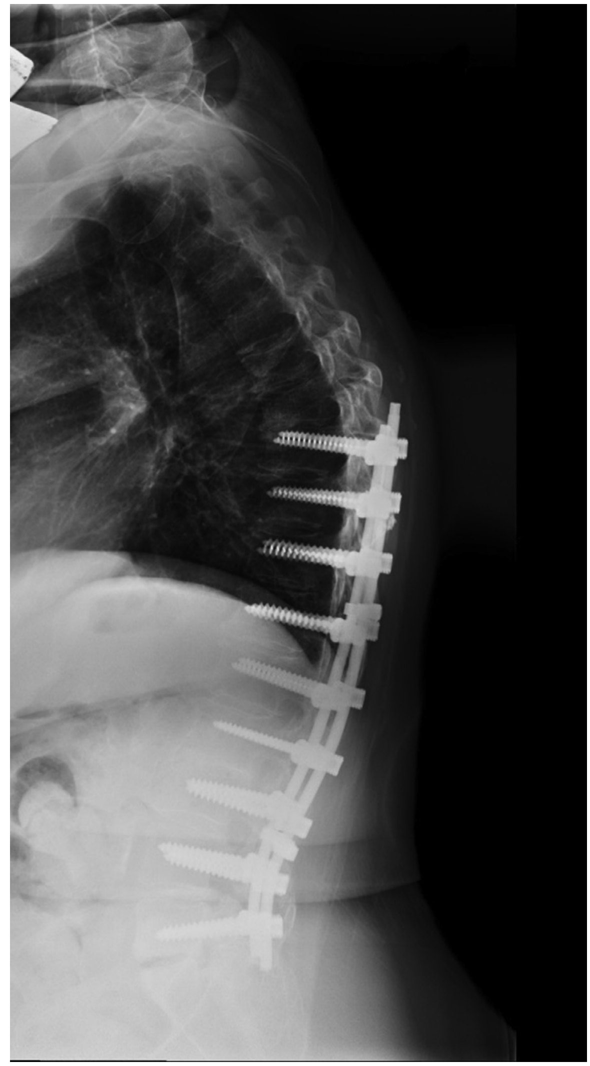

Fig. 3. Postoperative lateral standing radiograph showing proximal junctional kyphosis.

Comparison between proximal junctional fracture and control groups

Summarized in Table 1 are the preoperative CT scans' BMD values between the control and PJFr cohorts. We observed significantly lower BMD HU values in the PJFr group compared to the control group for: UIV+1 sagittal (p=0.007) and axial plane (p=0.02); UIV sagittal plane (p=0.04) and axial plane (p=0.03); and UIV-1 sagittal plane (p=0.05). No significance was seen at the UIV-1 axial plane (p=0.19).

Age, gender, history of osteoporosis, proximal anchor level (above T11 versus at or below T11), average levels of fusion, total anchor saturation, and proximal three-level anchor saturation were comparable between the groups (Table 2). The frequency of hooks (n=4, 36%) at the UIV level was statistically higher in the PJFr group than in the control group (n=2, 3%), p=0.005.

Preoperatively, the average measured major Cobb angle was significantly higher in the PJFr group (26° vs. 16°, p=0.04) and average TK, LL, CB, and SB measurements being similar between the groups. Postoperatively, there were significantly higher measurements for TK (12°, p=0.006), CB (p=0.02) and SB (p=0.001) in the PJFr group compared to the control group. Postoperative and final follow-upmeasurements of major Cobb angles and LL were comparable between groups. At the final follow-up, significant differences in TK (p=0.005), CB (p=0.005) and SB (p=0.009) remained between the PJFr and control cohorts, Table 2.

Fig. 4. Postoperative lateral standing x-ray showing vertebral body fracture one level distal to the upper instrumented vertebrae with hooks appearingly disengaged.

Comparison between proximal junctional kyphosis and control groups

Analysis of the CT scans' BMD values between the control and PJK groups exhibited no significant differences, Table 3. Additionally, age, gender, CCI, ASA, history of osteoporosis, proximal anchor level (above T11 versus at or below T11), UIV construct anchors, average fusion levels, total anchor saturation, proximal three-level anchor saturation were also similar between the groups, Table 4.

Preoperatively, measurements of the mean major Cobb angle (p=0.55) and CB (p=0.11) were not significant between the groups. However, we noticed statistically lower preoperative measurements of TK (p=0.04), LL (p=0.05) and SB (p=0.01) within the control group, Table 4. Postoperatively, the PJK cohort displayed significantly higher major Cobb angle (p=0.03), TK (p=0.01), and SB (p=0.001) measurements versus the control group, Table 4. At the final follow-up, the control group had statistically significant lower major Cobb angles (p=0.02), TK (p=0.01), and SB (p=0.01) measurements versus PJK group.

Table 1
CT Based BMD Comparison between No Proximal Junctional Deformity (**Control) Group and Proximal Junctional Fracture (PJFr) Group**.

Number of Patients			Control (±SD) 59	PJFr (±SD) 11	P value
Preoperative CT BMD (HU)	UIV +1	Sagittal	171 + 50	126 + 33	0.007
		Axial	165 + 53	126 + 40	0.02
	UIV	Sagittal	162 + 54	127 + 28	0.04
		Axial	163 + 48	131 + 23	0.03
	UIV -1	Sagittal	159 + 45	131 + 40	0.05
		Axial	163 + 53	141 + 32	0.19

UIV= Upper Instrumented Vertebrae.
UIV+1 = One level proximal Upper Instrumented Vertebrae.
UIV-1 = One level distal Upper Instrumented Vertebrae.
HU = Hounsfield Unit.

Comparison of proximal junctional kyphosis and proximal junctional fracture groups

Comparing the PJK and PJFr groups, the mean preoperative BMD values at the UIV+1 level were significantly lower in the sagittal plane (p=0.04) and axial plane (p=0.03) in the PJFr cohort, Table 5. Although there were no statistical differences at the UIV level, there was a trend toward lower mean preoperative BMD values in the PJFr group in the sagittal plane (p=0.12) and axial (p=0.10).

Average age, gender, CCI, ASA, proximal anchor vertebral level (above T11 versus at or below T11), UIV construct anchors, average fusion levels, total anchor saturation were comparable between the groups, Table 6. Additionally, no statistical differences were found for major Cobb angles, TK, LL, CB or SB at preoperative, postoperative or final follow ups between the groups, Table 6.

Correlation between Dual-Energy X-Ray Absorptiometry (DEXA) scans and Computed Tomography (CT) scans for bone mineral density

From the data obtained, DEXA scan T-scores were documented for 48 patients (52%) and missing for 46 patients for unknown reasons. Traditionally, T-scores are used to diagnose normal bone density (T > -1), osteopenia (T between -1 and -2.4), and osteoporosis (T < -2.4). Normal bone density was noted in 22 patients, osteopenia in 19 patients and osteoporosis in 7 patients. In the osteoporotic group, one patient exhibited high CT HUs values at all levels. Even though the osteoporotic group comprised a very small sample (n=7), we removed this outlier from our analysis (n=6). The preoperative CT BMD HU values and DEXA scan T-scores for BMD was analysed. We noticed lower mean BMD values utilizing CT scans in the osteoporotic group compared to the normal bone density group at all three vertebral levels in both planes (Table 7). Statistical significance was observed at the UIV in the sagittal plane (p=0.03) and axial plane (p=0.04), at UIV-1 in the axial plane (p=0.05); and a nearly statistical significance at UIV+1 in the axial plane (p=0.06).

Discussion

Prevention and treatment of proximal junctional pathologies associated with adult spine deformity surgery are some of the most intriguing problems faced by surgeons. There are very limited studies about the etiological factors for the incidence of proximal junctional fracture (PJFr) following adult spine deformity surgery [4]. The pathogenesis of PJFr and PJK have been well studied in the literature. Global sagittal imbalances, osteoporosis and age have been suggested as possible major risk factors for the pathogenesis of PJFr [4].

Determination of the optimal end vertebrae for upper instrumentation is of utmost importance in adult spinal deformity surgery that is extended to the pelvis or sacrum [10]. The risk of proximal deformity pathologies rates is also greater when surgery is extended to the pelvis and/or sacrum [4]. In some instances, relevant to the magnitude of the

Table 2
Demographic, Surgical and Radiographic Comparisons between No Proximal Junctional Deformity (Control) Group and Proximal Junctional Fracture (PJFr) Group.

Number of Patients	Control 59	PJFr 11	P value N/A
Age (years)	63.0 ± 7.0	65.6 ± 10.0	0.45
Gender	M = 29; F = 30	M = 4; F = 7	0.32
Charlson Comorbidity Index	0.6 ± 1.0	2.0 ± 3.3	0.007
American Society of Anesthesiologist scores	2.8 ± 0.4	2.4 ± 1.0	0.057
History of Osteoporosis	13 (22%)	3 (27%)	0.48
Proximal Anchor Level			0.53
Above T11	45 (77%)	8 (72%)	
T11 or below	14 (23%)	3 (28%)	
Upper Instrumented Vertebrae Construct Anchors			0.005
Screws	57	7	
Hooks	2	4	
Fusion Levels	11 ± 3	11 ± 3	0.96
Total Anchor Saturation (%)	94 ± 9	92 ± 13	0.53
Proximal 3-level Anchor Saturation (%)	96 ± 11	96 ± 7	0.87
Major Cobb Angle (°)			
Preoperative	16 ± 13	26 ± 14	0.04
Postoperative	7±6	10±5	0.09
Final Follow-up	7±5	9±5	0.26
Thoracic Kyphosis (T5-T12) (°)			
Preoperative	29 ± 16	31 ± 11	0.68
Postoperative	38 ± 12	50 ± 12	0.006
Final Follow up	39 ± 11	52 ± 13	0.005
Lumbar Lordosis (L1-S1) (°)			
Preoperative	29 ± 17	33 ± 22	0.55
Postoperative	43 ± 14	47 ± 14	0.35
Final Follow-up	45 ± 12	46 ± 13	0.77
Global Coronal Balance (mm)			
Preoperative	4 ± 9	4 ± 30	0.94
Postoperative	9 ± 16	24 ± 23	0.02
Final Follow-up	7 ± 11	21 ± 22	0.005
Global Sagittal Balance (mm)			
Preoperative	18 ± 38	40 ± 46	0.15
Postoperative	11 ± 20	42 ± 45	0.001
Final Follow-up	14 ± 38	54 ± 52	0.009

Table 3
CT based BMD Comparison between No Proximal Junctional Deformity (Control) Group and Proximal Junctional Kyphosis (PJK) Group.

Number of Patients			Control (±SD) 59	PJK (±SD) 22	P value
Preoperative CT BMD (HU)	UIV +1	Sagittal	171 + 50	162 + 51	0.52
		Axial	165 + 53	168 + 53	0.50
	UIV	Sagittal	162 + 54	153 + 50	0.43
		Axial	163 + 48	161 + 57	0.87
	UIV -1	Sagittal	159 + 45	150 + 48	0.84
		Axial	163 + 53	158 + 55	0.68

UIV= Upper Instrumented Vertebrae.
UIV+1 = One level proximal Upper Instrumented Vertebrae.
UIV-1 = One level distal Upper Instrumented Vertebrae.
HU = Hounsfield Unit.

curve and other pathologies, instrumentation to the sacrum/pelvis is necessary [3].

We believe bone mineralization at the upper end vertebrae or adjacent vertebrae may also be a potential contributing factor for the pathogenesis of PJFr. From observations in our study, the measured average BMD values were significantly lower in the preoperative CT scans in our PJFr sample at the UIV and UIV+1 in both sagittal and axial planes compared to the control group. In the PJFr versus PJK cohorts, there was a trend toward lower BMD values at the UIV level. Conversely, the average BMD values were comparable between the control and PJK cohorts at all levels and in both sagittal and axial planes.

There has been a debate over the influence of preoperative global sagittal imbalance in the development of PJK [12]. We observed 50% of patients in both the PJK and PJFr cohorts had preoperative global sagittal imbalances (SB) over 30mm and only observed in 1% of the control cohort. There was a slight trend toward higher mean preoperative global SBs in the PJFr group compared to the control group (40mm vs. 18mm), p=0.15. Of note, two patients within the control group had abnormally high SB values (>180 mm) and this irregularity may account for the nearly statistical difference. The mean preoperative SB values were significantly higher in the PJK group versus the control group (46 mm vs. 18mm, p=0.01). Higher preoperative SB values are a common risk factor which we observed with similar values observed in the PJFr and PJK groups. Thus, these higher SB values in the PJFr and PJK cohorts lead us to believe that lower preoperative CT scan BMD values at the UIV and adjacent levels may not be an independent risk factor for the development of proximal fractures. Global SB may also be a major factor for PJK.

All the investigational parameters were similar between PJK and PJFr cohorts, except for CT scan BMD values. Therefore, the cumulative effect of preoperative low bone mineralization at the UIV and adjacent levels and higher abnormal sagittal imbalances may have contributed to the development of proximal junctional fractures postoperatively. We also observed the average coronal imbalance (CB) was significantly higher in PJFr versus control cohorts, no different between PJK versus control cohorts, and nearly significantly higher in PJFr versus PJK cohorts. CB may either be a confounding variable or a contributing risk factor that may have an additional effect on the pathogenesis of PJFr.

Spinal degeneration is a natural process that can happen at any vertebrae. Spinal stenosis, loss of intervertebral disc height and osteophyte formation are characteristic findings of the degenerative vertebrae [10]. At the same time, spinal degeneration can change the BMD of the corresponding vertebrae [13]. The insidious nature of a degenerative pathogenesis may give false impressions by masking its charac-

Table 4
Demographic, Surgical and Radiographic Comparisons between No Proximal Junctional Deformity (Control) Group and Proximal Junctional Kyphosis (PJK) Group.

Number of Patients	Control 59	PJK 22	P value N/A
Age (years)	63.0 ± 7.0	65 ± 8.0	0.29
Gender	M = 29; F = 30	M =10; F = 12	0.48
Charlson Comorbidity Index	0.6 ± 1.0	1.0 ± 1.3	0.17
American Society of Anesthesiologist scores	2.8 ± 0.4	2.6 ± 0.4	0.14
History of Osteoporosis	13 (22%)	3 (14%)	0.30
Proximal Anchor Level			0.58
Above T11	45 (77%)	17 (77%)	
T11 or below	14 (23%)	5 (23%)	
Upper Instrumented Vertebrae Construct Anchors			0.27
Screws	57	20	
Hooks	2	2	
Fusion Levels	11 ± 3	9 ± 2.5	0.16
Total Anchor Saturation (%)	94 ± 9	95 ± 11	0.70
Proximal 3-level Anchor Saturation (%)	96 ± 11	99 ± 3	0.25
Major Cobb Angle (°)			
Preoperative	16 ± 13	18 ± 9	0.55
Postoperative	7±6	10±3.6	0.03
Final Follow-up	7±5	12±6	0.02
Thoracic Kyphosis (T5-T12) (°)			
Preoperative	29 ± 16	37 ± 12	0.04
Postoperative	38 ± 12	46 ± 8	0.01
Final Follow-up	39 ± 11	47 ± 12	0.01
Lumbar Lordosis (L1-S1) (°)			
Preoperative	29 ± 17	37 ± 13	0.05
Postoperative	43 ± 14	43 ± 10	0.99
Final Follow-up	45 ± 12	43 ± 9	0.53
Global Coronal Balance (mm)			
Preoperative	4 ± 9	9 ± 19	0.11
Postoperative	9 ± 16	12 ± 13	0.53
Final Follow-up	7 ± 11	10 ± 10	0.32
Global Sagittal Balance (mm)			
Preoperative	18 ± 38	46 ± 42	0.01
Postoperative	11 ± 20	38 ± 41	0.001
Final Follow-up	14 ± 38	46 ± 55	0.01

Table 5
CT Based BMD Comparison between Proximal Junctional Kyphosis (PJK) Group and Proximal Junctional Fracture (PJFr) Group.

Number of Patients			PJK (±SD) 22	PJFr (±SD) 11	P value
Preoperative CT BMD (HU)	UIV +1	Sagittal	162 ± 51	126 + 33	0.04
		Axial	168 ± 53	126 + 40	0.03
	UIV	Sagittal	153 ± 50	127 + 28	0.12
		Axial	161 ± 57	131 + 23	0.10
	UIV -1	Sagittal	150 ± 48	131 + 40	0.26
		Axial	158 ± 55	141 + 32	0.37

UIV= Upper Instrumented Vertebrae.
UIV+1 = One level proximal Upper Instrumented Vertebrae.
UIV-1 = One level distal Upper Instrumented Vertebrae.
HU = Hounsfield Unit.

teristic findings at an early stage. Choosing this precocious degenerative vertebra for upper end instrumentation or one level distal to it, in high sagittal imbalance patients, may increase the risk of proximal junctional fractures [14]. Analysis of CT scan BMD values at the intended upper end vertebrae and adjacent vertebral levels may aid in the prediction of proximal junctional fractures and in planning optimal surgery techniques.

Osteoporosis is believed to be a major contributing factor for proximal junctional fractures [1,4]. Traditionally, DEXA scans have been used to detect osteoporosis. DEXA scans commonly survey BMD at the lumbar spine or the hips. However, they have been shown to overestimate BMD values in patients with spinal degenerations [7,15,16]. The diagnosis of osteoporosis is crucial to the management of adult spinal deformity due to the high incidence of complications.

The diagnostic efficacy of spinal CT scans in the assessment of real bone mineral density of the degenerative spine and its correlation with DEXA T-scores have been studied. Choi et al observed that CT scan BMD values provide a meaningful assessment and have a strong correlation with the DEXA T-score. However, in degenerative spine patients, the T-score tends to be higher than the actual BMD [17]. Similarly, our study observed a positive correlation between DEXA T-scores and CT scan BMD values. Significantly lower CT scan BMD values were noticed in osteoporotic patients at the UIV and adjacent levels. However, in certain planes, our observed CT scan BMD values did not reach statistical significance, and the reason may be due to a discrepancy in the anatomical sites used for surveying BMD for T-scores. Based on previous research, spinal DEXA scans can predict higher BMD in the degenerative spine [15].

Currently, there have been no studies to determine whether CT scans can overestimate BMD. Chest and abdominal CT scans utilized for unrelated clinical indications have been shown to be reliable in identifying osteoporosis as well as vertebral fracture risks for patients without any additional costs and radiation exposure [18–20]. Routinely performed, preoperative CT scans for spine surgery could potentially be used to determine the bone mineral density of the vertebrae at the intended surgical levels.

The role of increased age in proximal junctional fracture occurrences in long multilevel fusions to the pelvis in adult spine deformity patients has been investigated. Research has shown older patients are prone to junctional kyphosis or fractures in the spine [5]. The proximal junctional pathologies incidence rate (33%) noted in our study was comparable to the rate reported in literature for this age group [21]. In our study, the average age was similar for all groups. Preoperative comorbidities were higher in PJFr group; there-

Table 6
Demographic, Surgical and Radiographic Comparisons between Proximal Junctional Kyphosis (PJK) Group and Proximal Junctional Fracture (PJFr) Group.

Number of Patients	PJK 22	PJFr 11	P value N/A
Age (years)	65 ± 8.0	65.6 ± 10.0	0.99
Gender	M =10; F = 12	M = 4; F = 7	
Charlson Comorbidity Index	1.0 ± 1.3	2.0 ± 3.3	0.21
American Society of Anesthesiologist scores	2.6 ± 0.4	2.4 ± 1.0	0.41
History of Osteoporosis	3 (14%)	3 (27%)	
Proximal Anchor Level			0.54
Above T11	17 (77%)	8 (72%)	
T11 or below	5 (23%)	3 (28%)	
Upper Instrumented Vertebrae Construct Anchors			0.07
Screws	20	7	
Hooks	2	4	
Fusion Levels	9 ± 2.5	11 ± 3	0.30
Total Anchor Saturation (%)	95 ± 11	92 ± 13	0.48
Proximal 3-level Anchor Saturation (%)	99 ± 3	96 ± 7	0.20
Major Cobb Angle (°)			
Preoperative	18 ± 9	26 ± 14	0.06
Postoperative	10±3.6	10 ± 5	0.86
Final Follow-up	12±6	9 ± 5	0.26
Thoracic Kyphosis (T5-T12) (°)			
Preoperative	37 ± 12	31 ± 11	0.22
Postoperative	46 ± 8	50 ± 12	0.24
Final Follow-up	47 ± 12	52 ± 13	0.36
Lumbar Lordosis (L1-S1) (°)			
Preoperative	37 ± 13	33 ± 22	0.50
Postoperative	43 ± 10	47 ± 14	0.29
Final Follow-up	43 ± 9	46 ± 13	0.47
Global Coronal Balance (mm)			
Preoperative	9 ± 19	4 ± 30	0.61
Postoperative	12 ± 13	24 ± 23	0.07
Final Follow-up	10 ± 10	21 ± 22	0.11
Global Sagittal Balance (mm)			
Preoperative	46 ± 42	40 ± 46	0.72
Postoperative	38 ± 41	42 ± 45	0.81
Final Follow-up	46 ± 55	54 ± 52	0.74

Table 7
Correlation between Dual-Energy X-Ray Absorptiometry (DEXA) Scans and Computed Tomography (CT) Scans for Bone Mineral Density.

	n	**UIV + 1** **Sagittal plane (±SD)**	**Axial plane (±SD)**
T: > -1	22	163 ± 47	162 ± 50
T: -1 and -2.4	19	159 ± 49	148 ± 64
T: < -2.4	6	125 ± 49	101 ± 33
P value		0.24	0.06
	n	**UIV** **Sagittal plane (±SD)**	**Axial plane (±SD)**
T: > -1	22	160 ± 49	164 ± 51
T: -1 and -2.4	19	152 ± 53	151 ± 51
T: <-2.4	6	100 ± 32	102 ± 46
P value		0.03	0.04
	n	**UIV-1** **Sagittal plane (±SD)**	**Axial plane (±SD)**
T: > -1	22	155 ± 43	160 ± 50
T: -1 and -2.4	19	139 ± 49	144 ± 48
T: <-2.4	6	119 ± 32	105 ± 41
P value		0.18	0.05

fore, preoperative comorbidities may also contribute to further risk in its pathogenesis.

The frequency of hooks as proximal anchors for multilevel spinal instrumentation was significantly greater in PJFr patients (36%) compared to the control group (0.3%) in our study. There have been limited studies investigating the types of proximal anchors in proximal junctional fractures in adult spinal deformity surgeries [22]. Matsumura et al found that using transverse process hooks as the UIV anchor may prevent vertebral collapse in cases of fractures [22]. Mac-Thiong et al, in a biomechanical study, observed no correlation between the variety of proximal anchors and proximal junction fractures in the osteoporotic spine to decrease the risk of PJFr [23]. However, these studies did not compare differences in global sagittal imbalance. Proximal hook anchors may supplement vertebrae with lower CT BMD values and higher global sagittal imbalance in the pathogenesis of PJFr. In our study, proximal hooks rates were comparable between the control and PJK groups. The frequency of hooks as proximal anchors was significantly greater in the PJFr group compared to the control group in our study. Proximal hooks as anchors are confounding variables in our study.

Presently, there are no standard surgical techniques to address the prevention of proximal junctional fractures even when risk factors are identified. Several studies have investigated different surgical techniques to prevent proximal junctional fractures in patients undergoing spinal deformity surgery [24–26]. In a biomechanical study by Kebaish et al, vertebroplasty, at the UIV and UIV+1 levels, was shown to decrease the incidence of proximal junctional fractures following long spinal fusions in axially loaded cadaveric models [24]. In a clinical study by Theologis and Burch, 2-level cement augmentation at the UIV and UIV+1 reduced the number of proximal junctional fractures and associated revision surgeries [26]. It should be noted that each of these evolving techniques have their own disadvantages and inherent risks [10].

A major limitation of our study was the small sample size. Additionally, there were a broad range of diagnoses which could possibly be problematic with the validity of our findings and stratify the diagnosis and PJFr rate. Due to the small sample size, we were unable to perform an analysis. There were also inherent setbacks in the study due to its retrospective nature. Another limitation was the ability to investigate if lower CT BMD values have an impact on proximal junctional fractures in normal preoperative sagittal patients.

A prospective study with a greater number of patients will be necessary to investigate the role of preoperative CT scans in patients with lower BMD values at the UIV level and adjacent segments to predict their risk of proximal junctional fractures. Furthermore, studies will need to be conducted to determine a threshold of CT BMD values for the risk of proximal junctional fractures. While values are reported with respect to CT BMD values, readers should note the small sample size of this study. Notwithstanding, noting these measurements may aid in planning the proximal extent of constructs as well as surgical methods to prevent proximal junctional failures.

In conclusion, preoperative lower CT BMD values at the UIV and/or at adjacent vertebrae may amplify the proximal junctional fracture incidence in patients with abnormally high preoperative global sagittal imbalances. Hooks at proximal junctional levels may add affect in the pathogenesis of PJFr. Therefore, including preoperative CT BMD values, type of proximal junctional anchors, preoperative sagittal alignment, osteoporosis and other risk factors may also be beneficial in planning long multilevel fusions to the sacrum to decrease the incidence of proximal junctional fractures. It is also important to counsel patients about the risks of these fractures prior to surgery.

Summary sentence

Higher preoperative global sagittal imbalance with lower preoperative CT BMD values at UIV and UIV+1 vertebral body may increase the risk of proximal junctional fractures after adult spine deformity surgery. Proximal junctional hooks may supplement the pathogenesis.

Conflict of Interest

This study was performed with the approval of SUNY Upstate Medical University IRB and The Ohio State University Wexner Medical Center IRB and in accordance with the boards' regulations. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Kim HJ, Iyer S. Proximal junctional kyphosis. J Am Acad Orthop Surg 2016;24(5):318–26. doi:10.5435/JAAOS-D-14-00393.

[2] Nguyen NL, Kong CY, Hart RA. Proximal junctional kyphosis and failure-diagnosis, prevention, and treatment. Cur Rev Musculoskelet Med 2016;9(3):299–308. doi:10.1007/s12178-016-9353-8.

[3] Watanabe K, Lenke LG, Bridwell KH, Kim YJ, Koester L, Hensley M. Proximal junctional vertebral fracture in adults after spinal deformity surgery using pedicle screw constructs: analysis of morphological features. Spine (Phila Pa 1976) 2010;35(2):138–45 PMID: 20081508. doi:10.1097/BRS.0b013e3181c8f35d.

[4] Tamai K, Terai H, Suzuki A, et al. Risk factors for proximal junctional fracture following fusion surgery for osteoporotic vertebral collapse with delayed neurological deficits: a retrospective cohort study of 403 patients. Spine Surg Relat Res 2018;3(2):171–7. doi:10.22603/ssrr.2018-0068.

[5] Tomé-Bermejo F, Piñera AR, Alvarez-Galovich L. Osteoporosis and the management of spinal degenerative disease (I). Arch Bone Jt Surg 2017;5(5):272–82 PMID: 29226197; PMCID: PMC5712392.

[6] Pappou IP, Giradi FP, Sandhu HS, et al. Discordantly high spinal bone density values in patients with adult lumbar scoliosis. Spine (Phila PA 1976) 2006;31(14):1614–20. doi:10.1097/01.brs.0000222030.32171.5f.

[7] Li N, Li XM, Xu L, Sun WJ, Cheng XG, Tian W. Comparison of QCT and DXA: osteoporosis detection rates in postmenopausal women. Int J Endocrinol 2013;2013:895474. doi:10.1155/2013/895474.

[8] Lee S, Chung CK, Oh SH, Park SB. Correlation between bone mineral density measured by dual-energy X-ray absorptiometry and Hounsfield Units measured by diagnostic CT in lumbar spine. J Korean Neurosurg Soc 2013;54(5):384–9. doi:10.2240/jkna.2013.54.5.384.

[9] Schreiber JJ, Anderson PA, Rosas HG, Buchholz AL, Au AG. Hounsfield units for assessing bone mineral density and strength: a tool for osteoporosis management. J Bone Joint Surg Am 2011;93(11):1057–63. doi:10.2106/JBJS.J.00160.

[10] Shufflebarger H, Suk SI, Mardjetko S. Debate: determining the upper instrumented vertebra in the management of adult degenerative scoliosis: stopping at T10 versus L1. Spine (Phila Pa 1976) 2006;31(19):S185–94 Suppl. doi:10.1097/01.brs.0000232811.08673.03.

[11] Glattes RC, Bridwell KH, Lenke LG, Kim YJ, Rinella A. Edwards 2nd C. Proximal junctional kyphosis in adult spinal deformity following long instrumented posterior spinal fusion: incidence, outcomes, and risk factor analysis. Spine (Phila Pa 1976) 2005;30(14):1643–9. doi:10.1097/01.brs.0000169451.76359.49.

[12] Park S J, Lee CS, Chung SS, Lee JY, Kang SS, Park SH. Different risk factors of proximal junctional kyphosis and proximal junctional failure following long instrumented fusion to the sacrum for adult spinal deformity: survivorship analysis of 160 patients. Neurosurgery 2017;80(2):279–86. doi:10.1227/NEU.0000000000001240.

[13] Kaiser J, Allaire B, Fein PM, et al. Correspondence between bone mineral density and intervertebral disc degeneration across age and sex. Arch Osteoporos 2018;13(1):123. doi:10.1007/s11657-018-0538-1.

[14] Estublier C, Chapurlat R, Szulc P. Older men with severe disc degeneration have more incident vertebral fractures-the prospective MINOS cohort study. Rheumatology (Oxford, England) 2017;56(1):37–45. doi:10.1093/rheumatology/kew327.

[15] Gupta A, Upadhyaya S, Patel A, et al. DEXA sensitivity analysis in patients with adult spinal deformity. Spine J 2020;20(2):174–80. doi:10.1016/j.spinee.2019.08.011.

[16] Yu W, Gluer CC, Fuerst T, et al. Influence of degenerative joint disease on spinal bone mineral measurements in postmenopausal women. Calcif Tissue Int 1995;57(3):169–74. doi:10.1007/BF00310253.

[17] Choi MK, Kim SM, Lim JK. Diagnostic efficacy of Hounsfield units in spine CT for the assessment of real bone mineral density of degenerative spine: correlation study between T-scores determined by DEXA scan and Hounsfield units from CT. Acta Neurochir (Wein) 2016;158(7):1421–7. doi:10.1007/s00701-016-2821-5.

[18] Pickhardt PJ, Pooler BD, Lauder T, Munoz del Rio A, Bruce RJ, Binkley N. Opportunistic screening for osteoporosis using abdominal computed tomography scans obtained for other indications. Ann Intern Med 2013;158(8):588–95. doi:10.7326/0003-4819-158-8-201304160-00003.

[19] Lee SJ, Binkley N, Lubner MG, Bruce RJ, Ziemlewicz TJ, Pickhardt PJ. Opportunistic screening for osteoporosis using the sagittal reconstruction from routine abdominal CT for combined assessment of vertebral fractures and density. Osteoporos Int 2016;27(3):1131–6. doi:10.1007/s00198-01503318-4.

[20] Marinova M, Edon B, Wolter K, Katsimbari B, Schild HH, Strunk HM. Use of routine thoracic and abdominal computed tomography scans for assessing bone mineral density and detecting osteoporosis. Curr Med Res Opin 2015;31(10):1871–81. doi:10.1185/03007995.2015.1074892.

[21] Kim JH, Kim SS, Suk SI. Incidence of proximal adjacent failure in adult lumbar deformity correction based on proximal fusion level. Asian Spine J 2007;1(1):19–26. doi:10.4184/asj.2007.1.1.19.

[22] Matsumura A, Namikawa T, Kato M, et al. Effect of different types of upper instrumented vertebrae instruments on proximal junctional kyphosis following adult spinal deformity surgery: pedicle screw versus transverse process hook. Asian Spine J 2018;12(4):622–31. doi:10.31616/asj.2018.12.4.622.

[23] Mac-Thiong JM, Levasseur A, Parent S, Petit Y. The influence of proximal anchors on the risk of proximal junctional fracture in the osteoporotic spine: biomechanical comparison between pedicle screws and transverse process hooks. J Spinal Disord Tech 2014;27(2):E49–54. doi:10.1097/BSD.0b013e318292b914.

[24] Kebaish KM, Martin CT, O'Brien JR, LaMotta IE, Voros GD, Belkoff SM. Use of vertebroplasty to prevent proximal junctional fractures in adult deformity surgery: a biomechanical cadaveric study. Spine J 2013;13(12):1897–903. doi:10.1016/j.spinee.2013.06.039.

[25] Aydogan M, Ozturk C, Karatoprak O, Tezer M, Aksu N, Hamzaoglu A. The pedicle screw fixation with vertebroplasty augmentation in the surgical treatment of the severe osteoporotic spines. J Spinal Disord Tech 2009;22(6):444–7. doi:10.1097/BSD.0b013e31818e0945.

[26] Theologis AA, Burch S. Prevention of acute proximal junctional fractures after long thoracolumbar posterior fusions for adult spinal deformity using 2-level cement augmentation at the upper instrumented vertebra and the vertebra 1 level proximal to the upper instrumented vertebra. Spine (Phila Pa 1976) 2015;40(19):1516–26. doi:10.1097/BRS.0000000000001043.