Review Article

ASJ Asian Spine J. 2024;18(5): 719-730
https://doi.org/10.31616/asj.2023.0402
PISSN 1976-1902 • eISSN 1976-7846

# Hounsfield units and vertebral bone quality score for predicting mechanical complications after adult spinal deformity surgery: a systematic review and meta-analysis

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**Received** Dec 7, 2023; **Revised** Feb 10, 2024; **Accepted** Mar 11, 2024
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The purpose of this systematic review and meta-analysis is to assess existing literature and determine the association between the Hounsfield unit (HU) value and the vertebral body quality (VBQ) score with mechanical complications (MCs) after adult spinal deformity (ASD) surgery. Although bone quality is considered an increasingly important factor for MCs after ASD surgery, the utility of the HU value assessed by computed tomography and the VBQ score assessed by magnetic resonance imaging remains unknown. A systematic review of PubMed, Embase, and Cochrane Library databases was performed to find studies evaluating the association between the HU value and the VBQ score with MCs after ASD surgery. In the subsequent meta-analysis, MC outcomes were combined using a random-effects model, and the standardized mean difference and 95% confidence interval were calculated. The final analysis included a total of 20 studies. Nineteen studies reported HU values, and two studies reported VBQ scores. Proximal junctional kyphosis/failure (PJK/PJF) was reported as the MC in 16 studies, whereas other MCs were included in 6 studies. Six studies with a pool of 506 patients with ASD revealed that preoperative HU values at the upper instrumented vertebra (UIV) and UIV+1 were significantly lower in patients with PJK/PJF (standardized mean difference, –0.74; 95% confidence interval, –1.09 to –0.40). Three studies suggested an cutoff HU value of approximately ≤120, yielding a pooled sensitivity of 0.77, specificity of 0.67, and diagnostic odds ratio of 7.01. However, two studies reported conflicting results on the relationship between the VBQ score and PJK/PJF. Low HU values predicted the risk of certain MCs, particularly PJK/PJF, after ASD surgery. An HU value of <120 should alert surgeons to be cautious about the postoperative occurrence of PJK/PJF. Future studies are needed to validate the cutoff HU value and evaluate the utility of the VBQ score.

**Keywords:** Scoliosis; Osteoporosis; Hounsfield unit; Computed tomography; Magnetic resonance imaging

## Introduction

Adult spinal deformity (ASD) is a complex condition characterized by abnormal spine alignment in the sagittal and/or coronal plane. Although advancements in indications, techniques, and instrumentation have improved outcomes and decreased the number of surgical complications, mechanical complications (MCs) are still common and often have devastating implications, including the need for revision surgery [1,2].

Many studies have attempted to identify common risk factors for MCs, focusing on instrumentation, techniques, and patient-specific factors that increase patients' risk [3-7]. Given the high prevalence of osteo-

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porosis in patients undergoing ASD surgery, bone quality has become an important area of research. Although dual-energy X-ray absorptiometry (DXA) is the gold standard for diagnosing osteoporosis, its use is limited in degenerative spinal conditions [8]. In contrast, Hounsfield units (HUs) and Vertebral Bone Quality (VBQ) scores allow for more precise estimates of bone density in degenerated spines and allow for specific measurements of bone density in the surgical zone of interest [9-11].

The HU value is a quantitative measure that reflects the radiodensity of the bone and serves as a surrogate marker for bone mineral density (BMD). To measure the HU value, a circle is drawn around a region of interest, and relevant software automatically calculates the attenuation HU value [10]. This value enables surgeons to measure the bone quality at a specific level and region [9]. Because the upper instrumented vertebra (UIV) and the vertebra one level above the UIV (UIV+1) are subject to the highest loading force after long segment fusion [12], the HU value at the UIV may be more informative than systemic measures of bone quality in predicting postoperative MCs. As originally described by Ehresman et al. [11], the VBQ score is another alternative measure of BMD using a sagittal magnetic resonance (MR) image of the lumbar spine. Although the VBQ score cannot evaluate regional BMD, it may provide additional and distinct data about bone quality by assessing fatty infiltration of the vertebral bone. The relationship between the BMD and spinal deformity has been studied extensively in recent years; however, the precise effects of these surrogate measures on the risk of MCs and failure remain unclear.

Therefore, a systematic review with meta-analysis is warranted to synthesize the available evidence and comprehensively evaluate this relationship. This review aimed (1) to assess the clinical usefulness of HU values and VBQ scores in predicting MCs after ASD surgery and (2) to determine the cutoff HU value to predict MCs after ASD surgery. We hypothesized that the HU value, and potentially the VBQ score, will be predictors of MCs.

## Materials and Methods

### Institutional review board approval

This study is a retrospective systematic review of publicly accessible documents, and thus institutional review board approval was not required.

### Literature research

This systematic review and meta-analysis was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis guidelines. PubMed, Embase, and Cochrane Library were searched from their inception to July 14, 2023. Search terms included keywords and medical subject headings related to spine surgery, ASD, computed tomograhy (CT), HU, magnetic resonance imaging (MRI), and VBQ (Appendix 1). Language was restricted to English; however, no restriction was placed on the publication date.

### Study selection

The inclusion criteria were as follows: (1) studies involving patients with ASD, (2) studies that measured outcomes of the incidence and risk factors of MCs, and, (3) studies that compared patients with and without MCs. MCs include proximal junctional kyphosis/failure (PJK/PJF), distal junctional kyphosis/failure, pseudarthrosis, or hardware failure. The exclusion criteria were as follows: (1) abstracts, letters, reviews, or case reports; (2) studies that analyzed repeated data; (3) studies that did not report outcomes of interest; and (4) cadaveric and animal studies. Studies were also included if they assessed patients with degenerative pathologies; however, inclusion was limited to patients who underwent posterior fusion of ≥4 segments. All candidate citations were imported into Covidence software (Melbourne, VC, Australia). After removing duplicates, two independent reviewers (H.N. and G.K.) screened titles and abstracts based on the selection criteria. Relevant studies were then screened via a full-text review. Discrepancies were settled by discussion among reviewers.

### Data extraction and methodological quality assessment

Data regarding authors, publication year, study location, study design, participant, characteristics, demographics, follow-up time, type of outcomes and MCs, measurement location of outcomes, MC incidence, cutoff value, and relevant statistics were extracted. Two independent reviewers evaluated the risk of bias and quality of each study using the Newcastle–Ottawa Scale (NOS). The NOS is a tool for evaluating the quality of evidence of nonrandomized studies including three main domains: patient selection, comparability, and outcomes [13]. The total NOS score ranges from 0 to 9,

and studies that scored ≥6 were considered to have high quality [14].

### Statistical analysis and data synthesis

Meta-analysis was performed to compare the HU value and VBQ score by PJK/PJF occurrence because of the limited number of publications available for other MCs. Forest plots were generated using standardized mean differences (SMDs), and 95% CIs were reported. Study heterogeneity was analyzed using the chi-squared test and $I^2$ statistics, where a $p$-value of <0.10 for the chi-squared test and $I^2$ >50% indicated heterogeneity [15]. To address heterogeneity, the leave-one-out method was used in the sensitivity analysis by single elimination of the studies [16,17]. Publication bias was not assessed because each analysis included <10 studies [18]. To validate the proposed cutoff value, sensitivity and specificity were extracted from the original articles, and forest plots were drawn to estimate pooled sensitivity, specificity, and diagnostic odds ratio (OR) [19,20]. A $p$-value of <0.05 was considered statistically significant. All statistical analyses were performed using Review Manager ver. 5.4 (The Cochrane Collaboration, London, UK) and MetaDTA ver. 2.0.4 (https://crsu.shinyapps.io/MetaDTA/) [19,20].

## Results

### Literature search

The search strategy identified 362 studies after duplicate removal, and a total of 20 studies were eligible for inclusion (Fig. 1) [21-40]. Nineteen studies assessed HU values, and two studies reported VBQ scores (Table 1). MCs included PJK and/or PJF in 16 studies, overall MCs in two, early instrumentation failure in one, rod fracture in one, screw pullout in one, and adjacent segment degeneration in one (Table 2). PJK is a broad term that encompasses PJF, which is a severe form of PJK, defined as PJK with structural failure or requiring reoperations [29,31,34,37]. Thus, studies describing the outcomes of PJK were presumed to include PJF, unless if they were explicitly differentiated. Consequently, the review categorized and described proximal junctional complications as PJK/PJF (which included both PJK and PJF), PJK, and PJF. The studies by Chanbour et al. [21,22], Hills et al. [23], Maruo et al. [31], Yoshie et al. [32], and Mikula et al. [33], Pinter et al. [35] and two studies by Hiyama et al. [27,28] were reported by the same groups, and these overlapping patient cohorts

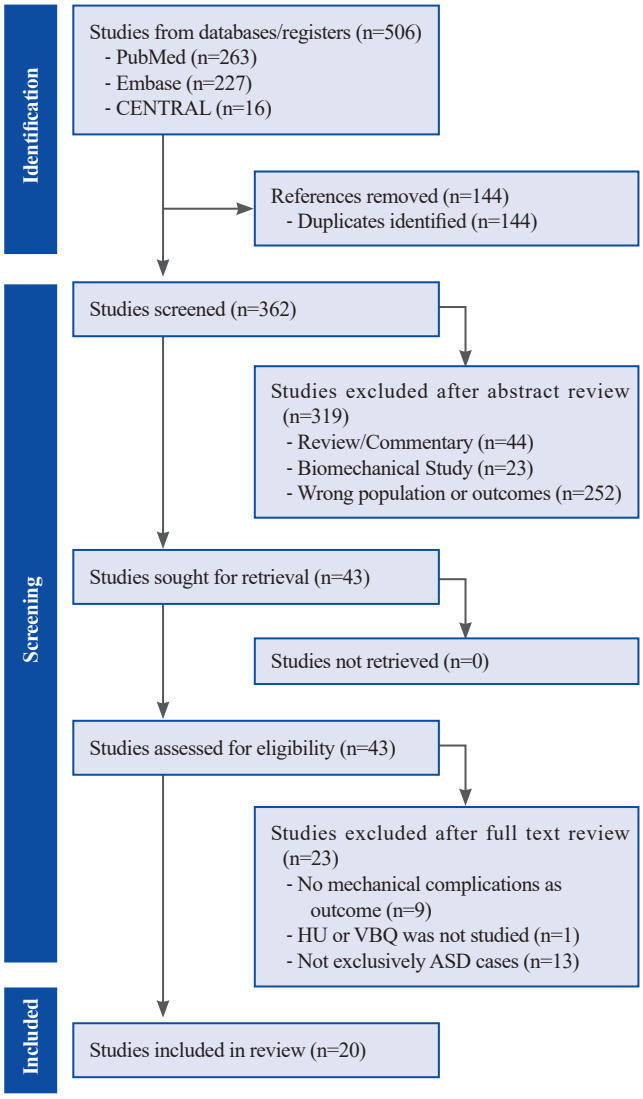


**Fig. 1.** Flow chart showing results of literature search. HY, Hounsfield unit; VBQ, vertebral body quality; ASD, adult spinal deformity.

were excluded from further meta-analysis. All studies were rated as having high quality according to the NOS, scoring 6–8 points (Table 3).

### Methodology of HU measurements

Among the studies analyzed, heterogeneity was noted in the methodology of HU measurements. Of the included studies, 12 followed the original method of measuring the vertebral body HU value described by Schreiber et al. [10], that is, three axial measurements within a single vertebral body are averaged to give a single HU value: just above the inferior endplate, middle of the body, and just below the superior endplate. Alternatively, three studies measured HU values within only one axial slice [24,25], and Kurra et al. [30] and

**Table 1.** Study outcomes

| Authors | Type of outcome | Measurement location for HU | Type of MC | OR/HR | ROC-AUC | Cutoff value |
|---|---|---|---|---|---|---|
| Chanbour et al. [21] (2023) | HU | UIV-4/UIV+4 | Overall MC | - | - | - |
| Chanbour et al. [22] (2023) | HU | UIV-4/UIV+4 | PJK/PJF, overall MC | OR 0.99 | 0.63 | 163 HUs: sensitivity=NA, specificity: NA |
| Hills et al. [23] (2022) | HU | UIV-4/UIV+4 | PJK/PJF | aOR 1.8 (decrease in HU from 180 to 120) | - | - |
| Cho et al. [24] (2023) | HU | L3, posterior fusion mass | PJK/PJF, rod fracture | - | - | - |
| Cho et al. [25] (2023) | HU | UIV | Screw pullout | - | - | - |
| Duan et al. [26] (2020) | HU | UIV, UIV+1, UIV+2 | PJK/PJF | - | 0.71 (UIV), 0.68 (UIV+1), 0.68 (UIV+2) | 104 HUs (UIV): sensitivity=0.84, specificity=0.52; 113 HUs (UIV+1): sensitivity=0.72, specificity=0.52; 110 HUs (UIV+2): sensitivity=0.88, specificity=0.45 |
| Hiyama et al. [27] (2022) | HU | UIV, UIV+1, UIV+2 | PJF | - | - | - |
| Hiyama et al. [28] (2023) | HU and VBQ | UIV, UIV+1, UIV+2, L1–L4 | PJF | - | - | - |
| Kuo et al. [29] (2023) | VBQ | - | PJK/PJF | aOR 1.75 | - | - |
| Kurra et al. [30] (2022) | HU | UIV-1, UIV, UIV+1 | PJK (with or without fracture) | - | - | |
| Maruo et al. [31] (2023) | HU | UIV+1 | PJF | - | - | - |
| Yoshie et al. [32] (2023) | HU | UIV, UIV+1 | PJK/PJF | - | 0.85 (UIV), 0.83 (UIV+1) | 122.8 HUs (UIV): sensitivity=0.89, specificity=0.74; 114.9 HUs (UIV+1): sensitivity=0.73, specificity=0.79 |
| Mikula et al. [33] (2021) | HU | UIV/UIV+1, L3/L4 | PJK/PJF | aOR 0.94 (UIV/UIV+1); aOR 0.99 (L3/4) | 0.89 | 122 HUs (UIV/UIV+1): sensitivity=NA, specificity=NA; 73 HU (UIV/UIV+1): specificity >0.9; 202 HU (UIV/UIV+1): sensitivity >0.9 |
| Mikula et al. [34] (2022) | HU | UIV/UIV+1, L3/L4 | PJK/PJF | OR 0.98 (UIV/UIV+1); OR 0.96 (L3/4) | 0.77 | 159 HUs (UIV/UIV+1): sensitivity >0.7, specificity >0.7; 136 HU (UIV/UIV+1): specificity >0.9; 193 HU (UIV/UIV+1): sensitivity >0.9 |
| Pinter et al. [35] (2023) | HU | UIV, UIV+1, L3, L4 | PJK, PJF | aOR 0.80 for PJK (UIV); aOR 0.79 for PJF (UIV) | - | - |
| Penalosa et al. [36] (2021) | HU | L1–4 | Early instrumentation failure | - | - | - |
| Uei et al. [37] (2018) | HU | T8–S1 | PJF | - | - | - |
| Wang et al. [38] (2021) | HU | L1 | PJF | HR 8.984 (<89.25 HU) | 0.8 | 89.25 HUs: sensitivity=0.78, specificity=0.80 |
| Wang et al. [39] (2023) | HU | FCRV | ASD | - | - | - |
| Yao et al. [40] (2021) | HU | UIV/UIV+1 | PJK/PJF (non-bony or bony) | aOR 5.74 (<120 HU) | - | 120 HUs: sensitivity=0.71, specificity=0.70 |

HU, Hounsfield unit; MC, mechanical complications; OR, odds ratio; HR, hazard ratio; ROC, receiver operating characteristic; AUC, area under the curve; UIV, upper instrumented vertebra; PJK, proximal junctional kyphosis; PJF, proximal junctional failure; NA, aOR, adjusted odds ratio; VBQ, vertebral body quality; FCRV, first coronal reverse vertebrae; ASD, adult spinal deformity.

**Table 2.** Study and demographics

| Authors | Country | Study design | No. of participants | | Patient characteristics | Gender (%) | Mean age (yr) | Overall follow-up time (mo) |
|---|---|---|---|---|---|---|---|---|
| | | | Total | Patients with MC | | | | |
| Chanbour et al. [21] (2023) | USA | Case control study | 145 | 85 | ASD patients | F (81.4) | 63.9±11.3 | Median 26.5 |
| Chanbour et al. [22] (2023) | USA | Retrospective cohort study | 145 | 42 (PJK), 74 (overall MC) | ASD patients | F (83.4) | 64.4±10.7 | Min 24 |
| Hills et al. [23] (2022) | USA | Retrospective cohort study | 145 | 47 (PJK) | ASD patients | F (81.4) | Median 66.2 | Median 26.5 |
| Cho et al. [24] (2023) | USA | Retrospective cohort study | 165 | 31 (PJK), 57 (rod fracture) | ASD patients undergoing 3CO | F (66.6) | 63.2±12.6 | 45.9±23.9 |
| Cho et al. [25] (2023) | Korea | Retrospective cohort study | 74 | 27 | ASD patient | F (87.8) | 69.2±5.6 | 32.1±22.1 |
| Duan et al. [26] (2020) | USA | Retrospective cohort study | 54 | 29 | ASD patients | F (64.8) | 64.9±7.6 | 38.3±13.7 |
| Hiyama et al. [27] (2022) | Japan | Retrospective cohort study | 52 | 13 | ASD patients | F (100.0) | 70.2±9.2 | 17.7±9.5 |
| Hiyama et al. [28] (2023) | Japan | Retrospective cohort study | 53 | 14 | ASD patients | F (100.0) | 70.2±9.2 | 32.3±14.3 |
| Kuo et al. [29] (2023) | USA | Retrospective cohort study | 116 | 34 | ASD patients | F (65.6) | 64.1±6.8 | 25.6±13.1 |
| Kurra et al. [30] (2022) | USA | Case control study | 92 | 22 (PJK), 11 (PJK with fracture) | ASD patients | F (53.3) | 64 (range, 42–81) | 18 (range, 2.4–48) |
| Maruo et al. [31] (2023) | Japan | Retrospective cohort study | 57 | 7 (in TPTD group) | ASD patients | F (76.0) | 73.5±6.8 | Min 12 |
| Yoshie et al. [32] (2023) | Japan | Retrospective cohort study | 60 | 26 | ASD patients | F (75.0) | 71.7±7.3 | 37.1±14.5 |
| Mikula et al. [33] (2021) | USA | Retrospective cohort study | 150 | 47 | Patients with instrumentation from pelvis to T10–L2 | F (53.3) | 66±7.4 | 31.8±20.2 |
| Mikula et al. [34] (2022) | USA | Retrospective cohort study | 81 | 27 | Patients with instrumentation from pelvis to T1–6 | F (74.0) | 66±6.9 | 38±25 |
| Pinter et al. [35] (2023) | USA | Retrospective cohort study | 150 | 28 (PJK), 19 (PJF) | Patients with instrumentation from pelvis to T10–L2 | F (53.3) | 67±7.4 | Min 24 |
| Penalosa et al. [36] (2021) | USA | Retrospective cohort study | 46 | 9 | ASD patients | F (63.0) | 51±15.3 | 44 (range, 8–84) |
| Uei et al. [37] (2018) | Japan | Retrospective cohort study | 54 | 14 | ASD patients | F (92.6) | 73.9±5.8 | 38.2±19.2 |
| Wang et al. [38] (2020) | China | Retrospective cohort study | 104 | 23 | Patients with instrumented fusion of ≥4 levels | F (82.7) | 63.2±8.0 | 35.7±7.0 |
| Wang et al. [39] (2023) | China | Retrospective cohort study | 116 | 30 | ASD patients | F (75.9) | 63.9±7.0 | Min 24 |
| Yao et al. [40] (2021) | USA | Retrospective cohort study | 108 | 23 | ASD patients | F (70.0) | 58.4±14.9 | 13.1 |

Values are presented as number or mean±standard deviation, unless otherwise stated.
MC, mechanical complications; ASD, adult spinal deformity; F, female; PJK, proximal junctional kyphosis; 3CO, three-column osteotomy; TPTD, teriparatide; PJF, proximal junctional failure.

**Table 3.** The quality assessment according to Newcastle Ottawa Score

| Authors | Selection | Comparability | Outcome | Total |
|---|---|---|---|---|
| Chanbour et al. [21] (2023) | 4 | 1 | 3 | 8 |
| Chanbour et al. [22] (2023) | 4 | 1 | 2 | 7 |
| Hills et al. [23] (2022) | 4 | 1 | 2 | 7 |
| Cho et al. [24] (2023) | 4 | 1 | 2 | 7 |
| Cho et al. [25] (2023) | 4 | 1 | 2 | 7 |
| Duan et al. [26] (2020) | 4 | 1 | 2 | 7 |
| Hiyama et al. [27] (2022) | 4 | 1 | 2 | 7 |
| Hiyama et al. [28] (2023) | 4 | 1 | 2 | 7 |
| Kuo et al. [29] (2023) | 4 | 1 | 2 | 7 |
| Kurra et al. [30] (2022) | 4 | 1 | 1 | 6 |
| Maruo et al. [31] (2023) | 4 | 1 | 2 | 7 |
| Yoshie et al. [32] (2023) | 4 | 1 | 2 | 7 |
| Mikula et al. [33] (2021) | 4 | 1 | 2 | 7 |
| Mikula et al. [34] (2022) | 4 | 1 | 2 | 7 |
| Pinter et al. [35] (2023) | 4 | 1 | 2 | 7 |
| Penalosa et al. [36] (2021) | 4 | 1 | 1 | 6 |
| Uei et al. [37] (2018) | 4 | 1 | 3 | 8 |
| Wang et al. [38] (2021) | 4 | 1 | 2 | 7 |
| Wang et al. [39] (2023) | 4 | 1 | 2 | 7 |
| Yao et al. [40] (2021) | 4 | 1 | 2 | 7 |

Wang et al. [38] averaged the HU values on the axial and sagittal images. Two studies also assessed the HU value within pedicles on one axial plane [25,37], and one study assessed the HU value within the posterior fusion mass [24].

### HU as a predictor of PJK/PJF

The definition of PJK was consistent among studies as proximal junctional angle ≥10° and at least 10° greater than the preoperative measurement [12]. Because two studies further divided the patients with PJK into two subgroups [30,40], the mean and standard deviation of the subgroups were combined to include them in the meta-analysis. The HU value in the UIV or the mean HU value of the UIV and UIV+1 (UIV/UIV+1) of patients with PJK/PJF was significantly lower than that of patients without PJK/PJF (SMD, −0.75; 95% CI, −1.02 to −0.48; $p<0.001$; $I^2=48\%$) (Fig. 2). Sensitivity analysis revealed stable outcomes, suggesting the robustness of our meta-analysis. Additionally, two studies examined the incidence of PJF [28,31], which was defined as PJK combined with structural fracture as previously reported [41]. Fig. 3 shows that the HU value in the UIV+1 was significantly lower in the PJF group than in the non-PJF group (SMD, −0.54; 95% CI, −0.89 to −0.19; $p=0.003$; $I^2=0\%$). Uei et al. [37] also reported that the HU value of the pedicles at T8 and T9 were significantly lower in patients with PJK requiring reoperations.

### Cutoff HU value to predict PJK/PJF

Six studies reported cutoff HU values at the UIV and UIV+1 level, and three studies reported sensitivity and specificity, which were finally included for further analysis. The three included studies proposed cutoff values of roughly ≤120 (range, 104–122.8), and the pooled sensitivity, specificity, and diagnostic OR were 0.77 (95% CI, 0.70–0.84), 0.67 (95% CI, 0.58–0.75), and 7.01 (95% CI, 4.00–12.3), respectively (Fig. 4). Mikula et al. [33,34] examined two patient cohorts, patients undergoing fusion surgery from the pelvis to (1) T10–L2 and (2) T1–T6, and proposed cutoff HU values of 122 and 159 at the UIV/UIV+1 for each cohort, respectively. Yao et al. [40] showed that HU values of <120 at the UIV/UIV+1 had a 5.74 times higher risk for bony PJK than those with HU values >120. Chanbour et al. [22] also reported that a cutoff HU value of 163 at the UIV−4/UIV+4 may predict PJK. Wang et al. [38] reported a cutoff HU value of <89.25 at L1, which demonstrated a hazard ratio of 8.98.

### HU as a predictor of other MCs

Cho et al. [25] found that screw pullout was significantly associated with lower HU values for both UIV vertebrae and pedicles. However, Chanbour et al. [21,22] did not find significant difference in the HU values with or without overall MCs or in patients with distal junctional kyphosis, pseudoarthrosis/rod fractures, or hardware failure compared with controls, except that the PJK group had significantly lower HU values at the UIV−4/UIV+4. Penalosa et al. [36] analyzed the incidence of early instrumentation failure within 6 months of initial pedicle subtraction osteotomy and found no differences in the HU values at L1–L4.

### VBQ score to predict PJK/PJF in patients with ASD

The VBQ score was calculated by dividing the mean signal intensity in the L1–L4 vertebral bodies by the signal intensity of the cerebrospinal fluid at L3 using the signal intensity obtained from a midsagittal, non-contrast-enhanced T1-weighted MR image of the lumbar spine [11]. Kuo et al. [29] showed that the VBQ score was the only significant predictor of PJK/PJF on

| Study or subgroup | PJK/PJF Mean±SD | Total | No PJK/PJF Mean±SD | Total | Weight (%) | SMD IV, random, 95% CI |
|---|---|---|---|---|---|---|
| **8.1.1 HU value at UIV vertebral body** | | | | | | |
| Pinter et al. [35] (2023) | 118.2±41.4 | 47 | 148.3±34.5 | 109 | 21.9 | -0.82 (-1.17 to -0.46) |
| Kurra et al. [30] (2022) | 151±50 | 33 | 163±48 | 59 | 18.6 | -0.24 (-0.67 to 0.18) |
| Duan et al. [26] (2020) | 120.41±45.67 | 29 | 152.8±43.99 | 25 | 14.2 | -0.71 (-1.26 to -0.16) |
| Yoshie et al. [32] (2023) | 103.4±22.9 | 26 | 149±42.6 | 34 | 13.9 | -1.27 (-1.83 to -0.71) |
| **Subtotal (95% CI)** | | **135** | | **227** | **68.6** | **-0.74 (-1.13 to -0.34)** |
| Heterogeneity: tau$^2$=0.10; $\chi^2$=8.70, df=3 ($p$=0.03); $I^2$=66% | | | | | | |
| Test for overall effect: Z=3.66 ($p$=0.0002) | | | | | | |
| **8.1.2 HU value at UIV/UIV+1 vertebral body** | | | | | | |
| Mikula et al. [34] (2022) | 148±43 | 27 | 192±47 | 54 | 16.4 | -0.95 (-1.44 to -0.47) |
| Yao et al. [40] (2021) | 131.75±33 | 23 | 168.7±66.8 | 40 | 15.0 | -0.64 (-1.17 to -0.11) |
| **Subtotal (95% CI)** | | **50** | | **94** | **31.4** | **-0.81 (-1.17 to -0.45)** |
| Heterogeneity: tau$^2$=0.00; $\chi^2$=0.73, df=1 ($p$=0.39); $I^2$=0% | | | | | | |
| Test for overall effect: Z=4.44 ($p$<0.00001) | | | | | | |
| **Total (95% CI)** | | **185** | | **321** | **100.0** | **-0.75 (-1.02 to -0.48)** |
| Heterogeneity: tau$^2$=0.05; $\chi^2$=9.63, df=5 ($p$=0.09); $I^2$=48% | | | | | | |
| Test for overall effect: Z=5.49 ($p$<0.00001) | | | | | | |
| Test for subgroup differences: $\chi^2$=0.07, df=1 ($p$=0.80); $I^2$=0% | | | | | | |

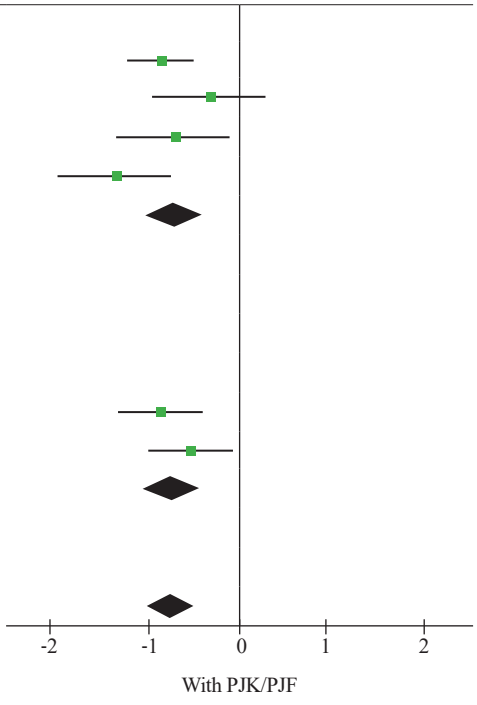


**Fig. 2.** Preoperative upper instrumented vertebra (UIV) and UIV/UIV+1 Hounsfield unit (HU) and postoperative proximal junctional kyphosis (PJK)/proximal junctional failure (PJF). SD, standard deviation; SMD, standard mean difference; IV, inverse variance; CI, confidence interval; df, degrees of freedom.

| Study or subgroup | PJF Mean±SD | Total | No PJF Mean±SD | Total | Weight (%) | SMD IV, random, 95% CI |
|---|---|---|---|---|---|---|
| Pinter et al. [35] (2023) | 118.7±38.7 | 19 | 143.4±45.1 | 137 | 52.3 | -0.55 (-1.04 to -0.07 |
| Hiyama et al. [28] (2023) | 122.8±37.9 | 14 | 145.1±46.8 | 39 | 32.0 | -0.49 (-1.11 to 0.13) |
| Maruo et al. [31] (2023 | 104.7±24.5 | 7 | 121.1±28.5 | 19 | 15.7 | -0.58 (-1.46 to -0.31) |
| **Total (95% CI)** | | **40** | | **195** | **100.0** | **-0.54 (-0.89 to -0.19)** |
| Heterogeneity: tau$^2$=0.00; $\chi^2$=0.03, df=2 ($p$=0.98); $I^2$=0% | | | | | | |
| Test for overall effect: Z=3.01 ($p$=0.003) | | | | | | |

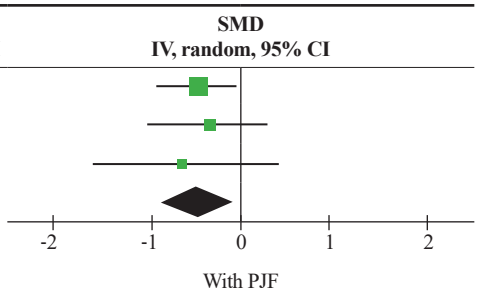


**Fig. 3.** Preoperative upper instrumented vertebra (UIV)+1 Hounsfield unit (HU) and postoperative proximal junctional failure (PJF). SD, standard deviation; SMD, standard mean difference; IV, inverse variance; CI, confidence interval; df, degrees of freedom.

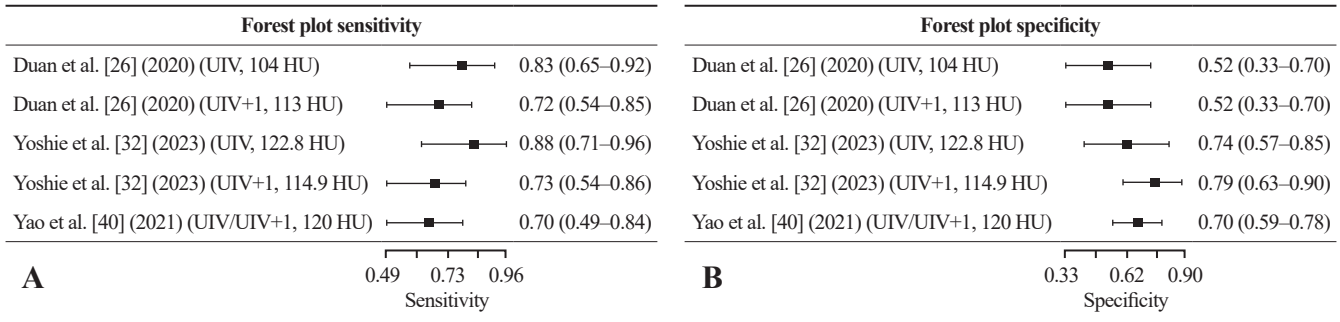


**Fig. 4.** Pooled sensitivity **(A)** and specificity **(B)** of cutoff Hounsfield unit (HU) at upper instrumented vertebra (UIV) and/or UIV+1 for predicting proximal junctional kyphosis (PJK)/proximal junctional failure (PJF) occurrence.

the multivariate analysis (OR, 1.75; 95% CI, 1.56–1.95). In contrast, Hiyama et al. [28] found that the VBQ score did not correlate with PJF ($p$=0.47), whereas the HU values at the UIV ($p$=0.035) and L4 ($p$=0.033) significantly correlated with PJF.

## Discussion

Poor bone density is a well-known risk factor for MCs after ASD surgery. Gupta et al. [42] found that osteoporosis increased the risk of revision within 2 years of the index procedure because of hardware failure, pseudoarthrosis, and PJF. Typically, BMD is assessed by DXA scans of the hip, femur, or lumbar spine [43], and recent studies have shown that a lower BMD T-score is associated with higher PJK incidence [34,43-49]. Hyun et al. [44] also demonstrated that the mean T-scores in patients with PJK averaged −2.5, as compared with −1.3 in patients without PJK, which was significant. Yagi et al. [43] compared 24 propensity-matched pairs of patients with ASD and found that a T-score <−1.5 was significantly associated with higher incidence of PJF.

Although DXA is still considered the gold standard for assessing BMD, the biggest potential strength of utilizing the HU value is that is allows measurement of bone density in the surgical zone of interest. Among MCs, PJK/PJF may have the most effect on bone quality, as the UIV and UIV+1 vertebral bone must tolerate the stress between the instrumented and uninstrumented spines [12]. According to Uei et al. [37], HU values vary between vertebral levels even in the same patient, suggesting that junctional HU values may be more strongly related to PJK/PJF than DXA or quantitative CT (QCT), which only measure bone quality in a representative part of the body. Additionally, several shortcomings of DXA have been reported. Because of the nature of the ASD pathology, BMD can be easily distorted by osteophytes and areas of sclerosis because of degenerative changes [8]. Moreover, in patients who have undergone bilateral hip replacement surgery, BMD cannot be evaluated at the femoral neck by DXA.

Not surprisingly, this meta-analysis showed that a lower HU value around the UIV was associated with significant PJK/PJF incidence, which is consistent with the results of previous studies evaluating BMD by DXA. Our results also demonstrated that a cutoff HU value of <120 around the UIV had pooled sensitivity and specificity of approximately 70% and a diagnostic OR of 7. However, a cutoff value aimed at achieving high sensitivity to "rule out" PJK/PJF, which can indicate a "safety zone" for the HU value, is warranted to propose a target HU value for preoperative osteoporotic treatment.

The VBQ score has become a topic of interest in the evaluation of osteoporosis because patients undergoing spine surgery routinely undergo MRI to assess the degree of nerve compression. Additionally, the VBQ score could provide additional and distinct assessment of bone quality over and above radiation-based bone quality assessment using DXA or CT because it can assess fatty infiltration in vertebral body using MRI [11]. Previous studies have shown that the VBQ score can reduce interference from degenerative changes compared with conventional DXA scans [50,51]; however, in a study of 61 patients undergoing lumbar spine surgery, Kim et al. [52] proposed a cutoff value of 2.6 to detect osteoporosis, but only a weak correlation was observed between the VBQ score and the QCT-derived BMD ($r$=−0.27). The VBQ score can be an alternative tool in assessing bone quality; however, its effectiveness as a predictor of PJK/PJF may be inferior to HU assessment because it can only assess lumbar spine bone quality and does not directly measure the bone quality around the UIV.

This study has several limitations. First, the measurement methodologies of the HU value and the assessed vertebral levels varied. Therefore, the measurement methodology of the HU value using the original method appears necessary in future studies to accumulate consistent clinical evidence and allow readers to accurately interpret previous results. Although Ehresman et al. [11] reported that the VBQ score was not significantly affected by the difference in MRI systems, the HU value was reported to be influenced by tube voltages and body habitus [10]. This information was not consistently reported in the included studies, and this limitation may affect the proposed cutoff value. Therefore, future studies should also report the tube voltage and other factors that may affect HU values. Second, this systematic review only included retrospective studies. Although the results should be interpreted cautiously, the included studies were of high quality according to the NOS, and the meta-analysis showed a clear association between the HU values and PJK/PJF occurrence without significant heterogeneity. Third, the limited number of studies may be underpowered to answer certain questions, such as the cutoff HU value and the utility of the VBQ score. Despite the range of values proposed by previous studies, our approach to propose a cutoff value may be justified because similar approaches have been employed previously [53]. As this study is the first to focus on this topic to date, this study would be important for spine surgeons who must

be aware of the utility and limitations of these surrogate markers for assessing bone quality in ASD surgery.

## Conclusions

A low vertebral body HU value was a strong predictor of the risk of PJK/PJF after ASD surgery. However, the utility of the HU value in predicting other MCs was not well supported. Despite limited evidence on the cutoff HU value, an HU value at the UIV/UIV+1 of ≤120 had a pooled diagnostic OR of 7.01 for predicting PJK/PJF. However, the HU value can be influenced by the measurement method, tube voltage, and body habitus. Future studies are needed to validate the proposed cutoff HU value, should use the original measurement method of vertebral body HU, and should report tube voltage to accumulate consistent evidence. To date, the VBQ score has not shown sufficient validity in predicting MCs after ASD surgery in contrast to the HU value.

### Key Points

- Low vertebral body Hounsfield unit (HU) value is a risk of proximal junctional kyphosis/failure (PJK/PJF) after adult spinal deformity (ASD) surgery, but does not predict other mechanical complications.
- An HU value at the upper instrumented vertebra (UIV)/UIV+1 of ≤120 had a pooled diagnostic odds ratio of 7.01 for predicting PJK/ PJF, but this value can be influenced by the measurement method, tube voltage, and body habitus.
- To date, the vertebral body quality score has not shown sufficient validity in predicting mechanical complications after ASD surgery.

## Conflict of Interest

Han Jo Kim has the following disclosures: AAOS: board or committee member; Acuity Surgical: IP royalties; HS2: stock or stock options; HSS Journal, Asian Spine Journal: editorial or governing board; International Spine Society; Group (ISSG): IP royalties; ISSGF: research support; K2M: IP royalties; Operative Neurosurgery: editorial or governing board; SI BONE: research support; SPINE STUD: stock or stock options; and Zimmer: IP royalties. Except for that, no potential conflict of interest relevant to this article was reported.

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Conceptualization: HN, FL, HJK. Data curation: GSK, HN. Formal analysis: HN, GSK, FL, HJK. Funding acquisition: NA. Methodology: HN, GSK, FL, HJK. Project administration: HJK. Visualization: HN, GSK, FL, HJK. Writing–original draft: HN, GSK, FL, HJK. Eriting–review & editing: HN, GSK, FL, HJK. Final approval of the manuscript: all authors.

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**Appendix 1.** Search strategy

**PubMed:**

1. (["adult spinal deformity" or "ASD" or "scoliosis" or "spine surgery"] and ["Hounsfield unit" or "QCT"] not ["adolescent" or "congenital" or "child"])
2. (["adult spinal deformity" or "ASD" or "scoliosis" or "spine surgery"] and (["vertebral bone quality" or "VBQ"]) not ["adolescent" or "congenital" or "child"])
3. (["adult spinal deformity" or "ASD" or "scoliosis" or "spine surgery"] and (["bone density" or "bone quality" or "bone mineral density" or "BMD"] and ["CT scan" or "quantitative computed tomography" or "MRI" or "magnetic resonance imaging" or]) not ["adolescent" or "congenital" or "child"])

**Embase:**

1. ('adult spinal deformity'/exp or 'ASD'/exp or 'scoliosis'/exp or 'spine surgery'/exp) and ('Hounsfield unit'/exp or 'QCT'/exp) not ('adolescent'/exp or 'congenital'/exp or 'child'/exp)
2. ('adult spinal deformity'/exp or 'ASD'/exp or 'scoliosis'/exp or 'spine surgery'/exp) and ('vertebral bone quality'/exp or 'VBQ'/exp) not ('adolescent'/exp or 'congenital'/exp or 'child'/exp)
3. ('adult spinal deformity'/exp or 'ASD'/exp or 'scoliosis'/exp) and ('bone density'/exp or 'bone quality'/exp or 'bone mineral density'/exp or 'BMD'/exp) and ('CT scan'/exp or 'MRI'/exp or 'magnetic resonance imaging/exp) not ('adolescent'/exp or 'congenital'/exp or 'child'/exp)

**Cochrane library:**

1. (["adult spinal deformity" or "ASD" or "scoliosis" or "spine surgery"] and ["Hounsfield unit" or "QCT"]) nat ("adolescent" or "congenital" or "child")
2. (["adult spinal deformity" or "ASD" or "scoliosis" or "spine surgery"] and ["vertebral bone quality" or "VBQ"]) not ("adolescent" or "congenital" or "child")
3. (["adult spinal deformity" or "ASD" or "scoliosis" or "spine surgery"] and (["bone density" or "bone quality" or "bone mineral density" or "BMD"] and ["CT scan" or "quantitative computed tomography" or "MRI" or "magnetic resonance imaging"]) not ("adolescent" or "congenital" or "child")