

Agreement of Radiographic Parameters Between Digitally Reconstructed Radiographs from Weight-Bearing Cone-Beam CT and Whole-Spine Radiographs

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Abstract

Purpose

Current spinal deformity diagnosis relies on whole-spine radiographs, while Weight-bearing Radiology 3D (WR3D) offers accurate, low-dose three-dimensional reconstruction in the standing position. This study aims to evaluate the potential of digitally reconstructed radiographs (DRRs) generated from WR3D images as a substitute for standard whole-spine radiographs.

Methods

In this retrospective comparative study of 67 patients who underwent both WR3D examination and whole-spine radiographs, DRRs were generated using segmentation and projection algorithms. Two observers independently measured coronal and sagittal radiographic parameters of the spine and pelvis on both imaging modalities, with intraclass correlation coefficients (ICCs) calculated. Paired samples *t*-tests and Bland-Altman analyses were performed, with mean absolute errors (MAEs) and Pearson correlation coefficients calculated.

Results

DRRs exhibited superior interobserver reliability compared to radiographs, particularly for pelvic incidence (PI, ICC = 0.95 vs. 0.70), pelvic tilt (PT, ICC = 0.98 vs. 0.83), sacral slope (SS, ICC = 0.94 vs. 0.79), and upper thoracic parameters. High agreement between the two imaging modalities was observed in measurements of all coronal parameters, cervical lordosis (C2-C7), thoracolumbar kyphosis (T10-L2), lumbar lordosis (L4-S1, L1-S1), PI, and PT ($p > 0.05$), while differences were observed for other sagittal parameters ($p < 0.05$).

Conclusions

DRR images based on WR3D show high agreement with radiographs for measuring most structural parameters. However, certain differences exist for global balance parameters and sagittal curvature parameters.

Introduction

Spinal alignment is inherently a three-dimensional (3D) construct, involving multi-planar deformities in the coronal, sagittal, and axial planes [1]. Many spinal deformities, most notably adolescent idiopathic scoliosis (AIS) and adult spinal deformity (ASD), are governed by complex biomechanical interactions in 3D space that cannot be fully captured in two-dimensional (2D) imaging. Therefore, accurate diagnosis and surgical planning increasingly rely on 3D imaging to fully characterize vertebral rotation and spatial

relationships [2, 3]. With rapid advances in imaging technology, 3D classification systems are gaining increasing attention [4].

In clinical practice, imaging in the weight-bearing state better reflects the true pathological state of spinal deformities and the patient's functional balance [5]. It is well established that the alignment of the human spine differs significantly between supine and standing positions [6]. Weight-bearing induces changes in vertebral rotation, lower limb alignment, and the magnitude of coronal and sagittal curvatures [6–8]. Therefore, the ideal imaging modality for spinal assessment should simultaneously provide 3D spatial information and capture the weight-bearing physiological state.

While conventional CT provides high-resolution 3D data, it is performed in the supine position, failing to capture the weight-bearing state of the spine. Furthermore, the substantial radiation dose associated with repeated CT scans remains a major concern, particularly for pediatric populations requiring long-term follow-up [9]. Conversely, conventional radiographs, though weight-bearing and relatively low-dose, lack 3D information and suffer from structural superposition. To bridge this gap, the novel Weight-bearing Radiology 3D (WR3D) system, which integrates digital radiography with cone-beam computed tomography (CBCT), allows for 3D reconstruction in the standing position while significantly reducing the radiation burden to approximately 10% of conventional CT [10].

Despite the availability of 3D data, current clinical guidelines, such as the Lenke, King, and PUMC classifications, remain anchored in 2D radiographic parameters [11–13]. This creates a "translational gap" between modern 3D diagnostic capabilities and established 2D clinical workflows. Digitally reconstructed radiograph (DRR) technology offers a potential solution to bridge this gap. DRRs are 2D projections synthesized from 3D volumes [14]. By generating DRRs, clinicians can theoretically obtain the "simulated radiographs" required by current guidelines while simultaneously holding a 3D volume for advanced analysis. Such a "one-stop" imaging solution could maintain compatibility with historical clinical data while potentially enhancing the precision of spinal assessment. However, the clinical application of DRRs relies on the rigorous validation of their measurement agreement with conventional radiographs.

The purpose of this study is to evaluate whether DRRs generated from WR3D data can serve as a valid alternative to conventional whole-spine radiographs. To this end, we performed a series of radiographic parameter measurements on both DRRs and whole-spine radiographs and evaluated the agreement between these two imaging modalities.

Materials and Methods

Ethical approval and participant selection

This retrospective study was approved by the ethics committee of [Anonymized Hospital/Institution] (Approval No. [Anonymized Number]). A dataset was collected from patients who underwent both WR3D

imaging and standard anteroposterior and lateral whole-spine radiography as part of [Anonymized Project/Study Name] at [Anonymized Hospital/Institution].

A retrospective dataset was established from consecutive patients who underwent WR3D examination and whole-spine anteroposterior and lateral radiograph examinations between August 2024 and December 2025.

Inclusion criteria were: (1) Completion of both WR3D and conventional radiography within a 14-day interval. (2) Confirmation of clinical stability during this interval, defined as no changes in symptoms, treatment regimens, or disease progression. (3) Availability of written informed consent from the patients or legal guardians (for patients under 18 years).

The exclusion criteria were: (1) History of spine surgery with internal fixation; (2) Severe spinal deformities, fractures, tumors, or other pathologies significantly distorting vertebral morphology; (3) Poor image quality of radiographs or WR3D images; (4) Incomplete radiograph or WR3D imaging data lacking complete anatomical structures from the cervical spine to the femoral heads; (5) Patients imaged while wearing orthotic braces. Patient enrollment procedures are illustrated in Figure 1.

Radiograph acquisition protocol

The WR3D system ([Anonymized Company]) was used for standing 3D imaging [10]. As illustrated in Figure S1 (Appendix 1), during scanning, patients stood on the platform with their arms raised overhead, grasping the upper ring. The scan range typically extends from the vertex of the skull to below the femoral heads.

Whole-spine radiographs were obtained using a standard protocol. Patients were positioned in a standing posture with knees fully extended and feet together. For the posteroanterior view, patients stood facing the image receptor with their anterior chest pressed against it and arms relaxed at their sides. For the lateral view, patients were positioned with arms flexed forward and hands resting on the clavicles or supported to avoid overlapping the thoracic spine.

DRR generation algorithm

The algorithm for projecting WR3D images into 2D space to generate DRR images primarily consists of two steps: segmentation and projection. The overall architecture of the algorithm is illustrated in Figure 2.

First, a segmentation model based on 3D-UNet was employed to segment the spine, ribs, pelvis, and femoral heads. For the spine, the vertebral bodies were segmented, excluding the transverse and spinous processes. For the pelvis, the ilia and the proximal part of the S1 vertebra were segmented, excluding the rest of the sacrum and the coccyx. The network performed voxel-wise binary classification

on the input 3D volumetric data, assigning a value of 1 to voxels within target bone regions and 0 otherwise, yielding a binary 3D skeletal voxel model with a Dice coefficient > 0.95 [15]. Given the exclusion of patients with severe deformities and a history of spine surgery with internal fixation (Figure 1), the vertebral bodies of all enrolled patients in this study were successfully segmented.

After obtaining the segmented skeletal structures, the projection algorithm proceeds as follows:

(1) Projection direction definition: The anteroposterior (AP) direction was defined as perpendicular to both the line connecting the centers of the left and right femoral heads and the plumb line; the lateral direction was orthogonal to the AP direction and the plumb line.

(2) Image enhancement: Voxel intensities within the segmented bone regions of the original 3D volume were enhanced to generate an augmented 3D dataset. Without segmentation and enhancement, all osseous and soft-tissue structures within the target region would overlap, thereby degrading image clarity.

(3) Projection: Average intensity projections along the AP and lateral directions were applied to the enhanced volume to produce AP and lateral DRRs, respectively.

Radiographic parameters measurement

Radiographic parameters of the spine and pelvis were measured on the radiographs according to the Spinal Deformity Study Group guidelines [16]. Detailed definitions and measurement protocols for all parameters are provided in Appendix 1 (Section S2).

Coronal Parameters: Cobb angles of the proximal thoracic curve (PTC), main thoracic curve (MTC), and thoracolumbar/lumbar curve (TLC); T1 tilt (T1T); coronal balance (CB); pelvic obliquity (PO); sacral obliquity (SO); and thoracic trunk shift (TTS).

Sagittal parameters: cervical lordosis (CL: C2-C7); thoracic kyphosis (TK: T2-T5 and T5-T12); lumbar lordosis (LL: L1-L4, L4-S1, and L1-S1); thoracolumbar kyphosis (TLK: T10-L2); T1 slope (T1S); sagittal balance (SB); sacral slope (SS); pelvic incidence (PI); and pelvic tilt (PT).

Schematic diagrams of coronal and sagittal measurement parameters are shown in Figure S2 and Figure S3 in Appendix 1. Radiographic measurements were independently performed by two well-trained medical students. To ensure data integrity, an experienced spine surgeon, blinded to the observers' identities, reviewed the measurements and corrected any obvious errors. Observers were blinded to previous measurements and diagnoses.

Statistical analysis

For descriptive statistics, the average values of the parameters measured by two observers were utilized to calculate the mean value and standard deviation (SD).

Interobserver reliability for parameter measurement was assessed using the intraclass correlation coefficient (ICC) based on an absolute-agreement, two-way random-effects model [ICC(2,1)]. Reliability was interpreted as: <0.50 (poor), 0.50–0.75 (moderate), 0.75–0.90 (good), and >0.90 (excellent) [17]. Corresponding 95% confidence intervals (CIs) were reported for all ICCs.

For comparison between DRRs and radiographs, the mean of two independent observers' measurements was used for each modality. Systematic bias between modalities was evaluated using paired-samples *t*-tests on observer-averaged measurements. To control for Type I error accumulation across the tested radiographic parameters, *p*-values were adjusted for multiple comparisons using the Benjamini–Hochberg False Discovery Rate (FDR) procedure. Statistical significance was defined as an FDR-adjusted *p*-value < 0.05. Agreement between DRR and radiograph measurements was further assessed via Bland-Altman analysis, reporting the mean difference (radiograph – DRR) and 95% limits of agreement (LoA). The mean absolute error (MAE) quantified the average magnitude of absolute differences. The correlation between the two imaging modalities was assessed using the Pearson correlation coefficient (*r*), interpreted as: <0.10 (negligible), 0.10–0.39 (weak), 0.40–0.69 (moderate), 0.70–0.89 (strong), and ≥ 0.90 (very strong) [18]. Detailed statistical tables and figures are all shown in Section S3 in Appendix 1.

All statistical analyses were conducted using Python 3.9.23 and several scientific computing packages, including NumPy (v2.0.2) [19], SciPy (v1.13.1) [20], pandas (v2.3.3) [21], seaborn (v0.13.2) [22], Matplotlib (v3.9.4) [23], scikit-learn (v1.6.1) [24], and pingouin (v0.5.5) [25].

Results

Demographic characteristics of patients

As illustrated in Fig. 1, 91 patients were initially enrolled, and 67 were ultimately included after exclusions. Demographic characteristics of these patients are summarized in Table 1. Among them, 15 were male (22.4%), and 52 were female (77.6%), consistent with the female predominance in AIS. Regarding diagnosis, 60 patients (89.6%) had scoliosis, including 44 AIS patients (65.7%), along with other types, such as adult or neuromuscular scoliosis. 7 patients (10.4%) did not have scoliosis. The overall distribution of parameters from both imaging modalities is presented in Table 2. Boxplots of the parameter distributions are shown in Figures S4 and S5 in Appendix 1.

Table 1
Demographic characteristics of included patients.

Characteristics	Category	Value
Total sample size	-	n = 67
Sex	Female	52 (77.6%)
	Male	15 (22.4%)
Age (years)	Mean $\pm$ SD	16.42 $\pm$ 10.41
	Range	7–71
Diagnosis	Scoliosis	60 (89.6%)
	Non-scoliosis	7 (10.4%)

Table 2
Comparison and agreement analysis of radiographic parameter measurements between conventional radiographs and DRRs.

Parameters	n	Radiograph	DRR	MAE	<i>p</i>	<i>r</i>
		Mean ± SD	Mean ± SD			
coronal						
Cobb angle (°)	134	29.57 ± 15.79	29.82 ± 15.91	3.26	0.621	0.964
MTC (°)	51	31.55 ± 16.02	32.25 ± 15.65	2.88	0.377	0.968
PTC (°)	32	23.08 ± 10.82	22.16 ± 10.73	2.67	0.240	0.958
TLC (°)	51	31.67 ± 17.27	32.21 ± 17.55	4.01	0.621	0.959
T1T (°)	67	4.52 ± 3.62	4.43 ± 3.27	2.08	0.892	0.711
CB (mm)	67	15.15 ± 11.90	12.52 ± 8.75	9.72	0.237	0.298
PO (°)	67	1.51 ± 1.47	1.61 ± 1.48	0.84	0.621	0.680
SO (°)	67	4.49 ± 3.46	4.73 ± 3.38	2.10	0.621	0.639
TTS (mm)	54	14.57 ± 12.58	14.30 ± 11.60	8.90	0.911	0.557
sagittal						
CL (°)	67	9.66 ± 8.12	11.05 ± 7.35	5.78	0.251	0.542
T2-T5 TK (°)	67	13.22 ± 7.59	8.69 ± 5.70	5.93	< 0.001*	0.599
T5-T12 TK (°)	67	25.34 ± 14.70	22.34 ± 12.84	6.10	0.008*	0.857
T10-L2 TLK (°)	67	12.97 ± 10.76	11.90 ± 8.95	4.64	0.240	0.860
L1-L4 LL (°)	67	23.27 ± 9.06	19.31 ± 9.18	6.02	< 0.001*	0.723
L4-S1 LL (°)	67	32.86 ± 8.86	34.63 ± 9.04	5.86	0.215	0.610
L1-S1 LL (°)	67	51.20 ± 11.67	51.01 ± 13.62	6.84	0.911	0.782
T1S (°)	67	19.10 ± 8.50	11.58 ± 6.61	7.79	< 0.001*	0.701
SB (mm)	67	26.17 ± 21.41	17.01 ± 13.59	16.38	0.001*	0.482
PI (°)	67	44.57 ± 9.57	45.48 ± 11.11	4.40	0.455	0.793
PT (°)	67	9.71 ± 6.64	9.63 ± 6.24	3.94	0.911	0.643
SS (°)	67	35.95 ± 8.15	38.64 ± 9.83	5.49	0.013*	0.682
<i>p</i> , Benjamini–Hochberg FDR-adjusted <i>p</i> -value from paired samples <i>t</i> -test across all 21 parameters; <i>r</i> , Pearson correlation coefficient;						

* Statistically significant difference ($p < 0.05$).

Notes,

n, Denotes the number of parameters that were successfully measured. The sample size (n) varies between parameters due to anatomical and pathological factors. Some patients presented with multiple distinct spinal curves (e.g., double major scoliosis), allowing for the measurement of more than one regional Cobb angle (e.g., MTC, TLC). Conversely, patients diagnosed without scoliosis did not exhibit a measurable curve in a specific spinal region, making the corresponding Cobb angle measurement not applicable. Besides, the thoracic trunk shift (TTS) was only measured in patients with the apical vertebra of the major curve lying between T1 and T12.

Inter-Rater reliability analysis

All radiographic parameters demonstrated moderate to excellent interobserver reliability, with intraclass correlation coefficients (ICCs) ranging from 0.69 to 0.99 (Table 3) [17]. With the exception of SO (ICC = 0.71), T2-T5 TK (ICC = 0.72), PI (ICC = 0.70) measured on radiographs, as well as SO measured on DRRs (ICC = 0.69), all parameters exhibited ICC values above 0.75, reflecting good to excellent interobserver reliability. In the coronal plane, Cobb angle, CB, and TTS demonstrated excellent reliability, with ICCs exceeding 0.90. In the sagittal plane, DRRs generally yielded higher ICC point estimates compared to conventional radiographs. Notably, DRRs demonstrated superior reliability for pelvic parameters, including PI (ICC: 0.95 vs. 0.70), PT (ICC: 0.98 vs. 0.83), and SS (ICC: 0.94 vs. 0.79), with non-overlapping 95% CIs. Furthermore, an upward shift in point estimates was observed on DRRs for T2-T5 TK (ICC: 0.82 vs. 0.72) and T5-T12 TK (ICC: 0.96 vs. 0.89). Although the 95% CIs for these parameters exhibited partial overlap, the higher point estimates suggest a trend toward enhanced measurement reproducibility when utilizing the DRR modality.

Table 3
Inter-rater reliability of parameter measurements in patients
between two observers.

Parameters	Radiograph		DRR	
	ICC	95% CI	ICC	95% CI
coronal				
Cobb angle (°)	0.99	(0.98, 0.99)	0.98	(0.98, 0.99)
MTC (°)	0.98	(0.97, 0.99)	0.98	(0.97, 0.99)
PTC (°)	0.98	(0.96, 0.99)	0.95	(0.91, 0.98)
TLC (°)	0.99	(0.98, 0.99)	0.99	(0.99, 1.00)
T1T (°)	0.80	(0.60, 0.89)	0.82	(0.70, 0.89)
CB (mm)	0.97	(0.95, 0.98)	0.95	(0.91, 0.97)
PO (°)	0.88	(0.81, 0.92)	0.90	(0.84, 0.93)
SO (°)	0.71	(0.56, 0.81)	0.69	(0.44, 0.82)
TTS (mm)	0.98	(0.96, 0.99)	0.93	(0.88, 0.96)
sagittal				
CL (°)	0.78	(0.66, 0.86)	0.76	(0.63, 0.85)
T2-T5 TK (°)	0.72	(0.52, 0.84)	0.82	(0.72, 0.88)
T5-T12 TK (°)	0.89	(0.81, 0.94)	0.96	(0.93, 0.97)
T10-L2 TLK (°)	0.88	(0.81, 0.92)	0.81	(0.71, 0.88)
L1-L4 LL (°)	0.82	(0.72, 0.89)	0.87	(0.80, 0.92)
L4-S1 LL (°)	0.77	(0.54, 0.88)	0.87	(0.80, 0.92)
L1-S1 LL (°)	0.88	(0.80, 0.93)	0.94	(0.90, 0.96)
T1S (°)	0.81	(0.69, 0.88)	0.84	(0.75, 0.90)
SB (mm)	0.98	(0.96, 0.99)	0.99	(0.98, 0.99)
PI (°)	0.70	(0.53, 0.81)	0.95	(0.92, 0.97)
PT (°)	0.83	(0.74, 0.89)	0.98	(0.97, 0.99)
SS (°)	0.79	(0.52, 0.90)	0.94	(0.90, 0.96)

Comparison of agreement and correlation analysis of DRR vs. Radiograph parameter measurements

Overall, high agreement between the two imaging modalities was observed in measurements of all coronal parameters and part of the sagittal parameters (p -values of paired t -tests > 0.05) (Table 2). The MAE of all coronal Cobb angles was 3.26° . Subgroup analysis showed MAEs for Cobb angles of PTC, MTC, and TLC were all $\leq 5^\circ$, with p -values of paired t -tests all > 0.05 , indicating no systematic difference between DRRs and radiographs for Cobb angle measurement. As shown in Fig. 3, for the coronal Cobb angle, the 95% LoA ranged from -8.62° to 8.11° . For coronal balance parameters, the MAE for CB and TTS measurements across both imaging modalities was 9.72 mm and 8.90 mm. Moreover, the 95% LoA for CB was (-21.87, 27.11) mm, indicating a large discrepancy in balance distance parameters (Fig. 3). In addition to assessing agreement, scatter plot analysis confirmed a statistically significant positive correlation between all measurements obtained from radiographs and those from DRRs (all $p < 0.05$) (Figure S9, S10, S11 in Appendix 1). Among them, the correlation for the coronal Cobb angle was very strong ($r = 0.964$). Other coronal parameters (except CB, $r = 0.298$) showed moderate to strong correlations (r ranging from 0.557 to 0.711), indicating DRRs reflect the coronal spinal morphology trends captured by radiographs [18].

Among the sagittal plane curvature parameters, no statistically significant differences were observed between the two imaging modalities for the measurement of C2-C7 CL, T10-L2 TLK, L4-S1 LL, and L1-S1 LL (all $p > 0.05$). Conversely, systematic differences were observed in the measurement of T2-T5 TK, T5-T12 TK, and L1-L4 LL between the two modalities (all $p < 0.05$), with the MAE being 5.93° , 6.10° , and 6.02° . Significant systematic differences were also noted in the measurement of T1S ($p < 0.001$) and SB ($p = 0.001$). There is also a high MAE (16.38 mm) for SB between the two imaging measurements. In the Bland-Altman plots (Fig. 3), SB exhibited greater scatter dispersion and a wider LoA range (-28.17, 46.49) mm, with a mean bias of 9.16 mm, suggesting systematic differences between the two modalities when evaluating overall balance indicators. Among the pelvic parameters, PI and PT exhibited no significant difference between two modalities ($p > 0.05$, with the MAE being 4.40° and 3.94°), whereas SS showed systematic differences ($p < 0.05$, with the MAE being 5.49°). As shown in Figure S11 in Appendix 1, sagittal parameters generally showed moderate to strong correlations (r ranging from 0.482 to 0.860).

Discussion

Our study demonstrated that DRRs exhibit high agreement with conventional radiographs for measuring key parameters (specifically, the coronal Cobb angle, T10-L2 TLK, L1-S1 LL, and PI), while revealing systematic differences in global balance and specific sagittal segmental parameters. To our knowledge, this is the first study to systematically evaluate the clinical value of DRRs generated by WR3D.

DRRs can reproduce coronal Cobb angle measurements in high agreement with radiographs (MAE 3.26°), well below the clinically accepted threshold of 5° , and superior to the 2.8° - 8° variability reported in traditional manual measurements [26–28]. This high fidelity validates the clinical utility of the DRRs: they allow clinicians to utilize the established Cobb angle measurement based on 2D images while simultaneously accessing 3D volumetric data. The robust performance of DRRs in coronal Cobb angle

measurement may be attributed to several potential factors, including "anatomically true" projection, anatomical clarity, and minimal impact of posture.

A pivotal advantage of DRR technology over conventional radiography lies in its parallel projection and standardization. Conventional radiographs use point-source cone-beam projection, which inherently introduces geometric magnification and distortion [29, 30]. Distortions can misrepresent the true spatial relationships of long-segment parameters, such as CB and SB, depending on the radiograph tube centering. In addition, positioning errors in conventional radiography—such as slight patient rotation or movement—may affect coronal Cobb angle reproducibility [31]. In contrast, our DRR generation algorithm utilizes parallel projection and anchors the projection plane to the patient's internal bony anatomy (the bi-femoral head line) rather than the external detector, by design eliminating both geometric distortion and positioning errors. While the differences in global balance parameters warrant caution, DRR technology provides a distinct and potentially more standardized biomechanical representation. This algorithmic correction may theoretically allow DRRs to better approximate an "anatomically true" projection compared with conventional radiographs.

Beyond geometric standardization, the DRR generation process offers a perception of improved anatomic clarity, resulting in superior reproducibility among multiple observers. Unlike conventional radiographs, where overlapping soft tissues and ribs often blur vertebrae and femurs, our DRRs are generated via 3D-UNet segmentation, which isolates the bony structures and enhances edge definition, allowing observers to identify the edge of the vertebral body and femoral heads with greater confidence and reproducibility. Previous studies have shown that the measurement of T2-T5 Cobb angles on conventional radiographs demonstrates low consistency [32, 33], with an ICC rarely exceeding 0.80, even with computer-assisted measurement [34]. In this study, DRRs demonstrated a trend towards higher ICCs for the assessment of upper thoracic (T2–T5 TK) and pelvic (PI, PT, and SS) parameters compared to conventional radiographs. As shown in Fig. 4, the DRRs appeared to offer improved visual delineation of anatomical landmarks in the upper thoracic segment, pelvis, and femur in the sagittal view. Such enhanced visual perceptibility could potentially support the clinical feasibility of 2D parameter measurements. Despite its clarity of segmented bones, DRRs exhibit lower spatial resolution compared with conventional radiographs, with notably poor contrast in soft tissues and unsegmented bony regions (e.g., transverse and spinous processes, and the coccyx). Additionally, the distinct boundary lines observed below S1 and the femoral heads stem from incomplete segmentation.

It should be noted that differences in global balance parameters (SB) and thoracic alignment (T2-T5 TK) were observed between the two imaging modalities. These differences can be explained by the spinal biomechanical characteristics caused by patient posture, as the arm position is a well-established modulator of sagittal alignment [35, 36]. Standard radiograph protocols use an elbow-flexed posture, whereas WR3D imaging requires patients to elevate their arms. We speculate that postural influence may account for the observed difference in thoracic (T2-T5 TK, T5-T12 TK) curvature and T1S measurements between modalities. In contrast, lower thoracic (T10-L2 TLK) and lumbar (L4-S1 LL, L1-S1 LL) parameters showed no significant differences, suggesting limited postural influence on these segments.

Among pelvic parameters, the fixed anatomical parameter PI showed no significant difference between the two imaging modalities, whereas SS was posture-dependent [37, 38]. Regarding coronal Cobb angles, the influence of arm positioning was negligible compared to larger curve magnitudes. This discrepancy suggests that clinicians should exercise caution when measuring parameters susceptible to postural variations on DRRs.

This study has limitations. First, the evaluation was conducted on a single-center retrospective dataset. The segmentation algorithm performs poorly in postoperative patients with spinal implants and those with severe spinal deformities, failing to generate DRRs of diagnostic quality. Consequently, the study's findings cannot be generalized to these excluded populations. Second, while WR3D demonstrates strong visual and perceptual advantages given the inherent errors of conventional radiographs, it remains to be verified whether DRRs can accurately reflect true spine anatomy using quantitative analysis.

Future research should focus on refining segmentation algorithms to improve the visualization of non-body structures (transverse/spinous processes) and evaluating how the use of DRRs influences Lenke or PUMC classification, osteotomy planning, and postoperative assessment. In the long term, evaluating the agreement of DRRs represents an initial step toward integrating weight-bearing 3D imaging into routine practice. By demonstrating preliminary comparability between DRRs and standard radiographs, this baseline study supports future efforts to leverage WR3D volumetric datasets for developing 3D spinal classification systems and automated surgical planning tools.

In conclusion, this study generated DRRs from WR3D data using existing 3D segmentation and projection algorithms and evaluated their agreement with conventional radiographs in measuring radiographic parameters. Compared to conventional radiographs, DRR images demonstrate superior interobserver measurement reliability. The study shows that DRRs have high agreement with conventional radiographs for measuring key structural parameters (coronal Cobb angle, T10-L2 TLK, L1-S1 LL, PI), but exhibit certain differences for global balance parameters and sagittal curvature parameters. Overall, DRRs offer a conceptually attractive "one-stop" imaging framework for spinal deformity assessment, potentially unifying 3D diagnostic information with 2D clinical routines. Nevertheless, these benefits remain largely hypothetical at this stage regarding postural effects on global balance.

Abbreviations

WR3D: Weight-bearing Radiology 3D

CBCT: Cone Beam CT

AIS: Adolescent idiopathic scoliosis

DRR: Digitally reconstructed radiograph

3D: Three-dimensional

2D: Two-dimensional

AP: Anteroposterior

PTC: Proximal thoracic curve

MTC: Main thoracic curve

TLC: Thoracolumbar/Lumbar curve

T1T: T1 tilt

CB: Coronal balance

PO: Pelvic obliquity

SO: Sacral obliquity

TTS: Thoracic trunk shift

CL: Cervical lordosis

TK: Thoracic kyphosis

LL: Lumbar lordosis

TLK: Thoracolumbar kyphosis

T1S: T1 slope

SB: Sagittal balance

PI: Pelvic incidence

PT: Pelvic tilt

SS: Sacral slope

SD: Standard deviation

ICC: Intraclass correlation coefficient

FDR: False Discovery Rate

LoA: Limits of Agreement

MAE: Mean absolute error

r: Pearson correlation

Declarations

Author Contribution

X.N. and G.C. contributed equally to this work.X.N.: Conceptualization, Methodology, Data Curation, Formal analysis, Investigation, Writing-original draft.G.C.: Conceptualization, Validation, Writing-Reviewing and Editing, Project administration.J.W.: Data Curation.H.C.: Data Curation.J.S.: Writing-Reviewing and Editing.X.Y.: Data Curation.L.X.: Resources, Funding acquisition.Y.W.: Original data acquisition.R.Q.: Original data acquisition.S. M.: Original data acquisition.Z.Z.: Original data acquisition.Z.C.: Software.C.Y.: Software.T.Z.: Conceptualization, Resources, Funding acquisition, Supervision.N.W.: Conceptualization, Resources, Writing- Reviewing and Editing, Funding acquisition, Supervision.

Data Availability

Due to ethical restrictions and patient confidentiality, the raw datasets are not publicly available. Data may be shared with qualified researchers upon reasonable request, subject to approval from the Institutional Review Board (IRB) of Peking Union Medical College Hospital.

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Figures

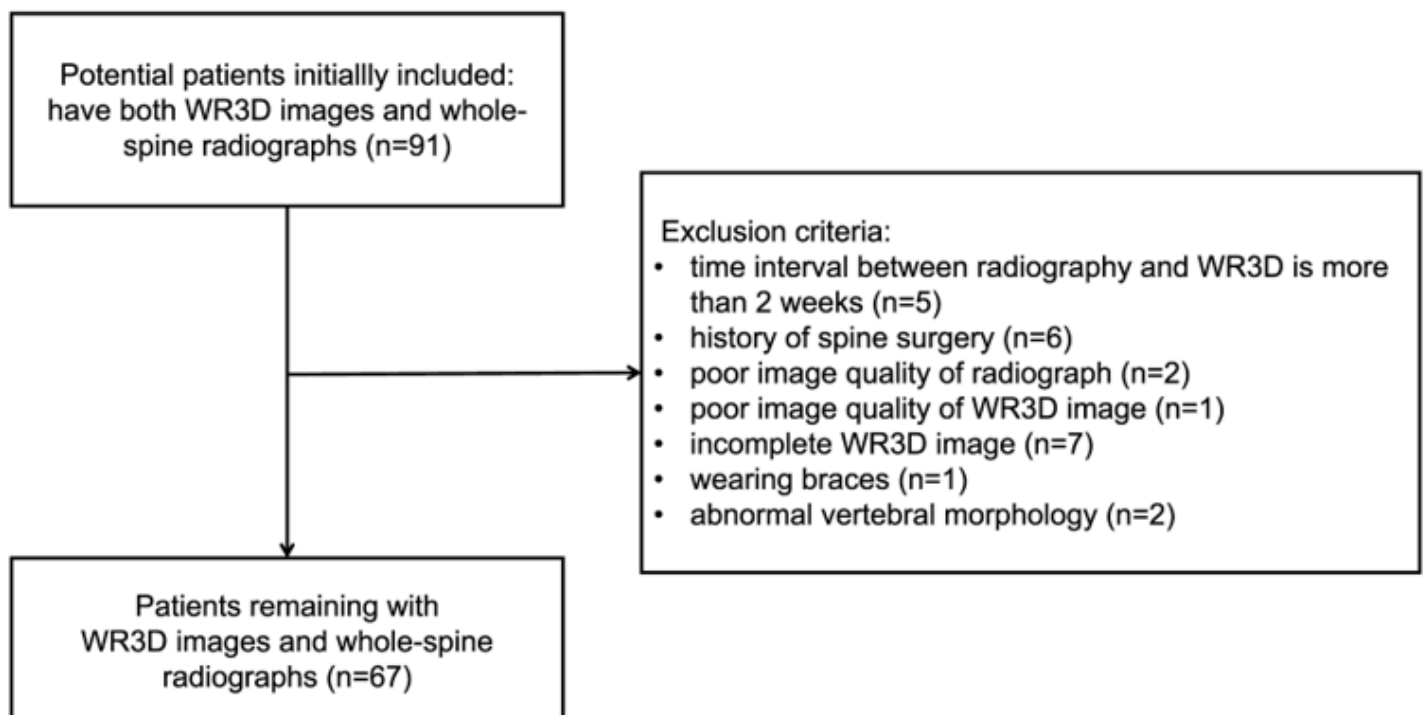


Figure 1

The diagram of flow of participants' inclusion and exclusion

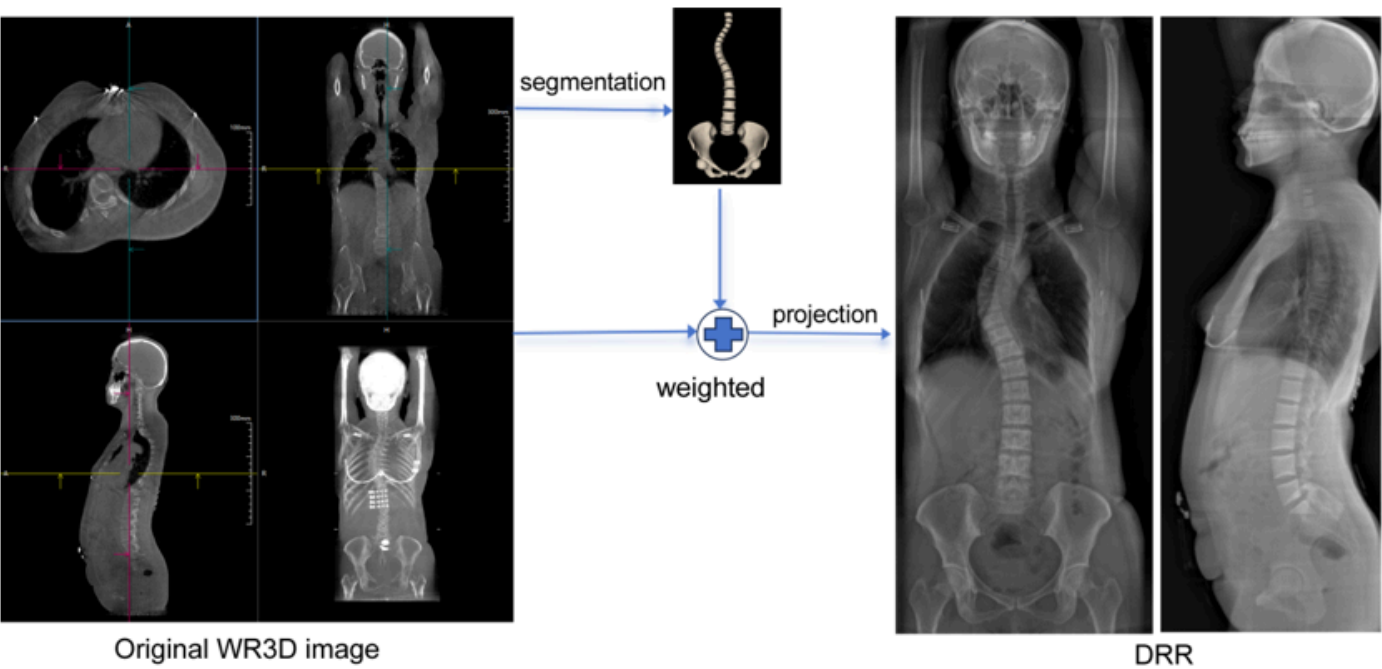


Figure 2

Schematic diagram of the overall architecture of the DRR generation algorithm.

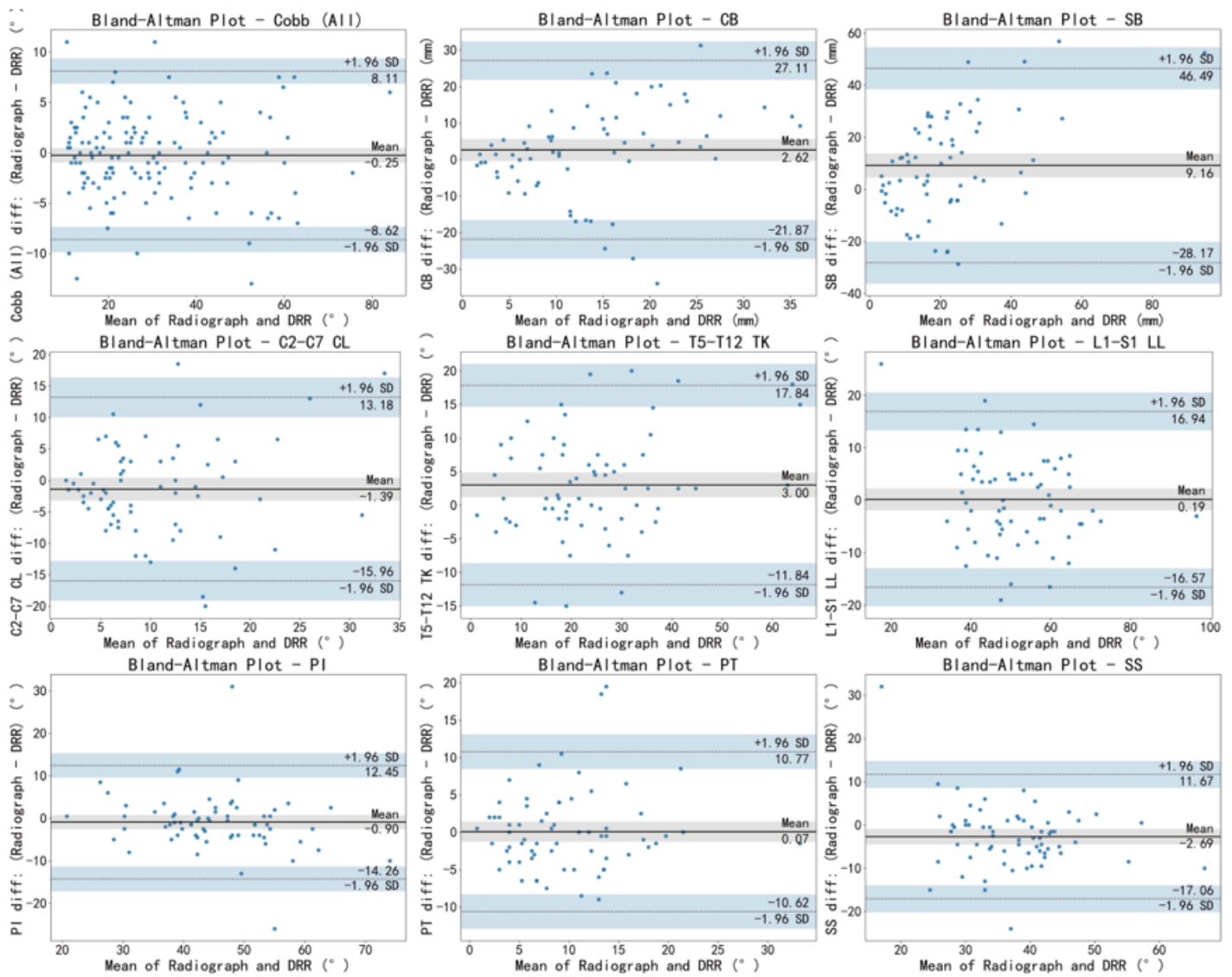


Figure 3

Bland-Altman plots comparing the measurements of selected key clinical parameters between DRR and radiographs. Solid lines show the mean differences, and dashed lines represent the 95% Limits of Agreement (95% LoA), defined as the range of mean difference ± 1.96 SD.

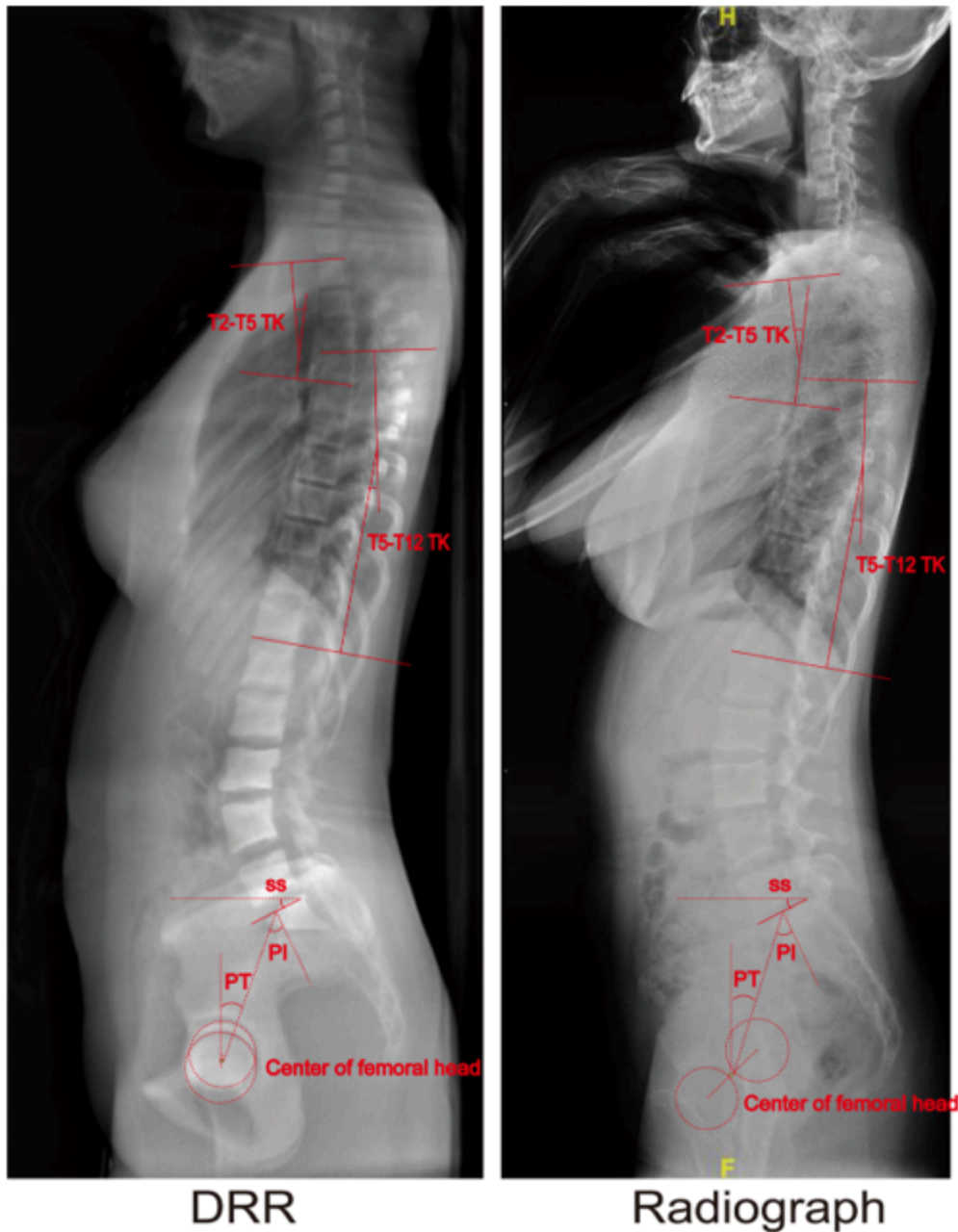


Figure 4

Representative comparison of image quality between digitally reconstructed radiograph (DRR) (left) and conventional radiograph (right) in the sagittal plane. Side-by-side comparison of a WR3D-based DRR (left) and a conventional radiograph (right) from the same patient in the sagittal plane. Notably, the DRR image exhibits a perception of improved anatomic clarity in the upper thoracic region, pelvis, and femoral heads on the sagittal view.

Supplementary Files

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