Automated Calculation and Estimation of Global Sagittal Alignment from Weight-Bearing X-Ray Imaging Using Deep Learning

Mark Ambrose Kurapatti, Yash Lahoti, Suhas Krishna Etigunta, Sri Guttikonda, Alexander Yu, Kareem S Mohamed, Wasil Ahmed, Samuel Kang-Wook Cho, Jun Sup Kim

INTRODUCTION: Accurate assessment of sagittal alignment is essential for guiding surgical decision-making and monitoring postoperative outcomes in patients with spinal deformity. However, traditional metrics such as the C7 sagittal vertical axis (SVA) do not account for head position or lower limb alignment, limiting their utility in comprehensive evaluations. As such, there has been increasing interest in the utility of global sagittal alignment (GSA) measures, which better reflect the complex interplay between the spine, head, pelvis, and lower extremities and is critical for evaluating compensatory mechanisms that may influence surgical planning and patient function. Cranial sagittal vertical alignment (CrSVA) parameters, including CrSVA to the sacrum (CrSVA-S), hip (CrSVA-H), knee (CrSVA-K), and ankle (CrSVA-A), as well as angular measures such as the cranium-hip-sacrum angle (CrHS), cranium-knee-sacrum angle (CrKS), and cranium-ankle-sacrum angle (CrAS), offer a more holistic understanding of postural alignment. However, manual calculation of these measurements is time-consuming and subject to interobserver variability. This study aims to develop and validate a convolutional neural network (CNN) model to automate the measurement of CrSVA and global angular parameters from weight-bearing biplanar full-body radiographs.

METHODS: We utilized a U-Net-based CNN trained on 667 sagittal full-body X-rays with anatomical landmarks manually annotated by spine surgeons, which served as the ground truth for training and evaluation. Landmarks included the nasion-inion line, sacrum, femoral heads, tibial plateaus, and talar domes. An additional 86 images were reserved for testing. The input image was standardized in resolution and passed through the CNN to generate a binary segmentation mask identifying landmark locations. From these coordinates, linear CrSVA distances and global angular parameters (CrHS, CrKS, CrAS) were computed. Model-predicted measurements were compared directly to the manual reference annotations using mean absolute error (MAE). Descriptive statistics were used to evaluate central tendencies and variability across measurements.

RESULTS: The CNN demonstrated high accuracy for CrSVA horizontal distances, with MAEs of 0.581 cm (CrSVA-H), 0.658 cm (CrSVA-K), 0.739 cm (CrSVA-A), and 0.889 cm (CrSVA-S). For angular measurements, performance was strongest for CrAS (0.552° MAE) and CrKS (0.960° MAE), while CrHS demonstrated the higher error (5.591° MAE), potentially reflecting the complexity of identifying femoral head centers in the presence of overlapping anatomy or implants. Sacral prediction tended to be underestimated, and ankle predictions showed broader error ranges, suggesting that lower extremity landmark variability remains a challenge for automated methods.

DISCUSSION AND CONCLUSION:

This study demonstrates the feasibility of automating comprehensive GSA assessment through a CNN applied to biplanar full-body imaging. The model accurately identified CrSVA horizontal distances and angular parameters, yielding results consistent with clinically acceptable thresholds for alignment analysis. The inclusion of such GSA parameters allows for a more complete evaluation of spinal posture, particularly in the context of compensatory head and lower extremity mechanisms that extend beyond traditional regional measures. The algorithm's rapid processing and standardized outputs could reduce measurement time, minimize inter-observer variability, and facilitate consistent preoperative to postoperative monitoring over time in the clinical spinal deformity setting.

Notably, prediction accuracy was highest for CrSVA-H and CrSVA-K, while CrHS presented greater variability. This may reflect anatomical complexity, imaging artifact, or implant presence, all of which should be considered in future refinements. The diverse patient population used in training, including varying degrees of deformity, instrumentation, and postural compensation, suggests the model's potential generalizability, though external validation is warranted in future studies.

Automated GSA assessment offers a promising tool for surgical planning, postoperative monitoring, and longitudinal outcome tracking in spinal deformity care. Further studies should assess model integration into clinical workflows and evaluate its influence on decision-making, outcomes, and efficiency across orthopaedic and neurosurgical spine centers.

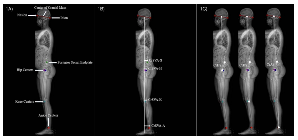

Figure 1. Images annotated on LabelMe software (Python, Wilmington, DE) showing A) landmarks for global sagittal alignment parameters, B) Cranial-Sagittal Vertical Axis (CrSVA) distance measurements (CrSVA-Hip, CrSVA-H; CrSVA-Sacrum, CrSVA-S; CrSVA-Knee, CrSVA-K; CrSVA-Ankle, CrSVA-A), and C) global sagittal angle measurements (cranium-hip-sacrum angle, CrHS; cranium-knee-sacrum angle, CrKS; cranium-ankle-sacrum angle, CrAS).

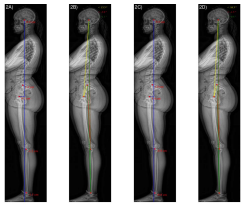

Figure 2. Predicted landmarks for global sagittal alignment are calculated (2B, 2D) from original input images (2A, 2C).

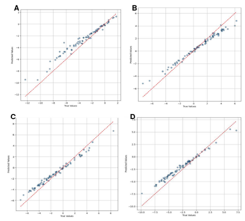

Figure 3. True (x) vs Predicted (y) Values for (a) CrSVA-S, (b) CrSVA-H, (c) CrSVA-K, and (d) CrSVA-A

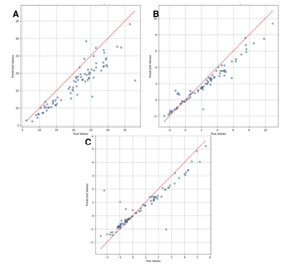

Figure 4. True (x) vs Predicted (y) Values for A)CrHS B) CrKS, and C) CrAS