

# Anatomy-Aware Regression Modeling of Distal Radius Morphology for Surgical Planning

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**INTRODUCTION:** Distal radius fracture is one of the most common fractures. Conventional evaluation relies on two-dimensional (2D) radiographic parameters such as palmar tilt, radial inclination, and ulnar variance. Advances in imaging have enabled three-dimensional (3D) CT-based models, allowing more precise characterization of distal radial morphology. Accurate understanding of this morphology is critical for fracture fixation, implant design, and surgical planning. However, traditional polynomial regression captures only global trends and fails to represent the triangular contour of the distal radius, where the radial margin tapers and the central region broadens. We hypothesized that an anatomy-aware regression model incorporating relative position would improve prediction of anteroposterior (AP) diameter, sagittal linear distance, and palmar tilt from transverse diameter. The aim of this study was to establish regression models to estimate these parameters of the distal radius based on transverse diameter and its relative position.

**METHODS:** This was a retrospective case-control study (Level III evidence). The radiographic database was reviewed to identify cases in which CT scans of normal wrists were taken. From this image database, we selected CT images of unaffected wrists that were taken for comparison with the affected side. The absence of prior history or symptoms in the unaffected wrists was confirmed through interviews and medical records. A total of 83 wrist CT images were evaluated, consisting of 42 males and 41 females, matched for age distribution (males: 20-95 years, mean age: 54.2 years; females: 18-91 years, mean age: 58.2 years). Patients with a history of traumatic arm injuries were excluded from the study, as well as those younger than 18 years. The CT images were obtained with the forearm in a neutral position. The scans covered from the level of the metacarpal bone to approximately 13 cm proximal to the radius joint surface.

### 3D bone morphology analysis

Computer analyzing software (BoneSimulator, Orthree, Osaka, Japan) was used to analyze the 3D bone model of distal radius. After importing image data into the software, a 3D surface models of the distal radius were constructed with a surface construction algorithm. The coordinate system was defined based on the 3D data of the distal radius. The long axis of the radius was calculated from the 3D surface model of the distal radius. The software finds the proximal-to-distal center curve of the radius shaft by analyzing its cross sections in various locations. Thereafter, the software calculated the central point at each level from the surface data of the radial diaphysis, and the approximate straight line based on the central points was defined as the long axis. The long axis of the radius was defined as the y-axis, the proximal direction was defined as positive and the distal direction as negative. The z-axis was parallel to the orthogonal projection of the line that initiated at the base on the sigmoid notch of distal radius and continued to the radial styloid process on the plane perpendicular to the y-axis. The radial direction of the z-axis was defined as positive, and the ulnar direction was defined as negative. The x-axis was defined to be perpendicular to the yz plane, and the palmar direction defined as positive and the dorsal direction defined as negative. The yz plane, xy plane, and xz plane were defined as the coronal plane, sagittal plane, and axial plane, respectively. The origin of the coordinates was defined as the intersection of the joint surface and the long axis of the radius. The transverse diameter ( $x$ ) was measured as the vertical distance from the tip of the radial styloid to the ulnar margin in the coronal plane (Figure 1-left). A normalized relative position ( $p$ ; radial margin = 0, ulnar margin = 1) was defined across the transverse diameter. Sagittal reference planes were created at 3-mm intervals, and coordinates of dorsal and palmar reference points at the edge of distal radius joint surface were recorded (Figure 1-b). At each position, the anteroposterior diameter ( $Y$ , mm), linear distance ( $D$ , mm), and palmar tilt ( $PT$ , °) were measured and used to construct regression models. Separate models were developed for males and females, and predictive accuracy was evaluated using the coefficient of determination ( $R^2$ ) and root mean square error (RMSE).

**RESULTS:** The overall model for anteroposterior diameter ( $Y$ ) was:  $Y = 1.45x + 26.31p - 0.0239x^2 - 24.51p^2 + 0.408(xp) - 18.25$  ( $R^2 = 0.908$ , RMSE = 1.21 mm). Male model:  $R^2 = 0.891$ , RMSE = 0.52 mm; Female model:  $R^2 = 0.885$ , RMSE = 0.48 mm. The overall model for linear distance ( $D$ ) was:  $D = 1.60x + 27.16p - 0.0265x^2 - 24.78p^2 + 0.383(xp) - 20.15$  ( $R^2 = 0.907$ , RMSE = 1.22 mm). Male model:  $R^2 = 0.908$ , RMSE = 1.24 mm; Female model:  $R^2 = 0.912$ , RMSE = 1.09 mm. The overall model for palmar tilt ( $PT$ ) was:  $PT = 2.17x + 12.86p - 0.0366x^2 + 3.57p^2 - 0.888(xp) - 17.83$  ( $R^2 = 0.097$ , RMSE = 5.52°). Male model:  $R^2 = 0.128$ , RMSE = 5.69°; Female model:  $R^2 = 0.052$ , RMSE = 5.27°. Figure 2 shows the 3D surface plot for the results of anteroposterior diameter and linear distance. Regression coefficients indicated that relative position had a greater effect in females, whereas transverse diameter contributed more strongly in males.

**DISCUSSION:** Regression models based on transverse diameter and relative position can predict the anteroposterior diameter and sagittal linear distance of the distal radius with high accuracy. In contrast, prediction of palmar tilt was less reliable, reflecting morphological complexity. The results of this study provide useful indices to support personalized surgical planning and implant design.

**SIGNIFICANCE/CLINICAL RELEVANCE:** Accurate prediction of radial cross-sectional geometry with near 1 mm error supports applications in personalized implant design, preoperative planning, and computer-assisted surgery. The anatomy-aware approach highlights the importance of integrating anatomical principles into predictive modeling to improve clinical utility.

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### FIGURES:

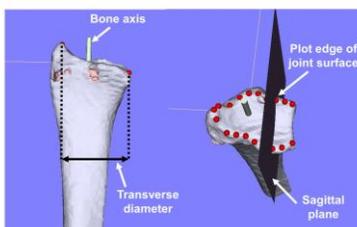


Figure 1

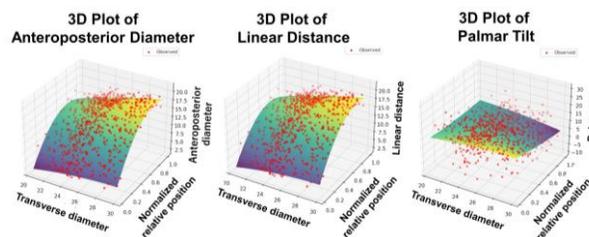


Figure 2