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Original Research

Dorsal Tilt of the Distal Radius Fracture Changes With Forearm Rotation When Measured on Radiographs



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Purpose: This study examined the impact of pronation and supination on the reliability of the radiographically measured values of dorsal tilt, radial inclination (RI), and ulnar variance (UV) in cadaveric forearms with artificially created distal radius fractures.

Methods: We prepared 21 human cadaveric forearms (11 right and 10 left) for radiostereometric analysis (RSA) by insertion of tantalum markers. Distal radius fractures were created midway between the marker segments. Radiographs and RSA images were taken at different degrees of supination and pronation. The precise degree of forearm rotation was calculated using RSA software. Two observers (H.B.T. and T.T.) independently measured tilt, RI, and UV on all radiographs in a blinded and randomized fashion. Univariate linear regression analyses were used to determine the relationship between forearm rotation and the measured radiographic values.

Results: The radiographically measured value of tilt was significantly impacted by forearm rotation. Supinating or pronating the forearm by 10° decreased and increased, respectively, the radiographic value of dorsal tilt by approximately 3°.

Conclusions: This study showed that the positioning of the fractured forearm during the radiographic procedure significantly impacted subsequent radiographic measurements of tilt. Dorsal tilt measurements increased (ie, fracture displacement measured more dorsal) with pronation and decreased (ie, fracture displacement measured more toward neutral, with less dorsal tilt) with supination of the forearm. However, measurements of RI ($p = 0.12$ and $p = 0.55$ for observer 1 and 2) and UV ($p = 0.34$ and $p = 0.17$, observer 1 and 2) were not significantly impacted by rotation.

Clinical relevance: Treatment of a distal radius fracture is, at least to some extent, based on radiographic quantification of fracture deformity. Therefore, unreliable measurements may adversely influence clinical decision making.

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The distal radius fracture (DRF) is a common musculoskeletal injury. The anatomic appearance/fracture deformity can be characterized by measuring various radiographic indices. Commonly used measurements concern angulation of the articular surface, such as the dorsal/palmar tilt and radial inclination (RI). Ulnar variance (UV), the length of the ulna relative to the radius, is often used as an indirect estimate of fracture compression. In combination with clinical guidelines suggesting the cutoff values for

acceptable alignment, radiographic measurements may influence clinical decision making at the time of fracture by guiding the choice among conservative treatment, reduction, and surgery.¹ Furthermore, routine follow-up radiographic imaging is used to assess fracture stability and healing. This makes the reliability of radiographic measurements, not only at the initial imaging but also between follow-up examinations, of utmost importance.

Positioning of the forearm during the radiographic procedure may affect the reliability of the radiographic measurements. Although differences in the magnitude of impact are reported, there appears to be some agreement that the rotation of the non-fractured forearm, specifically supination and pronation, impacts the measured values of tilt and, to some degree, RI and UV.^{2–5} However, it remains unclear to what extent rotation influences tilt, RI, and UV in the presence of a displaced DRF. Theoretically, the impact of rotation on measurements made on fractured wrists is different from the impact on nonfractured wrists. Since treatment, at least to some extent, is based on radiographic quantification of fracture deformity, unreliable measurements might adversely influence clinical decision making.

The objectives of this study were to estimate the impact of forearm rotation on the radiographic measurements of tilt, RI, and UV in a cohort of cadaver arms with artificially created extra-articular DRFs. We hypothesized that the forearm rotation would affect the radiographically measured values of tilt, RI, and UV obtained on radiographs of fractured wrists.

Materials and Methods

The regional ethics committee waived the requirement for official approval of this study since all donor arms were anonymous and came from individuals who donated their body to research (project ID: S-20180077).

Specimens

A radiostereometric analysis (RSA) is a validated research tool traditionally used to assess the movement of orthopedic implants via inserted markers.⁶ In the current study, RSA was used to quantify supination and pronation of donor arms. Twenty-one nonfractured arms (11 right and 10 left) were consecutively included. Tantalum markers, 0.8 mm and 1.0 mm, were inserted in 2 segments in the distal radius, with 8–9 markers adjacent to the radiocarpal joint and 4–6 markers proximal to the joint. The 2 marker segments were distanced from each other such that an artificial fracture could be created approximately midway between the segments at a later stage in the process. In the first 6 donor arms, a spring-loaded piston (RSA Biomedical AB) was used to inject markers into cancellous bone. Subsequent RSAs revealed that the tantalum markers became loose after the creation of the fracture. Therefore, a change in procedure was implemented. In arms 7–21, markers were placed in cortical bone in predrilled holes and secured with bone wax.

The donor arms were attached to a custom-made radiolucent platform with K-wires through the humerus and olecranon, with the elbow flexed approximately 90° and the ulna toward the platform. This setup allowed the radius to rotate over a stationary ulna, enabling supination and pronation. The longitudinal axes of the forearms were positioned along the y axis of a uniplanar calibration cage 43 (RSA Biomedical AB). Hence, according to the RSA global coordinate system, rotation around the y axes (Y^r) was equal to pronation (+) and supination (–) for right arms (Fig. 1). Signed values were reverted for left arms. A true-lateral nonrotated reference radiograph (0°) was acquired for each forearm. This radiograph was defined as an image where the palmar cortex of the pisiform



Figure 1. Lateral wrist radiograph. Rotation around the y axis is supination (–) and pronation (+) for right arms. Signed values are reverted for left arms.

was positioned over the central third of the interval between the palmar cortices of the distal scaphoid pole and the capitate.⁷ Radiographs were repeated until this position was obtained.

Beginning from this nonrotated (0°) baseline position, the forearms were rotated in steps of approximately 5° up to +15° of pronation and –15° of supination. Negative values indicate supination and positive values indicate pronation. As a result, 3 supinated radiographs, 1 nonrotated reference radiograph, and 3 pronated radiographs were taken for each arm. Radiographs and RSA images of the forearm were obtained in the same position before rotating the forearm to the next position. A K-wire in the proximal radius was used against a goniometer for estimates of rotation. Posteroanterior radiographs were made cross-table using a horizontal x-ray beam, which entailed a distance between the forearms and the detector. A calibration object of known size was included in the radiographs, and the UV measurements were corrected accordingly. Radiographs were taken with a ceiling-mounted tube, with the central ray directed at the radiocarpal joint and a focus-to-detector distance of 100 cm. Connecting the ceiling-mounted tube to a mobile unit allowed simultaneous acquisition of RSA images (Multitom Rax and Mira Max1, Siemens Healthineers). Radiostereometric analysis images were made with a 140-cm focus-to-detector distance and with the tubes angled 17°

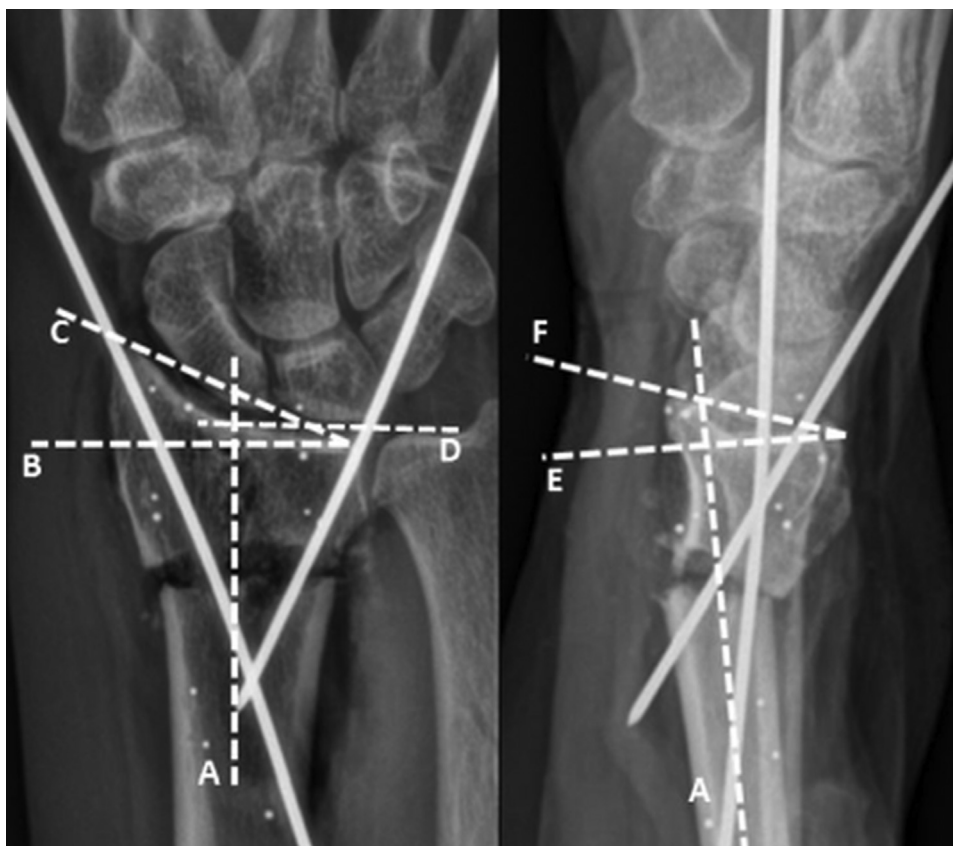


Figure 2. Line A indicates the longitudinal axis of the radius in each panel. Line B is perpendicular to line A, drawn from the distal ulnar palmar corner of the radial articular surface. Line C connects the distal ulnar palmar corner of the radial articular surface to the distal part of the radial styloid tip. Line D is parallel to line B. It is positioned up against the most distal point of the articular surface of the ulna. Line E is perpendicular to line A and can be drawn at a convenient level. Line F connects the distal palmar and dorsal margins of the radial articular surface. Tilt is defined as the angulation of the distal radial articular surface in the sagittal plane. It is measured as the angle between lines E and F. Radial inclination is defined as the angulation of the distal radial articular surface in the coronal plane. It is expressed as the angle between lines B and C. Ulnar variance is defined as the length of the ulna relative to the radius. It is quantified as the distance between lines B and D.

relative to the calibration cage. Radiostereometric analysis examinations of 14 nonrotated forearms were repeated, that is, these arms had double examinations. The precision of the RSA setup can be assessed by calculating the motion of the patient markers between the 2 examinations. In a perfect setting, the motion would be 0. Because of measurement error, a degree of motion will be calculated, and this amount of motion can be expressed as the precision of the RSA setup.

Next, the donor arms were detached from the platform and a transverse, dorsally angulated fracture with axial compression was created through a dorsal incision. A battery-operated drill with a 2-mm (0.079-in) K-wire was used to weaken the cortical bone in a jagged pattern approximately midway between the marker segments. An osteotome was used to further weaken the bone. The distal fragment was manually compressed in a proximal direction and dorsally angulated. Fractures were stabilized using 2–4 K-wires. We attempted to induce approximately 10° of dorsal tilt, the degree of displacement used for surgical decision making in many clinical practice guidelines.¹ The donor arms were reattached to the platform and the RSA and radiographic procedures were repeated. An experienced consultant hand surgeon (H.B.T.) inserted the markers and created all the fractures.

Eligibility criteria

The commercially available UmRSA software 7.0 (RSA Biomedical AB) offers 2 quality parameters. The condition number (CN)

quantifies the spatial marker configuration, and the mean error of rigid body (ME) is a measure of marker stability between examinations. The higher the ME, the more the markers have moved, that is, the looser the markers. Suspecting that creation of a fracture might cause markers to become loose, an upper limit of ME was set at 0.35.⁶ Movement of markers was assessed using the reference radiographs. The marker configuration in the nonfractured donor arm was compared with the marker configuration in the same arm after the creation of a fracture. Donor arms 3–5 were excluded because of having an ME >0.35. Furthermore, donor arm 2 was excluded because the K-wires were superimposed on the patient markers to a degree where the RSAs could not be made. Therefore, 17 donor arms were included (9 left and 8 right).

Radiographic measurements

The tilt, RI, and UV were measured independently in a blinded and randomized fashion by a consultant hand surgeon (H.B.T.) and a senior musculoskeletal radiologist (T.T.) with 19 years and 25 years of experience, respectively. Angulation in the sagittal and coronal planes was measured as tilt and RI, respectively. Fracture compression was indirectly estimated as UV (Fig. 2). To enable the calculation of the intraobserver agreement, both observers remeasured 61 radiographs. To reduce the risk of recall bias, there was a minimum of 4 weeks between their first and second readings. Measurements were made in a picture archiving and

Table 1
Precision of the RSA Setup as Calculated on the Basis of Double Examinations (n = 14 images)^a

Precision	X ^t (mm)	Y ^t (mm)	Z ^t (mm)	X ^r (°)	Y ^r (°)	Z ^r (°)
SD	0.03	0.02	0.05	0.14	0.16	0.06
Precision	0.06	0.04	0.12	0.30	0.35	0.14

^a X, Y, and Z are axis in a coordinate system. In the current study rotation around the Y axis is corresponding to forearm supination (–) and pronation (+). X^t, Y^t, and Z^t show translations in mm and X^r, Y^r, and Z^r show rotation in degrees. Precision is calculated as SD × 0.975 t quantile.

communication system (GE Healthcare) and stored in REDCap (Research Electronic Data Capture).

Statistical analyses

Spatial marker distribution was described by the mean CN and range. Micromotion at the fixation site was calculated by RSAs and presented as the mean and SD. The SD of the differences between the 2 RSA examinations was calculated. The precision of the RSA setup was expressed as the number below which 95% of the differences between the 2 examinations would be (SD × 2.160; t quantile, 0.975 for n = 14 observations).⁸ Univariate linear regression models tested associations between rotation and tilt, RI, and UV. The continuous variable of forearm rotation was used as the independent variable, and the radiographically measured values of tilt, RI, or UV were used as dependent variables. The goodness of fit of each model was reported as the R² value. In cases with nonsignificant findings, we conducted post hoc power analyses. Inter- and intraobserver agreements of radiographic measurements were calculated and depicted using Bland-Altman (BA) plots with limits of agreement (LoA). Assuming a normal distribution of differences, the LoA estimates the interval within which 95% of all measured differences, either between or within each of the 2 observers, will fall. Agreement was also calculated by including only the reference radiographs (n = 17). A P value <.05 was considered significant.

Results

Radiostereometric analysis: Quality of setup

The marker scatter assessed by the CN was, as expected, better for the distal segment than for the proximal segment, with mean values of 50 (range, 34–86) and 144 (range, 89–311), respectively. The higher CN of the proximal segments reflects the difficulty of achieving a good marker dispersion in the relatively smaller anatomic region 4–6 cm proximal to the radiocarpal joint as opposed to in the broader juxta-articular aspect of the radius. A CN <300 is recommended, although no statistically significant difference in precision between CN 300 and CN 1000 has been reported.^{9,10} The precision of the setup ranged from 0.04 mm to 0.12 mm for translation and from 0.14° to 0.35° for rotation (Table 1). The precision of forearm rotation (Y^r) was 0.35°, suggesting that at least 95% of differences measured between the double examinations are ≤0.35°. The mean (SD) micromotions of the distal fragment were calculated as –0.7 (0.64), 0.16 (0.98), and –0.09 (0.28) for rotation in the radioulnar, supination/pronation, and dorso-palmar directions, respectively. For translation in the dorso-palmar, proximal/distal, and radioulnar directions, the motions were –0.01 (0.12), 0.01 (0.04), and 0.01 (0.36), respectively.

Impact of rotation on radiographic measurements

The univariate linear regression model showed that the rotation of the forearm significantly influenced the measured values of tilt

for both observers, with slopes of –0.32° (95% confidence interval [CI], –0.53 to –0.12; P < .05) and –0.31° (95% CI, –0.50 to –0.12; P < .05) for observers 1 and 2, respectively. The negative slopes specify that pronation increased and supination decreased the dorsal tilt by 0.31° to 0.32° for each degree of forearm rotation. Variability of the data was evident in the regression analyses, as indicated by low R² values. However, a statistically significant impact of rotation could be observed for tilt measurements for both observers despite this large variability in the data, which appear to form consistent point clouds, meaning that the regression lines were not affected by outliers (Fig. 3). In contrast, no association between rotation and measured RI or UV was found by either observer (Table 2). For sample-size planning of future studies, our data may serve as a point of orientation. For instance, assuming a true slope value of –0.11 for RI, a covariate SD of 6.97, and a correlation between outcome and covariate of –0.1449, a sample size of 368 subjects is necessary to decline the null hypothesis of a slope of 0 with a power of 80% at a significance level of 5% (2-sided). The corresponding sample size for UV was 487, calculated using the slope of 0.03, a covariate SD of 6.97, and a correlation between outcome and covariate of 0.1263.

Agreement

When including all measurements (n = 119), the mean measured differences between observers and the corresponding interobserver LoAs were –1.41° ± 7.68°, –0.45° ± 5.03°, and 0.32 ± 1.93 mm for measurements of tilt, RI, and UV, respectively. The corresponding values for agreement including only measurements from the reference images (n = 17) were 0.12° ± 3.95°, –0.38° ± 5.5°, and 0.08 ± 1.29 mm for measurements of tilt, RI, and UV, respectively. Bland-Altman interobserver agreement for all measurements (n = 119) and reference image measurements (n = 17), including LoAs and 95% CIs, are presented in Table 3. Table 4 summarizes the intraobserver agreement (n = 61). Bland-Altman plots with LoAs and 95% CIs are used to graphically depict interobserver agreement for all images and the reference images isolated (Fig. 4). Tilt measurements appeared to be particularly affected by rotation. The widths of the BA LoAs are visually narrower when measurements are obtained on reference radiographs of nonrotated forearms as opposed to measurements taken of radiographs with the forearms in various degrees of supination and pronation. Additionally, the intraobserver agreement is visualized in BA plots (Fig. 5).

Discussion

Quantitative radiographic characterization of a DRF is often used in the treatment decision. It has previously been reported that the rotation of the nonfractured forearm during the radiographic procedure alters the radiographic measurements. Nonetheless, strikingly little data are available on the impact of rotation in the presence of a fracture. This study explored the influence of rotation on measurements of DRFs. Rotation significantly changed dorsal tilt measurements taken for the same arm at various degrees of supination and pronation.

In line with the previous studies on nonfractured arms, the present study showed that rotation impacted tilt measurements. In the current study, however, the magnitude of impact was less than what was previously reported.^{3,5} This inconsistency could be attributed to the fact that the anatomic appearance of a fractured distal radius is influenced by more variables than just rotation of the forearm. Reducing the multifaceted 3-dimensional nature of a DRF to various 2-dimensional radiographic measurements poses an inherent uncertainty, particularly in the presence of a fracture

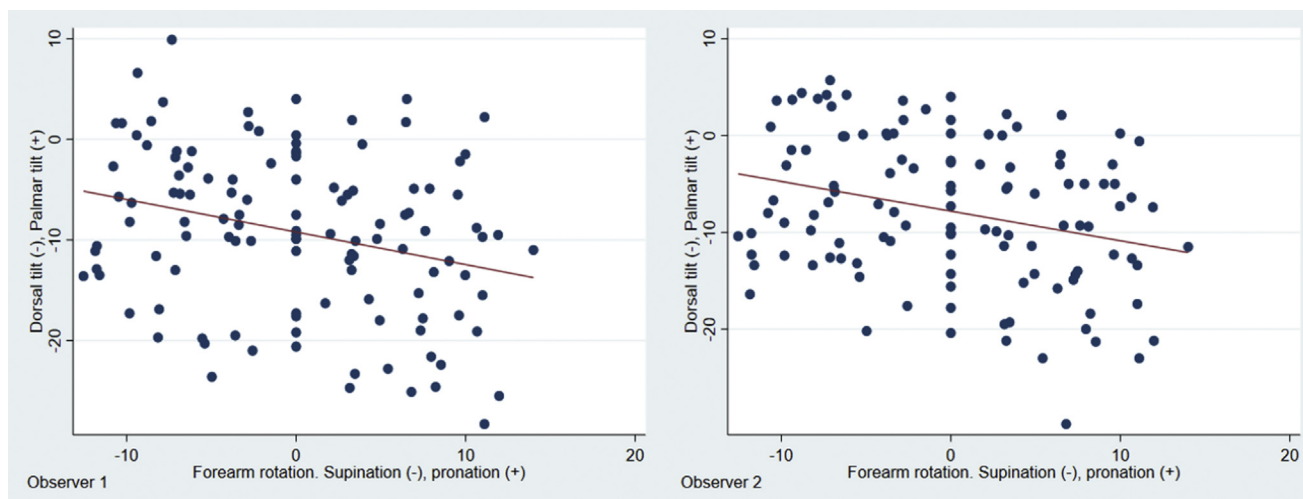


Figure 3. Scatter plots depicting point clouds forming around the regression lines for tilt measurements.

Table 2
Mean Measured Values and Results of Univariate Linear Regression Analyses*

Radiographic Measurements	Observer	Mean \pm SD (Range)	Slope (95% CI)	R ²	P Value
Tilt, °	1	-9.2 \pm 8.1 (-28.3 to 9.9)	-0.32 (-0.53 to -0.12)	0.08	<.05
	2	-7.8 \pm 7.5 (-29.8 to 5.7)	-0.31 (-0.50 to -0.12)	0.08	<.05
Radial	1	19.7 \pm 5.3 (1.30–34.9)	-0.11 (-0.25 to 0.03)	0.02	.12
Inclination, °	2	20.1 \pm 4.8 (12.4–32.4)	-0.04 (-0.16 to 0.09)	0.003	.55
Ulnar	1	0.1 \pm 1.2 (-2.2 to 3.1)	0.02 (-0.02 to 0.05)	0.01	.34
Variance, mm	2	-0.2 \pm 1.4 (-2.4 to 3.4)	0.03 (-0.01 to 0.06)	0.01	.17

* Analyses are for the impacts of rotation on tilt, RI, and UV using RSA values of rotation. n = 119 images. Tilt, dorsal (-), and palmar (+).

Table 3
Forearm Rotation Changes Reviewer Agreement*

Radiographic Measurements	Radiographs	Bias Mean (SD)	Bias 95% CI	Limits of Agreement	95% CI of Lower Limit of Agreement	95% CI of Upper Limit of Agreement
Tilt, °	All	-1.41 (3.92)	-2.12 to -0.69	-9.08 to 6.27	-10.25 to -8.24	5.43–7.44
	Reference	0.12 (2.00)	-0.91 to 1.16	-3.82 to 4.07	-6.08 to -2.87	3.12–6.32
Radial	All	-0.45 (2.57)	-0.91 to 0.02	-5.48 to 4.59	-6.25 to -4.93	4.04–5.35
Inclination, °	Reference	-0.38 (2.80)	-1.8 to 1.06	-5.87 to 5.12	-9.01 to -4.55	3.79–8.26
Ulnar	All	0.32 (0.98)	0.14–0.50	-1.61 to 2.25	-1.90 to -1.40	2.03–2.54
Variance, mm	Reference	0.08 (0.66)	-0.27 to 0.41	-1.22 to 1.35	-1.95 to -0.91	1.05–2.09

* Bland-Altman inter-rater agreement is based on data from all radiographs (n = 119 images) and that from the nonrotated reference radiographs (n = 17 images). Tilt, dorsal (-), and palmar (+).

Table 4
Bland-Altman Limits of Agreement and Mean Estimated Differences, Intra-Rater Agreement (n = 61 images)*

Radiographic Measurements	Observer	Bias Mean (SD)	Bias 95% CI	Limits of Agreement	95% CI of Lower Limit of Agreement	95% CI of Upper Limit of Agreement
Tilt, °	1	-0.27 (2.94)	-1.02 to 0.48	-6.02 to 5.48	-7.34 to -5.18	4.65–6.80
	2	-0.55 (3.84)	-1.54 to 0.43	-8.08 to 6.97	-9.80 to -6.98	5.87–8.69
Radial	1	1.12 (1.38)	0.77–1.47	-1.59 to 3.83	-2.21 to -1.20	3.44–4.45
Inclination, °	2	-0.18 (2.29)	-0.77 to 0.40	-4.68 to 4.31	-5.70 to -4.02	3.65–5.34
Ulnar	1	-0.02 (0.66)	-0.18 to 0.15	-1.30 to 1.27	-1.60 to -1.11	1.08–1.56
Variance, mm	2	0.06 (1.19)	-0.25 to 0.36	-2.29 to 2.39	-2.82 to -1.94	2.05–2.93

* Tilt, dorsal (-), and palmar (+).

where rotation and/or translation of fragments may obscure, or possibly even display, anatomic landmarks more clearly.

According to clinical practice guidelines, surgery is suggested in cases with more than approximately 10° of dorsal tilt.¹ When fracture displacement is close to this benchmark value, measurement reliability becomes particularly important. Two radiographic

examinations of a DRF taken with 10° of supination versus 10° of pronation may lead to an “apparent” change in the tilt of approximately 6°. Consequently, positioning of the forearm during the radiographic procedure can, in theory, adversely influence the treatment decision. This should also be considered for routine follow-up radiographs that assess fracture stability. If 2 consecutive

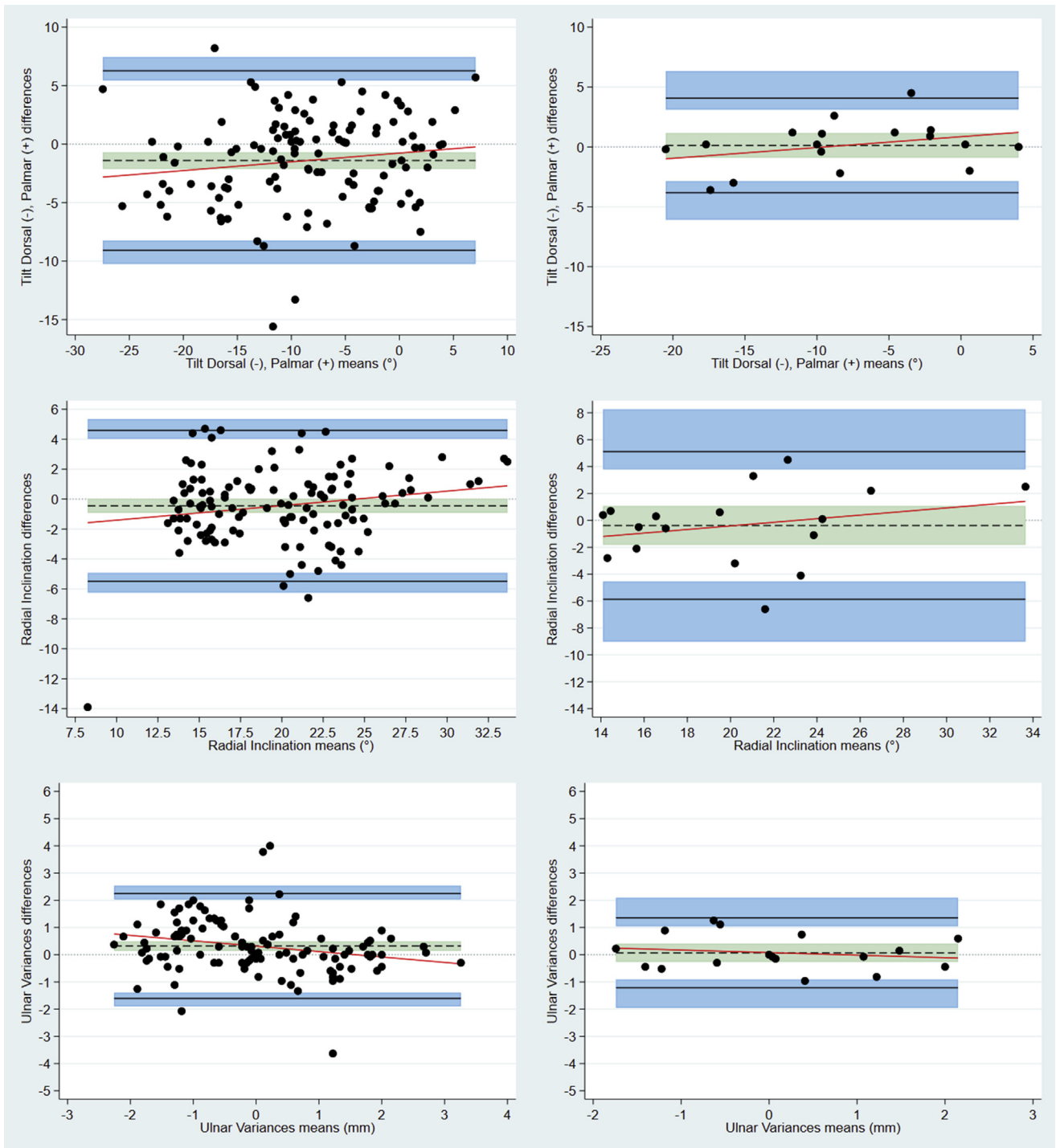


Figure 4. Bland-Altman inter-rater plots with 95% LoA including all measurements (n = 119; left column) and reference image measurements isolated (n = 17; right column). The solid black lines represent upper and lower LoA, with the shaded blue areas depicting the 95% CIs. The dotted black lines signify the mean measured difference between observers, and the shaded green areas depict the 95% CIs.

radiographs are taken with differing or even opposing degrees of rotation, fracture instability could be suspected on the basis of an apparent but not “true” change in tilt.

The radiographic procedure concerning rotation is not the only factor to consider when adding clinical value to radiographic measurements. Observer variation, expressed as BA LoA, is a range that statistically estimates boundaries within which 95% of the differences between or within observers lie.^{11,12} The bias and

interobserver BA LoA for tilt in the current study was $-1.41^\circ \pm 7.68^\circ$. From a clinical perspective, this implies that tilt measured in the same radiograph by 2 different observers may differ by as much as 15° , which is approximately twice as much as the BA LoA previously reported in a study of 33 patients with DRF ($-0.2^\circ \pm 4.6^\circ$).¹³ A possible explanation for this discrepancy could be that most measurements in the current study were made on intentionally rotated forearms. When estimating interobserver BA LoA using only

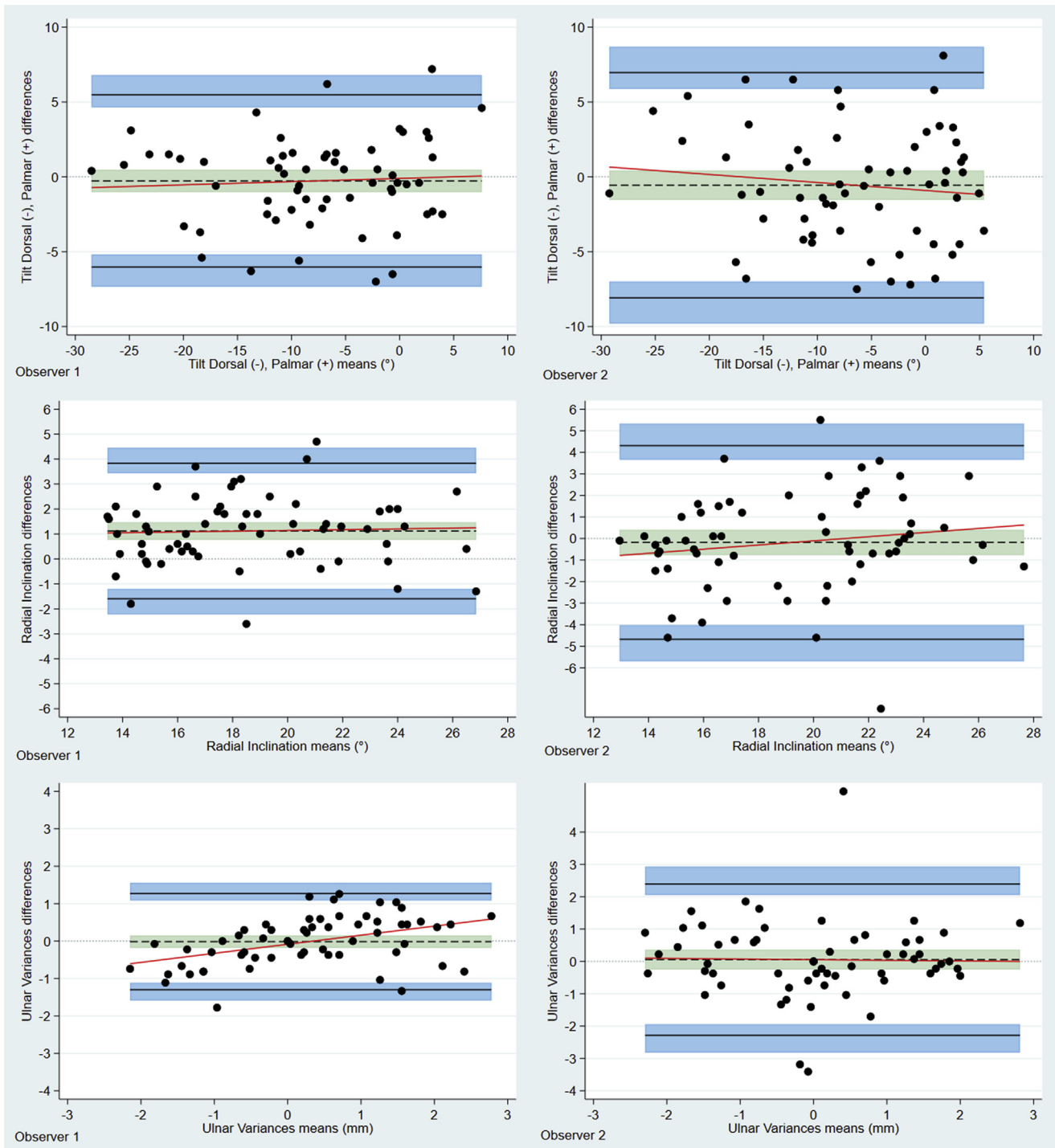


Figure 5. Bland-Altman plots depicting intra-rater agreement (n = 61; images) for observer 1 and observer 2. The solid black lines represent upper and lower LoA, with the shaded blue areas depicting the 95% CIs. The dotted black lines signify the mean measured difference between the first and second measurements, and the shaded green areas illustrate the respective 95% CIs.

the 0° reference radiographs, both bias and width of the LoA indeed improved to $0.12^\circ \pm 3.94^\circ$, which is strikingly comparable with the aforementioned findings.¹³ Measurement reliability seems to improve with strict adherence to a standardized radiographic procedure for the lateral radiograph. This highlights the need for attention to the radiographic procedure not only in clinical practice but, as importantly, in studies applying diagnostic or predictive values to the measurements.

Interpretation of the BA LoA by using only reference radiographs should be done with caution, since a sample of 17 may be inadequate for the estimation of a normal distribution. Another limitation in the current study was that radiographs were not excluded on the basis of the positioning of K-wires. Hence, K-wires superimposed on anatomic landmarks could potentially have introduced bias to the measurements. Nonetheless, the presence of surgical implants in

the radiograph mimics a real-life scenario in a clinical setting. Although rigorous efforts were made to secure the fracture using K-wires, micromotion at the fracture site is a limitation. Another limitation is the reproducibility of the fracture model, since the exact angulation and fracture compression could not be controlled during the creation of a fracture. Additionally, the fact that 2 highly experienced observers made all the measurements may affect the generalizability to clinical practice, where physicians of varying experience interpret the radiographs. The choice of highly experienced raters was made to test the study hypothesis of a correlation between forearm rotation and radiographic measurements. The use of a cadaveric model is another component that may compromise generalizability to an in vivo clinical setting. The concept of accuracy is not touched upon in the current study. Theoretically, the 0° nonrotated image may not be the image from which the most accurate measurements are acquired. Further studies exploring the concept of measurement accuracy are warranted. In this study, the impact of rotation on nonfractured wrists was investigated. Another equally important question is whether the forearm rotation exhibits a similar impact on measurements in the presence of an intra-articular DRF.

Based on data from this study, it appears problematic to reliably determine the values of not only the tilt but also RI and UV. Even though rotation did not impact RI and UV, the interobserver BA LoAs were still broad from a clinical perspective, at $-0.45^\circ \pm 5^\circ$ and 0.32 ± 1.93 mm, respectively. Strict standardized radiographic procedures were applied in this study. Detailed radiologic measuring techniques were introduced, and experienced observers made all the measurements. Substantial variance in measurements was still evident though. With this in mind, the interpretation of radiographic measurements of a DRF should be preceded by a standardized reproducible approach to both the radiographic procedure and radiologic measuring technique and should probably still be interpreted with caution.

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