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Non-operative treatment of both-bone forearm shaft fractures in children: Predictors of early radiographic failure

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INTRODUCTION

Forearm shaft fractures are the third most common fracture in children, and complete shaft fractures of the radius and ulna present a management challenge due to their inherent instability¹. Successful treatment of both-bone forearm shaft fractures results in restoration of anatomic alignment and full recovery of range of motion². Although closed reduction and casting is the preferred treatment method, outcomes remain variable and patients may require additional fracture manipulation or formal surgical intervention due to residual angulation. Previous studies estimate that the failure of non-operative treatment of mid-shaft fractures in pediatric populations ranges between 39% and 64%^{3,4}. Cadavaric and clinical studies have established a clear relationship between forearm shaft malunion and significant forearm stiffness^{2–11}. As many as 60% of children have residual loss of motion due to malunion of their both-bone forearm shaft fractures^{10,11}. In general, the risk of permanent stiffness increases with age due to waning remodeling potential. This accounts for the less predictable outcomes in older adolescents who often require more aggressive treatment^{2,10–15}. Similarly, remodeling capacity may diminish with more proximal fractures due to

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increasing distance from the more biologically active growth plates of the distal radius and ulna¹⁶.

Elastic stable intramedullary nailing (ESIN) is an effective treatment for forearm shaft fractures in children that has abundant support in the literature^{17–21}. This technique is best applied early in the post-fracture time period as it becomes progressively difficult to perform as callus formation occurs²². It would be quite advantageous for clinicians to be able to identify patients likely to fail non-operative treatment early in the treatment process during the time-period when surgical intervention is most likely to succeed. The purpose of this study was to evaluate the rate of radiographic failure of non-operative treatment of complete both-bone forearm shaft fractures. In addition, we investigated factors associated with failure and we assessed the time frame within which failure was most likely to occur.

MATERIALS & METHODS

This study was a retrospective review of radiographic records of pediatric patients with both-bone forearm shaft fractures. We also abstracted demographic data and surgical data (if surgery was undertaken) from the patients' medical charts. Our study was approved by the hospital's institutional review board. Females less than 17 years and males less than 18 years of age treated at our institution between January 2005 and January 2008 with complete both-bone shaft fractures were screened for inclusion. Potential participants were identified by searching the Orthopaedic billing records for diaphyseal fracture of the radius and ulna (ICD-9 code 813.23). Eligible participants were those with pre-reduction anteroposterior (AP) and lateral radiographs indicating complete cortical disruption of the diaphysis of both the radius and ulna, with open physes. Participants excluded were those with no post-reduction radiograph, incomplete fractures including greenstick fractures, fractures not of the shaft including radial neck and olecranon fractures, re-fractures, Monteggia, Galeazzi, pathologic, or open fractures, and multiple trauma patients. Translation was considered acceptable based on previous studies; rotation was not measured^{13,23}.

Fractures were initially reduced and sugar-tong splint immobilized in the emergency department by an orthopaedic resident. Participants either had an attempt at closed reduction and casting at presentation, or they underwent immediate surgery. Those who had closed reduction and casting were further categorized based on whether or not they underwent surgery within four weeks following reduction. In all cases, the decision to cast and the decision for surgical intervention were the opinion of the attending physician at the time of treatment. Imaging data were obtained from PACS digital radiographs.

The proximal end of the radial shaft was defined as the proximal extent of the bicipital tuberosity. The distal end of the shaft was defined radiographically by measuring the width of the distal radial physis, then plotting that distance proximally on the radius. This is an approximation of the proximal extent of Lister's tubercle and accounts for age and bone length. Fractures were classified as proximal, middle or distal based on an equal one-third division of the length of the shaft. Ulnar fractures were classified according to the corresponding level of the radius. Angulation of the radius and ulna were measured on AP and lateral radiographs at presentation, post-reduction, and weekly for up to four weeks of follow-up. All measurements were made twice by the same trained research assistant with the mean reported. For participants who underwent surgery or additional fracture manipulation following closed reduction and casting, the radiograph prior to intervention was used for follow-up. Angulation was defined as the total degree of deviation of the distal fragment in relation to the proximal fragment. FIGURE 1 illustrates these measurements.

The primary outcome was the degree of residual angulation present at defined time periods during follow-up. Based on reasonable evidence presented in the literature from both clinical and cadaveric studies, the threshold for acceptable shaft angles for females 8 years or younger and males 10 years or younger were 20 degrees for the distal-third, 15 degrees for the middle-third, and 10 degrees for the proximal-third^{9,13,19,22–26}. In order to account for skeletal maturity according to age and sex, angulations up to 10 degrees were considered acceptable at all shaft levels for females older than 8 and males older than 10 years^{4,7,13,19,22,25}. Failure of non-operative treatment was defined as exceeding these criteria. We also recorded fracture characteristics and the week in which initial radiographic evidence of failure was identified.

To evaluate the mean natural angulation of each segment, as well as the reliability of our measurement methods, we assessed a convenience sample of 30 forearm radiographs considered to represent the patient cohort based on age and sex. The radius was divided into thirds, and angular measurements were created for each segment using the midpoint of the segment as an imaginary fracture line. The principal investigator and trained research assistant independently measured each forearm twice; the second reading occurred one week following the initial reading. Our segmental analysis of the natural bow of the radius revealed an apex radial bow of 1.5 degrees in the proximal-third, 6.0 degrees in the middle-third, and 1.7 degrees in the distal-third. Based on these measurements, we applied a population-based correction factor of 6 degrees apex radial to AP measurements of the middle-third of the radius (i.e. apex radial measurements were decreased by 6 degrees, and apex ulnar measurements were increased by 6 degrees). Corrections were not applied to the distal and proximal segment measurements because their mean values were within the accepted margin of reader error of ± 5 degrees^{27,28}. Inter- and intra-rater reliability was assessed using limits of agreement.

Statistical Methods

Data were managed using Microsoft Excel (Microsoft Corporation, Redmond, WA), and analyses were conducted using SPSS v.17.0 (SPSS Inc., Chicago, IL). Logistic regression was used to assess the relationship between patient and fracture characteristics and the failure of closed reduction and casting. Initially, univariate associations were explored. Possible non-linearities were identified by categorizing continuous variables and comparing the odds of failure between categories. Then, a multivariate model was fit to the data in order to assess the relative importance of factors in predicting failure. Finally, a simple predictive model was constructed using a manual backwards stepwise procedure; variable removal was based on significance, effects on the parameter estimates for remaining variables, and changes in the model C-statistic. The C-statistic is a global measure of model accuracy. In secondary analysis, we used Student's t-test and chi-square tests to compare continuous variables between those who went straight to surgery and those who initially underwent an attempt at closed reduction and casting.

RESULTS

There were 1164 children with diaphyseal both-bone fractures treated at our institution during the study period. We confirmed 389 complete both-bone fractures on pre-reduction AP and lateral radiographs. Sixty-eight patients met exclusion criteria, including 33 who were missing either an AP or lateral pre-reduction radiograph. Of the 321 both-bone fracture patients that remained, 34 (10.6%, CI₉₅ 7.5% to 14.6%) underwent surgery that same day and 287 had closed reduction and casting. Five patients were lost to follow-up following closed reduction and casting, leaving 282 participants for the primary analyses estimating the rate of failure of non-operative treatment and identifying characteristics associated with failure of non-operative treatment.

Participants are described in TABLE 1. The mean age was 8.5 years and 63% were male. Bayonet apposition with shortening was present in 27% of cases. For the radius, proximal-third fractures accounted for 24% of fractures, 37% were middle-third, and 39% were distal-third. For the ulna, 16% were proximal-third, 44% were middle-third, and 40% were distal-third fractures. The mean largest angle present on AP or lateral radiograph at presentation was 31 degrees for both the radius and the ulna. The majority of radius fractures were apex volar (89%) and apex radial (54%).

In our study population, 144 (51.1%, CI₉₅ 45.1% to 57.0%) of the 282 participants exceeded the acceptable angulation criteria at follow-up. There were 53 patients from the non-operative treatment cohort who later underwent surgery. Of these, one patient did not have angulation data available prior to surgery, 40 had exceeded the angulation criteria, and 12 did not exceed the angulation criteria at the time of surgery (TABLE 2). The mean time to surgery was 10.6 days (SD= 6.7 days). Six patients received fracture re-manipulation with closed reduction and casting.

In the univariate logistic regression analysis, there was a non-linear effect of age with an apparent threshold at 10 years for both males and females; older participants (≥ 10 years) were more likely to fail (TABLE 3). Those with proximal level fractures, those with a smaller angle at presentation, and those with radius fractures having apex ulnar directionality were also more likely to fail. The odds of failure were nearly three-fold higher for the middle-third radius fractures compared to distal-third fractures (OR= 2.52, CI₉₅ 1.44 to 4.41), and for middle-third ulna fractures compared with distal-third ulna fractures (OR= 2.88, CI₉₅ 1.69 to 4.92).

The multivariate model (inclusive of all main effects) suggested that age, level of fracture for the radius, and angle of fracture for the ulna were the key predictors of failure (TABLE 4). The overall C-statistic for this model was high (0.814, CI₉₅ 0.763 to 0.864). Without considering complex interactions, the final predictive model included three binary variables: age ≥ 10 years v. 0–9 years, angle of fracture for the ulna < 15 degrees v. ≥ 15 degrees, and level of fracture for the radius proximal v. middle and distal (Table 5). The C-statistic for this derived model was 0.762 (CI₉₅ 0.705 to 0.818).

Of the 144 participants who failed closed reduction and casting within the four week period, 80 (55.6%) had their first radiographic evidence of failure during the first week post-reduction, 34 (23.6%) failed during the second week, 23 (16.0%) failed during the third week, and 7 (4.9%) failed during the fourth week (FIGURE 2). Immediately following closed reduction and casting, 75 participants (27%) exceeded the angulation criteria, indicating these participants were inadequately reduced. Of these 75, 63 failed to meet angulation criteria at the fourth week of follow-up (84%).

Our intra-rater limits of agreement suggested that 95% of the time repeat measurements were within 3 to 3.5 degrees of the initial reading. Our inter-rater limits of agreement suggest that 95% of the time readings between reviewers were within 4.3 degrees of each other. Finally, secondary analysis evaluating those who went immediately to surgery revealed that they were significantly older, had proximal level fractures, had a smaller degree of initial angulation, and the majority had bayonet apposition with shortening (TABLE 6).

DISCUSSION

Over time the treatment of both-bone forearm shaft fractures in children has become increasingly surgical in nature^{1,17–19,29,30}. However, before closed reduction and casting should be supplanted as the preferred method of treatment for these injuries, clinicians must

understand the circumstances in which surgery may be more advantageous²⁹. To our knowledge this is the largest shaft-specific complete both-bone forearm fracture study to characterize the early radiographic outcomes of non-operatively treated children. This is also the first known study to use a multivariate statistical analysis to model failure probability. Identifying those injuries most likely to fail non-operative treatment could provide key decision making information both for parents and the clinicians caring for children with these injuries.

Evaluation of 282 complete both-bone forearm shaft fractures treated by closed reduction and casting revealed that 51% of participants failed to meet angulation criteria with non-operative treatment within four weeks of follow-up. Our findings are consistent with previous studies. Kay et al. determined that 64% of their patients older than age 10 failed closed reduction and casting using an angulation criterion of 10 degrees⁴. Thomas et al. found that 39% of their patients with mid-shaft fractures had unsatisfactory results due to an angulation of >10 degrees, loss of range of motion, or a cosmetic deformity³. The results of our multivariate analysis indicate that those at highest risk of failure following closed reduction and casting are patients 10 years or older (OR= 2.79, CI₉₅ 1.47 to 5.29), those with proximal radius fractures (OR= 6.81, CI₉₅ 3.28 to 14.14), and those with initial ulna angulations <15 degrees (OR= 2.94, CI₉₅ 1.49 to 5.83). While the findings for age and level of fracture are intuitive, it is initially perplexing that a lesser initial angle of the ulna predicts failure, though the association was strong and consistent. We suggest that this is due to the relatively intact ulna allowing uneven static and dynamic forces to negatively influence the position of the radius. Re-angulation occurs as swelling decreases and the tensions afforded by the interosseous membrane and attaching muscles change. The location of attachment and relative strength of these structures will affect the position of the healing bones²².

Over half of participants who failed angulation criteria at follow-up had their first radiographic evidence of failure during the first week, with 95% failing within three weeks. Voto et al. made a similar observation, stating that the majority of fractures that re-angulated in their study did so by two weeks⁸. Our results also showed that 84% of participants who had post-reduction angulations exceeding the acceptable angulation criteria failed to meet the criteria at follow-up, illustrating that residual angulation generally does not improve within the first month following reduction. This suggests that anatomic reduction is imperative. Patients should also be monitored weekly within the first month in order to properly monitor closed fracture care. We note that bayonet apposition with shortening, leading to severe compromise of the interosseous space, was present in all 12 of our participants who underwent surgery though they did not fail the angulation criteria. This shows that clinicians base decisions on factors other than angulation alone. Based on limits of agreement, we found the maximum deviation between any two measurements was 4.3 degrees, which is consistent with previous estimates of variation in radiographic fracture angulation measurements of ± 5 degrees^{27,28}.

The anatomy of the forearm dictates its function. In 1959, Sage described the bow of the radius to be 9.3 degrees³¹. His approximation used the entire bone to estimate the bow of the radius, which averaged over the subtle curvatures of each segment. Clinically however, forearm shaft fractures are analyzed by thirds. After we evaluated 30 normal forearms and found a mean angulation of 6.0 degrees apex radial in the middle-third, we felt it appropriate to account for the natural bow of the radius using a population based correction factor. Since the mean angulation value for the distal and proximal thirds were within the range of error for our measurements, we chose to not correct these segments. In 1986, Roberts employed a similar technique and found a mean angulation of 3.7 degrees in the middle third of the radius³². Other methods of approximating the natural bow of the radius using axis deviation have been described and applied, although the calculations can be cumbersome in practice⁹.

Our hope is that future studies of forearm shaft fractures will apply methods similar to ours to account for the anatomy of the radius.

The importance of the normal curvature of the radius is recognized for its role in the normal rotation of the radius about the ulna^{6,33–35}. Normal range of forearm motion is approximately 71 degrees pronation and 84 degrees supination³⁶. Schemitsch and Richards, who examined both-bone fracture malunions in adults, claimed that loss of forearm rotation and grip strength could be expected if the normal radial bow magnitude and location were not restored relative to the non-injured extremity within 4–5%³⁵. Clinical studies of both-bone forearm shaft fractures in children show that range of motion is significantly affected by residual angulation of fractures. Daruwalla et al. found that 53% of patients had limited range of motion, and 13% had greater than 40 degrees of loss¹⁰. Carey et al. revealed that 60% of their patients 11–15 years had residual loss of motion, up to 30 degrees¹¹. Cadaveric studies described the loss of rotation expected with varying degrees of angulation. Matthews et al. found that approximately 30%, or 60 degrees, loss of pronation-supination resulted with an angulation of 20 degrees⁵. Tarr et al. described angulations of 15 degrees causing greater than 27% loss in range of motion, with middle-third deformities causing the greatest loss⁶. Sarmiento et al. confirmed these findings and showed greater supination losses in middle-third forearm shaft fractures and greater pronation losses in distal-third forearm shaft fractures⁷.

The criteria for failure that we used changed based on age and level of fracture, an approach based on biological phenomena and well supported in the literature^{9,13,19,22–26}. Though paradoxical outcomes occur (poor alignment with no loss of motion and anatomic alignment with significant loss of motion), there is a direct relationship between increasing radial shaft angulation and loss of forearm rotation^{5–7}. However, the remarkable remodeling potential that the radius and ulna possess in children is an important confounding factor of this relationship²⁶. Clinicians account for remodeling in their treatment decisions, allowing post-reduction angulations of greater than 10 degrees in younger children. Most clinicians agree that prognosis changes as the fracture level progresses from distal to proximal due to a greater capacity for remodeling at the distal end^{4,15,32,37}. The distal forearm in younger children is particularly adept at correcting non-anatomic alignments because 75% of the radial growth occurs at the distal physis¹⁶. Remodeling capacity declines with age, and is greatly diminished as females reach 8 years and males 10 years of age^{16,26}. Since remodeling capacity decreases with age and more proximal level shaft fractures, residual angulation of middle and proximal shaft fractures is more problematic in older children^{2,15,26}. The angulation criteria used in our study account for likely remodeling capacity.

One may argue as to what amount of loss of motion is clinically relevant. Morrey et al. found that most activities of daily living could be performed with only 100 degrees of rotation, 50 degrees of both pronation and supination³⁶. Others have found that patients are often unaware of their deficits of 35 up to 60 degrees loss of forearm motion due to compensation with shoulder abduction, and that cosmesis is often the patient's main concern^{2,10–13}. However, even if a child is unaware of a moderate loss of forearm rotation or daily activities are not impaired, it seems inappropriate to place a child at this disadvantage when better options exist. Certainly, informed decision makers would choose normal range-of-motion.

The imperfect correlation between residual angulation and loss of forearm rotation fuels the debate over the proper management of both-bone forearm fractures, particularly in older pediatric populations^{11,13}. Several studies show non-operative treatment to have low rates of re-angulation^{8,37}. However, high numbers of distal forearm fractures near the metaphysis

skew these results due to their more forgiving nature compared to mid-shaft fractures³⁸. Fracture re-manipulation with closed reduction and casting is another viable option if initial reduction is insufficient. Operative techniques, including ESIN, have been shown to effectively prevent re-angulation^{17–21}. However, surgery carries its own risk of complications, and it is wise to remember Sarmiento's advice that closed fracture treatment must not be abandoned for newer, less proven, surgical techniques, and that surgical intervention does not always restore a normal range of forearm motion^{7,39}. The current treatment protocol used at our institution implements the same criteria for acceptable shaft angles as indicated in our study and mimics the criteria proposed by Price et al.¹³. Bayonet apposition is considered acceptable, unless the interosseous space is significantly compromised, and malrotation of less than 45 degrees is accepted. Our audit of surgical decision making at our institution revealed that only 40 of the 144 participants who did not meet radiographic angulation standards actually underwent surgery. Barriers to demanding optimal radiographic outcomes include limited operating room access, patient choice, lack of adequate follow-up, perceived potential for remodeling, lack of noticeable range of motion loss despite angulation, and differing opinions among surgeons in our practice.

Our work must be interpreted within the context of the study design. Our predictive model was derived from a retrospective cohort, and future prospective validation is required. Another limitation of our study is that we used angular data from only two planes. Concurrent angulation in both the radioulnar and dorsoventral planes indicates a maximum angle that is out of the plane of either view, whereby the actual magnitude and direction can be approximated using geometry⁹. We also note that a cohort of our both-bone shaft fractures went immediately to surgery, suggesting that our prediction of failure may in fact be underestimated due to removal of the potentially more severe cases. We acknowledge that re-angulation may occur beyond one month of follow-up, though our results indicate it is more likely early in treatment. Finally, although the most accurate comparison for the normal bow of the radius would be personalized, based on comparison to an individual's "normal" forearm, the retrospective nature of our data prohibited this evaluation.

Closed reduction and casting plays an essential role in fracture care. However, clinicians must recognize when patients are at risk for suboptimal outcomes. We do not propose abandonment of closed reduction and casting for forearm shaft fractures. On the contrary, we support a prudent approach that evaluates a patient's likelihood of failing angulation criteria with closed reduction and casting, to appropriately balance the risk and potential benefits. According to this study, those at highest risk are patients 10 years or older, those with proximal-third radius fractures, and ulna fracture angles less than 15 degrees. These patients should be considered for surgery. Inadequate initial reduction and bayonet apposition with shortening, if the interosseous space is severely compromised, may also be important factors in surgical decision making. It appears that the greatest chance of failure occurs early in non-operative treatment, and generally speaking, residual angulation does not improve in the first month. Proper management of complete forearm fractures in children is challenging, however, clinicians can use predictors of age, level of fracture, initial angulation, and sufficiency of initial reduction to guide treatment and attempt to achieve the best possible outcome for the patient.

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FIGURE 1.

(A) Measurement of fracture level including determination of the distal end of the shaft. (B) Pre-reduction radiograph of a 10 y.o. male with a both-bone forearm fracture. The lateral view shows a proximal level radius fracture with 25° apex volar angulation. (C) Post-reduction radiograph shows the radius with 18° apex volar angulation. (D) At 4 weeks of follow-up, angulation of the radius is 19° apex volar with significant compromise of the interosseous space in the AP view.

FIGURE 2.

Histogram illustrating the week during which the first radiographic evidence of failure occurred for the 144 participants who eventually failed at follow-up.

Table 1

Characteristics of participants who underwent closed reduction, grouped by whether or not they exceeded angulation criteria. Data are given as mean and standard deviation or frequency and percent, as appropriate.

	All participants with angulation data N=282	Participants who did not fail by angulation criteria N=138	Participants who failed by angulation criteria N=144	P-value
Age at fracture	8	(3)	(3)	0.011
Sex				
Male	171	(60.6)	81	(56.3)
Female	111	(39.4)	63	(43.8)
0.123				
Arm				
Left	152	(53.9)	71	(51.4)
Right	130	(46.1)	67	(48.6)
0.419				
Bayonet Apposition present with fracture	75	(26.6)	30	(21.7)
0.071				
Radius				
Level of fracture				
Proximal	68	(24.1)	11	(8.0)
Middle	104	(36.9)	50	(36.2)
Distal	110	(39.0)	77	(55.8)
0.001				
Largest initial angle of fracture				
Mean (SD)	31.2	(19.5)	35.4	(21.3)
0° to <15°	68	(24.1)	27	(19.6)
15° to <30°	79	(28.0)	31	(22.5)
30° to <45°	72	(25.5)	35	(25.4)
45°+	63	(22.3)	45	(32.6)
0.001				
Largest angle of fracture at failure				
Mean (SD)	12.8	(6.8)	8.9	(4.0)
0.001				
Direction of fracture on lateral view				
Apex Dorsal	32	(11.3)	13	(9.4)
Apex Volar	250	(88.7)	125	(90.6)
0.318				
Direction of fracture on AP view				
Apex Radial	152	(53.9)	85	(61.6)
0.011				

	All participants with angulation data N=282	Participants who did not fail by angulation criteria N=138	Participants who failed by angulation criteria N=144	P-value
Apex Ulnar	130 (46.1)	53 (38.4)	77 (53.5)	
Ulna				
Level of fracture				
Proximal	45 (16.0)	5 (3.6)	40 (27.8)	
Middle	123 (43.6)	54 (39.1)	69 (47.9)	<0.001
Distal	114 (40.4)	79 (57.2)	35 (24.3)	
Largest initial angle of fracture				
mean (SD)	31.1 (20.6)	37.8 (21.5)	24.8 (17.7)	<0.001
0° to <15°	64 (22.7)	16 (11.6)	48 (33.3)	
14° to <30°	95 (33.7)	41 (29.7)	54 (37.5)	<0.001
30° to <45°	59 (20.9)	38 (27.5)	21 (14.6)	
45°+	64 (22.7)	43 (31.2)	21 (14.6)	
largest angle of fracture at failure				
Mean (SD)	9.0 (5.1)	7.0 (3.7)	11.0 (5.5)	<0.001
Direction of fracture on lateral view				
Apex Dorsal	26 (9.2)	11 (8.0)	15 (10.4)	0.478
Apex Volar	256 (90.8)	127 (92.0)	129 (89.6)	
Direction of fracture on AP view				
Apex Radial	164 (58.2)	87 (63.0)	77 (53.5)	0.103
Apex Ulnar	118 (41.8)	51 (37.0)	67 (46.5)	

Table 2

Description of participants who underwent closed reduction grouped by whether or not they exceeded angulation criteria and whether or not they went to surgery. Data are given as mean and standard deviation or frequency and percent, as appropriate.

	No failure by angulation criteria and no surgery N=126	No failure by angulation criteria but had surgery N=12	Failure by angulation criteria but no surgery N=104	Failed by angulation criteria and had surgery N=40
Age at fracture	8	(3)	(4)	(3)
Sex				
Male	80	(63.5)	54	(67.5)
Female	46	(36.5)	50	(32.5)
Arm				
Left	66	(52.4)	58	(57.5)
Right	60	(47.6)	46	(42.5)
Bayonet Apposition present with fracture	22	(17.5)	27	(45.0)
Radius				
Level of fracture				
Proximal	8	(6.3)	41	(40.0)
Middle	46	(36.5)	39	(37.5)
Distal	72	(57.1)	24	(22.5)
Largest initial angle of fracture				
Mean (SD)	36.5	(21.3)	28.2	(17.2)
0° to <15°	21	(16.7)	23	(45.0)
15° to <30°	30	(23.8)	42	(15.0)
30° to <45°	32	(25.4)	27	(25.0)
45°+	43	(34.1)	12	(15.0)
Largest angle of fracture at failure				
Mean (SD)	9.0	(4.0)	16.6	(8.7)
Direction of fracture on lateral view				
Apex Dorsal	11	(8.7)	13	(15.0)
Apex Volar	115	(91.3)	91	(85.0)
Direction of fracture on AP view				
Apex Radial	79	(62.7)	53	(35.0)

	No failure by angulation criteria and no surgery N=126	No failure by angulation criteria but had surgery N=12	Failure by angulation criteria but no surgery N=104	Failed by angulation criteria and had surgery N=40
Apex Ulnar	47 (37.3)	6 (50.0)	51 (49.0)	26 (65.0)
Ulna				
Level of fracture				
Proximal	4 (3.2)	1 (8.3)	26 (25.0)	14 (35.0)
Middle	48 (38.1)	6 (50.0)	53 (51.0)	16 (40.0)
Distal	74 (58.7)	5 (41.7)	25 (24.0)	10 (25.0)
Largest initial angle of fracture				
mean (SD)	39.0 (21.4)	24.4 (18.2)	25.6 (16.7)	22.8 (20.2)
0° to <15°	10 (7.9)	6 (50.0)	30 (28.8)	18 (45.0)
15° to <30°	38 (30.2)	3 (25.0)	42 (40.4)	12 (30.0)
30° to <45°	38 (30.2)	0 (0.0)	16 (15.4)	5 (12.5)
45° +	40 (31.7)	3 (25.0)	16 (15.4)	5 (12.5)
Largest angle of fracture at failure				
Mean (SD)	7.1 (3.8)	5.9 (2.8)	10.5 (5.7)	12.0 (4.8)
Direction of fracture on lateral view				
Apex Dorsal	8 (6.3)	3 (25.0)	13 (12.5)	2 (5.0)
Apex Volar	118 (93.7)	9 (75.0)	91 (87.5)	38 (95.0)
Direction of fracture on AP view				
Apex Radial	80 (63.5)	7 (58.3)	54 (51.9)	23 (57.5)
Apex Ulnar	46 (36.5)	5 (41.7)	50 (48.1)	17 (42.5)

Table 3

Univariate logistic regression models showing how each participant and fracture characteristic is independently associated with the odds of failure.

Variable	Reference	Odds Ratio	95% CI	P-Value
Age*				
10+	0–9	2.73	(1.60 – 4.64)	0.0002
Female v Male		1.46	(0.90 – 2.36)	0.1240
Left v Right		1.21	(0.76 – 1.94)	0.4190
Bayonet apposition v none		1.64	(0.96 – 2.80)	0.0720
Radius				
Level				
Middle	Proximal	0.21	(0.10 – 0.44)	0.0000
Distal		0.08	(0.04 – 0.18)	0.0000
Angle				
15–29°	<15°	1.02	(0.53 – 1.98)	0.9540
30–44°		0.70	(0.36 – 1.36)	0.2900
45°+		0.26	(0.13 – 0.55)	0.0000
Direction				
(Lateral view) Volar v dorsal		0.68	(0.32 – 1.45)	0.3200
(AP view) Ulnar v radial		1.84	(1.15 – 2.96)	0.0110
Ulna				
Level				
Middle	Proximal	0.16	(0.06 – 0.43)	0.0000
Distal		0.06	(0.02 – 0.15)	0.0000
Angle				
15–29°	<15°	0.44	(0.22 – 0.88)	0.0210
30–44°		0.18	(0.09 – 0.40)	0.0000
45°+		0.16	(0.08 – 0.35)	0.0000
Direction				
(Lateral view) Volar v dorsal		0.75	(0.33 – 1.68)	0.4790
(AP view) Ulnar v radial		1.48	(0.92 – 2.39)	0.1040

* In these analyses, there was a change in odds of failure at age ≥ 10 , providing a single cut point.

Table 4

Multivariate model considering only main effects and including all variables. The overall C-statistic for this model is 0.814 (CI₉₅ 0.763 to 0.864).

Variable	Reference	Odds ratio	95% CI	P-Value
Age				
10+	0–9	2.79	(1.47 – 5.29)	0.0017
Female v Male				
		1.59	(0.87 – 2.89)	0.1292
Left v Right				
		1.08	(0.60 – 1.94)	0.7968
Bayonet apposition v none				
		1.32	(0.66 – 2.64)	0.4333
Radius				
Level				
Middle	Proximal	0.31	(0.10 – 0.99)	0.0473
Distal		0.08	(0.01 – 1.08)	0.0575
Angle				
15–29°	<15°	2.98	(1.08 – 8.20)	0.0350
30–44°		2.21	(0.71 – 6.86)	0.1709
45°+		0.85	(0.22 – 3.25)	0.8084
Direction				
(AP view) Ulnar v radial		1.57	(0.73 – 3.38)	0.2444
(Lateral view) Volar v dorsal		0.63	(0.15 – 2.69)	0.5341
Ulna				
Level				
Middle	Proximal	0.54	(0.13 – 2.25)	0.4009
Distal		1.06	(0.07 – 15.96)	0.9680
Angle				
15–29°	<15°	0.35	(0.12 – 0.97)	0.0425
30–44°		0.25	(0.07 – 0.86)	0.0277
45°+		0.41	(0.10 – 1.67)	0.2118
Direction				
(AP view) Ulnar v radial		1.27	(0.27 – 6.03)	0.7674
(Lateral view) Volar v dorsal		1.04	(0.49 – 2.20)	0.9144

Table 5

Odds ratios for a simple model predicting failure based on angulation criteria following a closed reduction of a forearm fracture. The overall C-statistic for this model is 0.762 (CI₉₅ 0.705 to 0.818).

Variable	Odds Ratio	95%CI	P-value
Age (10+ v 0–9)	3.00	(1.68 – 5.35)	0.0002
Proximal fracture (radius)	6.81	(3.28 –14.14)	0.0000
Fracture angle <15° (ulna)	2.94	(1.49 – 5.83)	0.0020

Table 6

Description of participants and fractures grouped by whether or not they had an attempt at closed reduction and casting. Data are given as mean and standard deviation or frequency and percent, as appropriate.

	All Patients N=321	Participants who went straight to surgery N=34	Participants with closed reduction & cast attempt N=287	P-value
Age at fracture	9 (3)	12 (3)	8 (3)	<0.001
Sex				
Male	201 (62.6)	25 (73.5)	176 (61.3)	0.164
Female	120 (37.4)	9 (26.5)	111 (38.7)	
Arm				
Left	168 (52.3)	14 (41.2)	154 (53.7)	0.168
Right	153 (47.7)	20 (58.8)	133 (46.3)	
Bayonet Apposition present with fracture	98 (30.5)	19 (55.9)	79 (27.5)	0.001
Radius				
Level of fracture				
Proximal	86 (26.8)	18 (52.9)	68 (23.7)	
Middle	115 (35.8)	8 (23.5)	107 (37.3)	0.001
Distal	120 (37.4)	8 (23.5)	112 (39.0)	
Largest initial angle of fracture				
Mean (SD)	30.0 (19.2)	20.1 (14.4)	31.2 (19.4)	<0.001
0° to <15°	85 (26.5)	16 (47.1)	69 (24.0)	
15° to <30°	91 (28.3)	11 (32.4)	80 (27.9)	0.008
30° to <45°	79 (24.6)	5 (14.7)	74 (25.8)	
45°+	66 (20.6)	2 (5.9)	64 (22.3)	
Direction of fracture on lateral view				
Apex Dorsal	43 (13.4)	9 (26.5)	34 (11.8)	0.018
Apex Volar	278 (86.6)	25 (73.5)	253 (88.2)	
Direction of fracture on AP view				
Apex Radial	171 (53.3)	16 (47.1)	155 (54.0)	0.443
Apex Ulnar	150 (46.7)	18 (52.9)	132 (46.0)	

Ulna	All Patients N=321	Participants who went straight to surgery N=34	Participants with closed reduction & cast attempt N=287	P-value
Level of fracture				
Proximal	56 (17.4)	11 (32.4)	45 (15.7)	
Middle	140 (43.6)	15 (44.1)	125 (43.6)	0.028
Distal	125 (38.9)	8 (23.5)	117 (40.8)	
Largest initial angle of fracture				
mean (SD)	29.9 (20.3)	20.0 (13.7)	31.1 (20.6)	<0.001
0° to <15°	79 (24.6)	14 (41.2)	65 (22.6)	
15° to <30°	109 (34.0)	13 (38.2)	96 (33.4)	0.027
30° to <45°	66 (20.6)	5 (14.7)	61 (21.3)	
45°+	67 (20.9)	2 (5.9)	65 (22.6)	
Direction of fracture on lateral view				
Apex Dorsal	35 (10.9)	7 (20.6)	28 (9.8)	0.055
Apex Volar	286 (89.1)	27 (79.4)	259 (90.2)	
Direction of fracture on AP view				
Apex Radial	189 (58.9)	21 (61.8)	168 (58.5)	0.718
Apex Ulnar	132 (41.1)	13 (38.2)	119 (41.5)	