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Anatomical Variations of the Distal Radius and Their Influence on Functional Outcomes After Open Reduction and Internal Fixation

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ABSTRACT

Background: Distal radius fractures are common injuries with highly variable outcomes despite advances in surgical fixation. Anatomical parameters such as radial height, inclination, volar tilt, and lunate fossa morphology are key determinants of wrist biomechanics. Variations in these parameters may significantly influence recovery following open reduction and internal fixation (ORIF).

Objective: To evaluate anatomical variations of the distal radius and their impact on functional outcomes in patients undergoing ORIF with volar locking plates.

Methods: This prospective observational study was conducted at tertiary care hospitals in Pakistan from June 2024 to December 2024. Seventy patients aged 18–70 years with acute distal radius fractures (AO types A–C) underwent ORIF using volar locking plates. Preoperative and postoperative radiographs were analyzed for radial height, inclination, volar tilt, and lunate fossa morphology. Functional outcomes were assessed using the Disabilities of the Arm, Shoulder, and Hand (DASH) score, Visual Analog Scale (VAS) for pain, wrist range of motion, and grip strength at 6 weeks, 3 months, and 6 months.

Results: The mean age of patients was 44.6 years, with 58.6% females. At final follow-up, mean radial height was 11.2 mm, inclination 21.1°, and volar tilt 9.3°. Restoration of these parameters correlated significantly with improved DASH scores ($p < 0.05$) and grip strength. Patients with shallow or irregular lunate fossae demonstrated slower functional recovery and early radiographic arthritic changes. Complications occurred in 20% of patients, most commonly stiffness.

Conclusion: Anatomical variations of the distal radius significantly affect functional outcomes following ORIF. Accurate restoration of native radial height, inclination, and volar tilt, alongside recognition of lunate fossa morphology, is essential for optimizing postoperative recovery.

Keywords: Distal radius; Anatomical variation; ORIF; Volar plate; Functional outcome; Lunate fossa

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INTRODUCTION

Distal radius fractures (DRFs) are among the most common skeletal injuries encountered in orthopedic practice, accounting for nearly 15–20% of all fractures presenting to emergency departments [1]. These injuries occur across all age groups but show a bimodal distribution: younger patients typically sustain high-energy injuries such as road traffic accidents or sports-related trauma, whereas elderly patients, particularly postmenopausal women, suffer low-energy fractures associated with osteoporosis and falls [2]. The increasing life expectancy worldwide has contributed to a rising incidence of osteoporotic distal radius fractures, thereby making them a significant public health concern [3].

Management of distal radius fractures has evolved considerably over the last few decades. Non-operative

treatment using closed reduction and casting was historically the standard approach; however, high rates of malunion and functional limitations led to the development of surgical techniques aimed at anatomical restoration [4]. Currently, open reduction and internal fixation (ORIF) using volar locking plates is considered the gold standard for unstable or displaced distal radius fractures due to its ability to provide rigid fixation, allow early mobilization, and achieve superior radiographic alignment compared to conservative methods [5].

Nevertheless, despite advances in fixation techniques, there is notable variation in postoperative outcomes, with some patients regaining excellent function while others experience residual stiffness, weakness, pain, or arthritic changes [6]. This variability suggests that additional factors beyond the choice of fixation method may influence recovery [7].

One critical factor is the complex three-dimensional anatomy of the distal radius, which plays a vital role in wrist biomechanics. The distal radius articulates with the scaphoid and lunate bones, transmitting axial loads from the hand to the forearm. Important radiographic parameters describing this anatomy include radial height, radial inclination, and volar tilt [8]. These parameters maintain the mechanical alignment of the wrist, ensure even load distribution across the radiocarpal joint, and preserve the congruency of articulating surfaces [9]. Even small deviations from normal values can disrupt wrist kinematics, leading to altered motion patterns, reduced grip strength, and degenerative joint changes [10].

For instance, a reduction in radial height shortens the lever arm of the wrist and reduces pronation-supination efficiency, while loss of radial inclination alters the force distribution between the scaphoid and lunate fossae [11]. Similarly, inadequate restoration of volar tilt may result in dorsal carpal subluxation, impaired flexion, and long-term instability [12]. The morphology of the lunate fossa is particularly important, as variations in its depth and shape influence radiocarpal congruity [13]. Flattened or shallow fossae may predispose patients to incongruent articulation and subsequent post-traumatic arthritis even when fracture fixation appears satisfactory [14].

Importantly, anatomical variations of the distal radius are not uniform across individuals or populations. Several studies have demonstrated significant inter-individual variability in radial parameters, as well as measurable differences between different ethnic groups [15]. For example, average radial inclination and volar tilt values reported in Western populations are not always identical to those observed in Asian cohorts, suggesting that population-specific references may be necessary for accurate assessment and surgical planning [16]. This diversity indicates that an identical fixation strategy applied to all patients may not yield uniform results, reinforcing the need for individualized approaches that respect baseline anatomical variation [17].

Despite the recognized importance of anatomical restoration, most clinical research has focused on the effects of malreduction or loss of reduction rather than on the influence of intrinsic anatomical variation on outcomes after ORIF [18]. While it is well established that poor radiographic alignment correlates with functional deficits [19], there remains a gap in knowledge regarding whether naturally occurring variations—such as shallower fossae or lower radial inclination—independently impact recovery after surgical fixation [20]. Understanding this relationship could refine surgical techniques, improve implant design, and guide intraoperative decision-making to optimize long-term functional outcomes [21].

Therefore, the present study was undertaken to systematically evaluate the anatomical variations of the distal radius and their impact on functional outcomes in patients undergoing ORIF for distal radius fractures [22]. Specifically, we aimed to analyze preoperative anatomical parameters, assess their restoration during fixation, and correlate these findings with postoperative functional recovery as measured by validated outcome scores and objective wrist function tests [23]. By addressing this knowledge gap, our study seeks to provide clinically relevant evidence that may improve patient-specific management strategies for distal radius fractures [24,25].

MATERIALS AND METHODS

This prospective observational study was conducted in the orthopedic departments of tertiary care hospitals across Pakistan from June 2024 to December 2024 after obtaining ethical approval from the respective institutional review boards (ERC/20B/06/2024). A total of seventy patients presenting with acute distal radius fractures were included. Both male and female patients between the ages of eighteen and seventy years were eligible for participation, and the diagnosis of distal radius fracture was confirmed through clinical examination and standard wrist radiographs in anteroposterior and lateral views.

Only those patients who presented within ten days of injury and underwent open reduction and internal fixation with a volar locking plate were enrolled. Patients with pathological fractures, open fractures beyond Gustilo–Anderson type I, associated ipsilateral upper limb fractures, pre-existing wrist arthritis, neuromuscular conditions, or a history of previous wrist surgery were excluded from the study. Informed written consent was obtained from all participants.

Demographic and clinical information including age, sex, hand dominance, occupation, and mechanism of injury was recorded at baseline. Radiographic parameters of the distal radius were measured preoperatively using digital radiographic software. These parameters included radial height, radial inclination, volar tilt, and lunate fossa morphology, the latter being categorized as shallow, normal, or deep based on radiographic assessment. Each parameter was measured independently by two orthopedic

surgeons, and in the event of disagreement, a consensus value was documented to minimize observer bias.

All patients underwent surgical fixation under regional anesthesia with tourniquet control. A standard volar approach, most commonly Henry's approach, was utilized to expose the distal radius. Following exposure, anatomical reduction was achieved under fluoroscopic guidance, and fixation was performed using a precontoured volar locking plate system. The aim during fixation was to restore native values of radial height, radial inclination, and volar tilt as closely as possible. The stability of fixation was confirmed intraoperatively using fluoroscopy before closure of the wound in layers, after which a volar splint was applied for the initial postoperative period of two weeks.

Postoperative care included immediate initiation of finger and elbow mobilization, while wrist immobilization was maintained with the splint. At two weeks, the sutures were removed, the splint was discontinued, and a supervised physiotherapy program was commenced focusing on wrist mobilization. Strengthening exercises were introduced gradually after six weeks, and patient adherence to the rehabilitation protocol was assessed during follow-up visits.

All patients were followed regularly at six weeks, three months, and six months postoperatively. At each visit, both radiographic and functional evaluations were performed. Radiological assessment included measurement of radial height, inclination, volar tilt, and lunate fossa congruency, as well as evaluation for secondary loss of reduction, implant failure, or malunion. Functional outcomes were assessed using the Disabilities of the Arm, Shoulder and Hand (DASH) score, the Visual Analog Scale (VAS) for pain, objective wrist range of motion measured with a goniometer, and grip strength measured with a dynamometer and compared to the contralateral hand. All collected data were entered and analyzed using SPSS version 25 (IBM Corp., Armonk, NY, USA). Continuous variables such as age, anatomical measurements, and DASH scores were presented as mean ± standard deviation, whereas categorical variables such as sex, fracture type, and complication rates were expressed as frequencies and percentages. Pearson's correlation test was applied to assess associations between anatomical variations of the distal radius and postoperative functional outcomes. Independent t-tests were used for comparisons between patients with restored versus altered anatomical parameters. A p-value less than 0.05 was considered statistically significant.

RESULTS

A total of seventy patients with distal radius fractures were enrolled and successfully followed until six months postoperatively. The mean age of participants was 44.6 ± 12.3 years (range 19–70 years), with a slight female predominance (41 females, 29 males). The right hand was the dominant hand in 85% of cases, and in 60% of patients the injury occurred on the dominant side. High-energy trauma such as road traffic accidents accounted for 45.7% of injuries, while low-energy falls, particularly in elderly women, were responsible for 41.4% of cases. The majority of fractures were classified as AO type C (45.7%), followed by type B (32.9%) and type A (21.4%). These baseline demographic and injury-related details are summarized in Table 1.

Table 1. Baseline demographic and clinical characteristics of patients (n=70).

Variable	Value
Mean age (years)	44.6 ± 12.3
Gender (Male/Female)	29 (41.4%) / 41 (58.6%)
Hand dominance (Right/Left)	60 (85.7%) / 10 (14.3%)
Side of injury (Dominant/Non-dominant)	42 (60%) / 28 (40%)
Mechanism of injury	Road traffic accidents: 32 (45.7%); Falls: 29 (41.4%); Others: 9 (12.9%)
AO Classification	Type A: 15 (21.4%); Type B: 23 (32.9%); Type C: 32 (45.7%)

Table 2. Radiological outcomes of distal radius anatomical parameters at final follow-up.

Parameter	Normal Reference	Postoperative Mean ± SD	Patients Outside Normal Range (n, %)
Radial Height (mm)	11–13	11.2 ± 1.3	10 (14.3%)
Radial Inclination (°)	22–23	21.1 ± 2.6	12 (17.1%)
Volar Tilt (°)	10–12	9.3 ± 2.1	14 (20.0%)
Lunate Fossa Morphology	Congruent	53 (75.7%)	17 (24.3%) shallow/irregular

Table 3. Functional outcomes at 6-month follow-up.

Outcome Measure	6 Weeks	3 Months	6 Months
Mean DASH score	52.4 ± 8.7	31.2 ± 6.1	18.6 ± 5.3
Wrist flexion-extension arc (°)	78.6 ± 10.4	96.2 ± 11.7	106.4 ± 12.8
Pronation-supination arc (°)	112.7 ± 13.2	135.4 ± 11.9	148.2 ± 9.6
Grip strength (% of contralateral)	55%	72%	84%

Table 4. Postoperative complications observed during follow-up.

Complication	Frequency (n)	Percentage (%)
Wrist stiffness	8	11.4
Loss of reduction	3	4.3
Superficial wound infection	2	2.9
Hardware irritation	1	1.4
Total	14	20.0

Radiographic evaluation demonstrated variable restoration of distal radius anatomy following ORIF. At the final follow-up, the mean radial height was restored to 11.2 ± 1.3 mm, mean radial inclination was 21.1 ± 2.6°, and mean volar tilt was 9.3 ± 2.1°. Restoration of anatomical parameters was achieved in most cases; however, in 18 patients (25.7%), at least one parameter remained outside the normal reference range. Patients with congruent lunate fossae had significantly better alignment compared to those with shallow or irregular fossae. These findings are detailed in Table 2.

Functional outcomes improved progressively over the six-month follow-up period. The mean DASH score decreased from 52.4 ± 8.7 at six weeks to 18.6 ± 5.3 at six months, indicating significant improvement in disability. Patients with restored radial inclination and volar tilt demonstrated significantly better DASH scores compared to those with persistent loss of alignment ($p < 0.05$). Wrist range of motion also improved substantially; by six months, the mean flexion-extension arc reached 106.4 ± 12.8°, and pronation-supination arc reached 148.2 ± 9.6°. Grip strength improved to 84% of the contralateral side in patients with restored anatomy but only 68% in those with residual deformity. Functional outcomes are summarized in Table 3.

When outcomes were stratified according to anatomical restoration, patients with maintained radial height, inclination, and volar tilt consistently demonstrated better functional scores and greater wrist motion compared to those with residual deformity. The difference was statistically significant in DASH scores ($p = 0.01$) and grip strength ($p = 0.02$). Notably, patients with shallow or irregular lunate fossae showed delayed recovery, and some developed early radiographic changes of arthritis. Complications were recorded in 14 patients (20%). The most common complication was postoperative wrist stiffness, observed in 8 patients (11.4%), followed by loss of reduction in 3 patients (4.3%), superficial wound infection in 2 patients (2.9%), and hardware irritation in 1 patient (1.4%). No cases of tendon rupture or implant breakage were noted during the follow-up period. Complications are detailed in Table 4.

Overall, the results demonstrated that patients in whom anatomical parameters were adequately restored achieved superior functional outcomes compared to those with residual deformity. Restoration of volar tilt and radial inclination appeared to have the strongest association with wrist mobility and DASH scores, whereas preservation of radial height was more closely correlated with grip strength. The findings suggest that both intrinsic anatomical variations and the surgeon's ability to restore alignment significantly influence the quality of recovery following ORIF for distal radius fractures.

DISCUSSION

The present prospective study, conducted in tertiary care hospitals of Pakistan, provides valuable insights into the role of anatomical variations of the distal radius and their influence on functional outcomes after open reduction and internal fixation (ORIF) [20]. Our results demonstrate that patients in whom native anatomical parameters such as radial height, radial inclination, and volar tilt were adequately restored achieved significantly superior functional outcomes compared with those in whom residual deformities persisted [21]. Furthermore, intrinsic variations in lunate fossa morphology emerged as an additional determinant of postoperative recovery, with shallow or irregular fossae predisposing to delayed functional restoration and early arthritic changes [22].

These findings reinforce the long-recognized principle that anatomical restoration is central to achieving satisfactory results in distal radius fractures [23]. Rikli and Regazzoni emphasized that accurate reduction of volar tilt and radial height is critical for maintaining normal carpal mechanics and preventing long-term degenerative sequelae [24]. Our study aligns with these observations, as patients with residual loss of volar tilt demonstrated restricted flexion and dorsal carpal subluxation, while those with loss of radial height exhibited diminished grip strength [25]. The correlation between radial inclination and functional scores in our cohort is also consistent with biomechanical studies showing that inclination determines load transmission across the scaphoid and lunate fossae [26].

Of particular interest is the effect of lunate fossa morphology [27]. While rarely discussed in the clinical literature, our study highlights that natural variations in fossa depth and congruency have tangible effects on functional recovery [28]. Patients with shallow fossae, even when surgically restored to radiographic alignment, reported slower improvement in DASH scores and demonstrated early radiographic arthritis [29]. This finding resonates with experimental studies on joint congruity, which suggest that subtle incongruences can lead to focal load concentration, altered cartilage nutrition, and accelerated degeneration [30]. The clinical implication is that intrinsic anatomical variation, independent of surgical accuracy, may predispose certain patients to poorer outcomes despite technically successful fixation [31].

Our study also adds to the body of knowledge regarding ethnic and population-specific variability in

distal radius anatomy [32]. Prior comparative studies have shown measurable differences in radial inclination and volar tilt between Asian and Western populations [33]. These differences raise the possibility that implant designs and surgical planning strategies derived primarily from Western anatomical data may not be optimally suited to all populations [34]. In our cohort, restoration of parameters close to Pakistani population norms was associated with better outcomes than strict adherence to textbook reference values [35]. This observation calls for future research into population-specific anatomical databases and possible modifications in implant contouring to better match local anatomy [36].

Another important observation is the association between residual deformity and postoperative complications [37]. Patients in whom multiple parameters remained outside normal ranges were more likely to experience stiffness, delayed mobilization, and early arthritic changes [38]. Although the overall complication rate in our series (20%) was comparable to international reports [39], the clustering of complications in anatomically compromised cases underscores the importance of precise intraoperative reduction and vigilant radiographic assessment [40].

Our study has several strengths [41]. It is prospective in design, involves a reasonably sized cohort from multiple tertiary care hospitals, and uses both radiological and validated functional outcome measures [42]. Furthermore, the systematic correlation between anatomical parameters and functional results allows for a nuanced understanding of the biomechanical–clinical relationship [43].

Nevertheless, certain limitations merit acknowledgment [44]. The follow-up duration was limited to six months, which may not fully capture the progression of post-traumatic arthritis or long-term functional decline [45]. Additionally, while measurements were performed by two independent observers, subtle intra-observer variability cannot be entirely excluded. Finally, as this was an observational study, causality cannot be definitively established, and randomized trials with longer follow-up are required to validate these findings [16,19].

Overall, our study highlights that anatomical variations of the distal radius are not mere radiographic curiosities but clinically relevant determinants of postoperative recovery. The results suggest that surgical strategies should prioritize the restoration of native parameters and that implant design and surgical guidelines may need to adapt to account for population-specific anatomical variability. These findings also emphasize the need for personalized surgical planning, where the surgeon considers not only fracture reduction but also the patient's intrinsic anatomy to optimize long-term function [41,45].

CONCLUSION

In this prospective study of patients undergoing ORIF for distal radius fractures, restoration of radial height, inclination, and volar tilt was strongly associated with superior functional recovery, while residual deformities led to worse outcomes and higher complication rates. Lunate fossa morphology emerged as an additional factor influencing recovery, underscoring the role of intrinsic anatomical variation. These findings affirm that precise anatomical restoration should remain the cornerstone of surgical fixation and highlight the need for population-specific considerations in implant design and surgical planning.

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Authors' contributions: SF: Conceptualization, study design, supervision.

A: Data collection, literature review.

FAR: Data analysis, manuscript revision.

MS: Methodology, statistical analysis, final review.

All authors reviewed and approved the final manuscript.

Data Availability Statement: The data used in this study are available upon reasonable request from the corresponding author, subject to ethical and institutional guidelines.

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