

Analysis of fracture-line distribution in comminuted distal radius fractures using three-dimensional fracture mapping

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Abstract

Background

Distal radius intra-articular comminuted fractures are highly complex because of their unique anatomy and injury mechanisms, which poses substantial challenges for clinical management. Several classification systems are currently available for these fractures; however, no single system has been universally accepted. In recent years, advances in three-dimensional fracture mapping and the growing use of evidence-based approaches have provided new ways to investigate fracture morphology and injury patterns at different anatomical sites.

Methods

A total of 58 comminuted distal radius fractures involving the radiocarpal joint were included, comprising 29 Frykman type VII and 29 type VIII fractures. Three-dimensional models of the radius and fracture fragments were reconstructed using E-3D 21.10 software (Central South University, Changsha, China). After virtual reduction and model registration, fracture lines were mapped onto a three-dimensional radius template and converted into heat maps using the fracture analysis module to evaluate fracture-line distribution patterns from multiple perspectives.

Results

Heat maps of Frykman type VII and VIII fractures demonstrated high-density clustering of fracture lines in the volar lunate and scaphoid fossae, whereas the radial styloid articular surface, dorsal medial articular surface, and dorsal ulnar notch showed relatively low fracture-line density.

Conclusions

Three-dimensional fracture mapping combined with heat-map analysis demonstrated that fracture lines in comminuted distal radius fractures involving the radiocarpal joint were concentrated mainly in the lunate and scaphoid fossae. These findings provide imaging-based morphological information that may support fracture assessment and surgical planning.

Introduction

Distal radius fractures (DRFs) are among the most common fractures encountered in clinical practice, and approximately half involve the articular surface[1–2]. With population aging and the increasing frequency of high-energy trauma, the incidence of these fractures continues to rise[3–4]. Several classification systems, including the Frykman, AO, and Fernandez systems, are widely used to describe fracture patterns and guide treatment[5–7]. Among them, the Frykman classification is relatively concise

and useful for academic analysis of articular involvement. In the present study, we used the Frykman system as the analytical framework and focused on comminuted distal radius fractures involving the radiocarpal joint, particularly type VII and VIII injuries. However, conventional classification systems may not fully capture the three-dimensional morphology and spatial distribution of these complex fractures.

Over the past decade, fracture mapping technology has advanced substantially. This technique provides a visual representation of the three-dimensional anatomical patterns of complex fractures and identifies shared fracture characteristics through the analysis of large imaging datasets [8–9]. The core principle of this approach is the registration and mapping of individual three-dimensional fracture lines onto a standardized bone template, thereby enabling comparison and integrated analysis across patients and fracture types within a common coordinate system. When the sample size is sufficiently large, fracture-line clustering, trajectories, distribution density, and frequency can be displayed as heat patterns on the standard template. This approach supplements conventional experience-based fracture assessment with quantifiable and comparable morphological information. It also allows surgeons to evaluate fracture-line patterns and the extent of articular surface involvement while identifying potential high-risk regions and key support columns.

In the present study, we used CT-based three-dimensional reconstruction to analyze comminuted distal radius intra-articular fractures involving the radiocarpal articular surface. By constructing fracture maps, we aimed to describe the spatial distribution of fracture lines and provide imaging-based morphological information relevant to treatment planning.

Materials and methods

Subjects

From January 2019 to December 2023, 58 patients with distal radius fractures who met the selection criteria were included in this study. Inclusion criteria were: (1) age ≥ 18 years; (2) availability of complete CT data; (3) closed intra-articular distal radius fractures; and (4) distal radius fractures classified as Frykman type VII or VIII. Exclusion criteria were: (1) poor CT image quality with slice thickness > 3 mm; (2) pathological fractures; and (3) a history of wrist deformity or wrist surgery. This study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Mindong Hospital, Fujian Medical University (Approval No. K2024092304, Informed consent forms have been obtained from all participants.).

Three-dimensional reconstruction

CT data (DICOM 3.0 format) were imported into E-3D 21.10 software (Central South University, Changsha, China). A sequence with higher resolution, thinner slices, clear visualization of the radius, and adequate scan coverage was selected. The “New Threshold” tool was used to remove surrounding soft tissues while retaining the required bony structures. The “Mass Separation” function was then used to

mark the radius and its fracture fragments separately from other bone regions. “Execute Separation” was applied to generate masks for the radius and fracture fragments. Subsequently, the “Mass Separation” function was used again to separate the main radius from each fracture fragment and to generate individual masks for the radius and each fragment. The “Solid Modeling” module was then used to reconstruct three-dimensional models from the processed masks.

Fracture reduction

In the surgical planning menu of the E-3D 21.10 software, fracture fragments requiring reduction were selected, and the rotation center was adjusted to the most prominent feature point of each fragment. Fragments were translated and rotated until satisfactory reduction was achieved. After reduction of all fracture fragments, the radius model and all reduced fragment models were selected, and “Combine and Split” was used to generate an integrated reduction model. In the mesh processing menu, “Execute Smoothing” was applied repeatedly until fracture gaps became clearly visible. The processed model was then exported for subsequent analysis.

Fracture-line mapping

A new project file was created using a healthy radius as the standard model. All post-reduction fracture models were then imported and individually matched to the standard model. When substantial size discrepancies were present, the post-reduction model was scaled appropriately to minimize dimensional differences. Through translation and rotation, each post-reduction model was aligned to the corresponding spatial position of the standard model. Minor gaps could still be observed between the surfaces of different fracture fragments. The curve function was used to trace along these fracture-surface gaps and generate the fracture-line map.

Heat-map generation

Within the fracture-line mapping module of the E-3D software, the standard template model was used, and the selected curves were processed using the “Statistical Analysis” function to generate a fracture-line heat map. In the 3D view, blue represented areas with no curves, whereas red indicated areas with the highest curve density.

Statistical analysis

Statistical analyses were performed using SPSS software (version 27.0). Continuous variables were presented as mean $\pm$ standard deviation, and categorical variables were presented as frequencies and percentages. For analysis of fracture-line distribution in the scaphoid fossa and lunate fossa, cases were grouped according to Frykman type (VII vs. VIII). Between-group differences were assessed using the chi-square test. A two-sided P value < 0.05 was considered statistically significant.

Results

Baseline characteristics

This study included 58 patients with distal radius fractures involving the radiocarpal joint, including 35 females and 23 males, with ages ranging from 28 to 86 years (mean age, 58.81 years). There were 26 left-sided and 32 right-sided fractures. According to the Frykman classification, 29 cases were type VII and 29 were type VIII. No significant differences were observed in baseline characteristics, including sex, age, or affected side, between the two Frykman groups ($P > 0.05$; Table 1).

Table 1. Patient demographics and distal radius fracture characteristics (N = 58)

Baseline data	Type VII (n=29)	Type VIII (n=29)	Statistical value	P value
Sexmale/female	13/16	10/19	$\chi^2 = 0.648$	0.592
Age $\bar{x} \pm s$)	60.76 $\pm$ 11.41	56.86 $\pm$ 12.00	F = 1.268	0.210
Side of injuryleft/right	14/15	12/17	$\chi^2 = 0.279$	0.792

Three-dimensional mapping characteristics of Frykman type VII fractures

From the superior view, fracture lines were predominantly distributed in the volar regions of the lunate fossa and scaphoid fossa, corresponding to red regions of high density on the heat map. Fracture lines on the radial styloid articular surface formed a circular distribution around the base of the styloid process, whereas those in the main body of the styloid process were more scattered and corresponded to blue regions on the heat map. The dorsal medial articular surface also showed a low-density distribution and appeared blue on the heat map. In the anterior and medial views, fracture lines in the ulnar notch were mainly concentrated in the volar region, with relatively fewer lines on the dorsal side. The fracture-line distribution patterns observed in the remaining anterior and medial views were consistent with those seen in the superior view (Figures 1 and 2).

Three-dimensional reconstruction characteristics of Frykman type VII fractures

The 3D reconstruction images showed a comminuted fracture involving the radiocarpal articular surface of the distal radius, with multiple fracture fragments. Fracture lines were mainly distributed along the margins of the scaphoid and lunate fossae and extended from the volar aspect of the scaphoid fossa to the volar aspect of the lunate fossa, with further extension toward the sigmoid notch (Figure 3). Tomographic images showed that this Frykman type VII fracture involved both the radiocarpal and distal radioulnar articular surfaces, with marked displacement of the distal radial articular surface relative to the carpus (Figure 4).

Three-dimensional mapping characteristics of Frykman type VIII fractures

From the superior view, fracture lines were predominantly distributed in the volar regions of the lunate fossa and scaphoid fossa, corresponding to red regions of high density on the heat map. On the radial styloid articular surface, fracture lines were mainly concentrated at the base of the styloid process, whereas the overall fracture-line density remained low and appeared blue on the heat map. The dorsal medial articular surface showed a more scattered fracture-line distribution and was also represented by blue regions on the heat map. In the anterior and medial views, fracture lines were densely distributed in the volar region of the ulnar notch, whereas only sparse fracture lines were observed in localized dorsal areas. The remaining findings in the anterior and medial views were generally consistent with those in the superior view (Figures 5 and 6).

Three-dimensional reconstruction characteristics of Frykman type VIII fractures

The 3D reconstruction images showed disruption of the radiocarpal articular surface, with multiple fracture fragments. Fracture lines were distributed along the margin of the scaphoid fossa and extended from the volar aspect to the dorsal aspect and the base of the radial styloid process, with multiple intersecting lines (Figure 7). Computed tomography images showed that this Frykman type VIII fracture involved both the radiocarpal and distal radioulnar articular surfaces. Marked displacement was also observed between the distal radial articular surface and the carpus (Figure 8).

Distribution of fracture lines in the scaphoid fossa and lunate fossa

The proportions of Frykman types VII and VIII involving the scaphoid fossa were 72.4% and 79.3%, respectively, with no statistically significant difference between groups. The proportions involving the lunate fossa were 75.9% and 65.5% for Frykman types VII and VIII, respectively, and the difference between groups was not statistically significant (Table 2).

Table 2. Distribution of fracture lines in the scaphoid fossa and lunate fossa according to Frykman type (N = 58)

Area	VII (n=29) n(%)	VIII (n=29) n(%)	P value
Scaphoid fossa	21(72.4%)	23(79.3%)	0.539
Lunate fossa	22(75.9%)	19(65.5%)	0.387

Discussion

The fracture heat-map technique was first proposed in 2009, with its core principle based on overlaying fracture-line data from multiple cases to visualize characteristic fracture patterns in specific anatomical

regions [10–12]. Early work on this technique was reported by Armitage and colleagues [13], who introduced the concept of fracture-line overlay and spatial distribution into fracture morphology research. Over the past decade, this technique has been applied to the morphological analysis of fractures at multiple anatomical sites, including the scapula, humerus, femur, and tibia [14–16]. As fracture-mapping methods have evolved, the related workflows have also been refined [17–19]. In the present study, we used three-dimensional fracture mapping to integrate imaging data from comminuted distal radius fractures involving the radiocarpal articular surface. This approach was intended to characterize the spatial distribution of fracture lines in intra-articular fractures and to provide imaging-based morphological information relevant to treatment planning.

Distal radius fractures are among the most common fractures encountered in clinical practice, and treatment decisions directly affect wrist stability and load-bearing function [20]. Accurate preoperative assessment of articular involvement is therefore important for surgical planning. Several classification systems are currently used to evaluate these fractures, and the Frykman classification is commonly used for clinical communication and research grouping because of its relative simplicity and clarity [21]. Accordingly, this study used the Frykman classification for case grouping. Because comminuted radiocarpal articular fractures are common and are often associated with unsatisfactory functional outcomes, the present study focused on Frykman type VII and VIII fractures.

The three-dimensional fracture heat map showed high-density clustering of fracture lines in both the volar lunate fossa and volar scaphoid fossa in Frykman type VII and VIII fractures, suggesting that these regions may represent preferentially involved zones in comminuted intra-articular distal radius fractures. From a biomechanical perspective, the formation of these volar high-density regions is consistent with a composite stress pattern involving axial compression and volar shear forces. As the mechanical core of the intermediate column, the volar lunate fossa may be more susceptible to articular surface collapse under compressive loading, whereas simultaneous stress concentration in the volar scaphoid fossa suggests concurrent failure of the radial column support system during the same injury process [22].

These findings suggest that fixation failure in Frykman type VII and VIII fractures may be more closely related to inadequate reconstruction of subchondral support in these high-density regions than to implant strength alone. A key issue may be whether distal fixation can provide continuous subchondral support along the volar aspects of both fossae and achieve stable buttressing of the critical fragment at the volar rim of the lunate fossa. Insufficient support in these regions may result in secondary displacement of critical fragments, leading to radiocarpal incongruity or partial subluxation. Adams AJ et al. [23] described the relationship between loss of stability in key volar lunate fossa fragments and fixation failure. The present study adds spatial evidence to this observation by showing reproducible high-density clustering in the corresponding volar region.

Both Frykman type VII and VIII fractures are severe intra-articular comminuted injuries and are often accompanied by varying degrees of bone defects and free fragments. A major challenge in these injuries is the simultaneous disruption of articular congruity and subchondral support. In the setting of combined

compressive collapse and shear displacement, a single surgical approach often cannot adequately address all key steps of management within a single field of view, including restoration of articular congruity, elevation of collapsed fragments, management of subchondral voids, and provision of reliable support in biomechanically vulnerable regions. When collapse is substantial or dorsal comminution predominates, a combined volar and dorsal approach allows articular elevation and fragment reduction to be performed from different viewing angles, thereby improving the controllability and reproducibility of reduction [24]. Residual subchondral voids left after elevation of collapsed fragments may predispose the joint surface to secondary collapse during early loading. Filling these defects with bone graft or bone substitute can therefore provide structural support for the elevated articular surface and reduce the risk of re-collapse [24]. These strategies are consistent with the volar high-density regions identified in this study. Volar fixation helps establish a subchondral support framework in these regions, whereas the dorsal approach is more suitable for collapse elevation, management of dorsal comminution, and restoration of the three-dimensional curvature of the articular surface. Together, these approaches address both geometric reconstruction and mechanical support. Because Frykman type VII and VIII fractures often involve the ulnar notch, assessment of distal radioulnar joint (DRUJ) stability should be incorporated into reconstruction of the radiocarpal and distal radioulnar articular surfaces, with particular attention to the integrity of the triangular fibrocartilage complex (TFCC). As a key static stabilizer of the DRUJ, restoration of TFCC stability is closely associated with pronation-supination pain and functional outcomes [25].

Another important finding of this study is that, in most cases involving the articular surface of the distal radius, the radial styloid articular surface remained relatively intact, with only a small number of cases showing isolated fracture lines. This result suggests that the radial styloid may contain a denser trabecular support system, which could confer greater resistance to fracture [26]. This anatomical feature provides a theoretical basis for the biomechanical advantages of styloid screw fixation. In addition to the radial styloid region, the dorsal medial articular surface showed low-density involvement, indicating that under certain conditions it may serve as a relatively safe pathway for screw placement. Accordingly, when additional support is needed for volar comminuted fragments and the dorsal medial bony corridor is adequate, a dorsomedial-to-volar screw trajectory may be considered to provide buttress support for these fragments. However, because intraoperative imaging is limited in real-time assessment of screw trajectory and final depth, this approach has a low tolerance for errors in screw insertion angle, length, and tip position. Successful application of this technique depends on the surgeon's familiarity with anatomical landmarks and careful interpretation of fluoroscopic findings. Intraoperative multi-angle fluoroscopic confirmation of screw tip position and length remains important, and tendon-related complications should be considered when selecting the screw trajectory.

This study has several strengths. Three-dimensional fracture mapping provided a direct view of the complex morphology and spatial distribution of fracture lines on the distal radial articular surface. By focusing on Frykman type VII and VIII fractures, we were able to characterize fracture patterns in complex radiocarpal articular injuries. In addition, combining fracture-line maps with heat maps allowed complementary evaluation of fracture trajectories and overall distribution density.

This study also has several limitations. Because the analysis was based on virtual reduction, fracture mapping could depict only the surface course of fracture lines and could not fully capture fragment displacement or collapse. In addition, construction of fracture-line maps required substantial manual processing. Finally, no dedicated classification system based on distal radius articular-surface fracture maps is currently available. Further studies integrating anatomical and biomechanical data are needed to clarify the clinical value of this approach.

Conclusions

The three-dimensional fracture map demonstrated the trajectory and spatial distribution of fracture lines on the distal radial articular surface. By integrating fracture-line maps and heat maps, this study combined two complementary visualization methods to characterize both fracture-line trajectories and density distribution. The results showed that, in comminuted distal radius fractures involving the radiocarpal joint, fracture lines were predominantly concentrated in the lunate fossa and scaphoid fossa. This pattern may improve understanding of the involvement of these key anatomical regions. These findings may also inform future work on fracture classification, screw placement strategies, and internal fixation design.

Declarations

Participant Consent Form

Informed consent forms have been obtained from all participants

Availability of data and materials

The dataset supporting the conclusions of this article is included within the article.

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Authors' contributions

Hexin Zhang and Zhenbao Lu contributed equally to this work. The authors read and approved the final manuscript

Competing interests

The authors declare no competing interests.

Consent for publication

Not applicable.

Ethics approval and consent to participate

Not applicable.

Clinical trial number

Not applicable.

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Figures

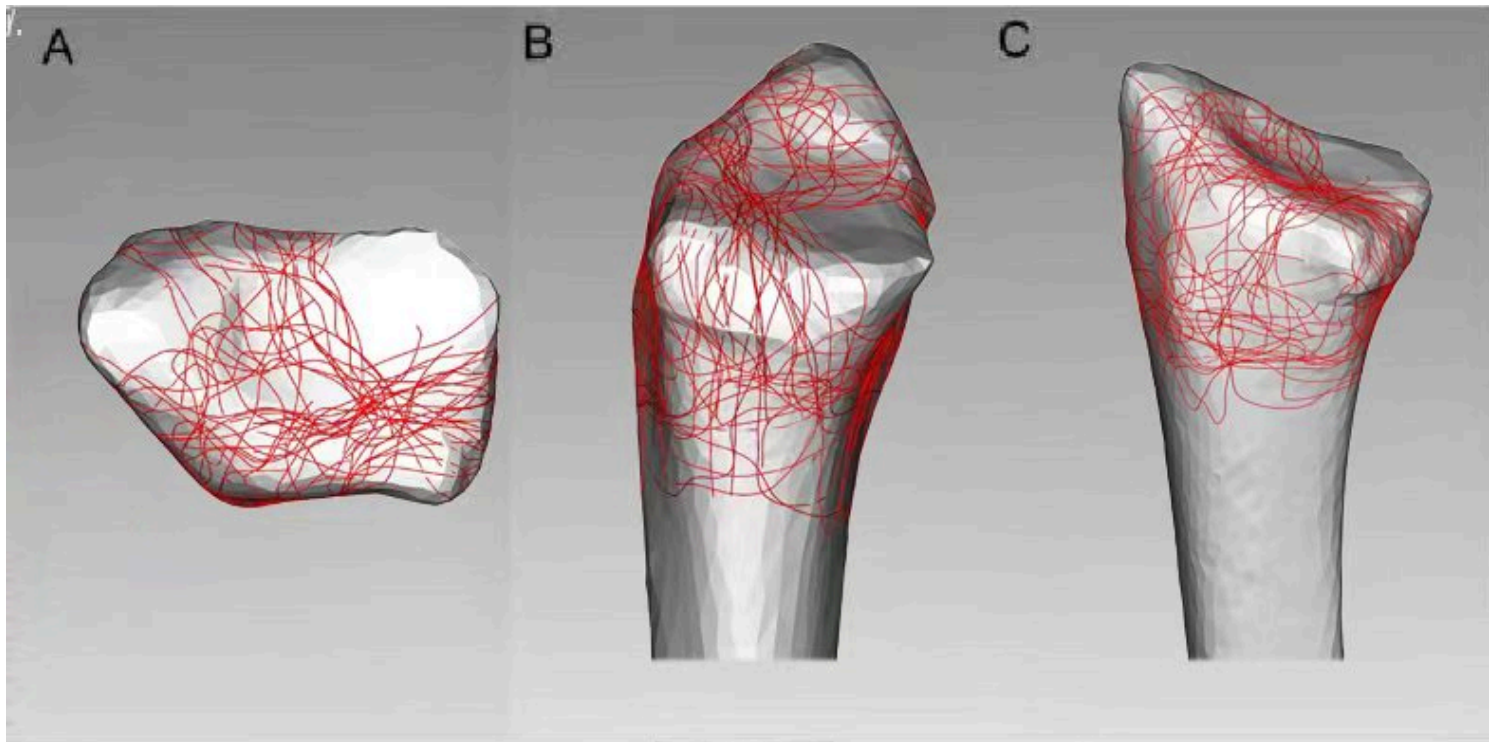


Figure 1

Fracture-line distribution map of a Frykman type VII distal radius fracture, generated using E-3D 21.10 software.

(A)superior view; (B)medial view; (C)anterior view.

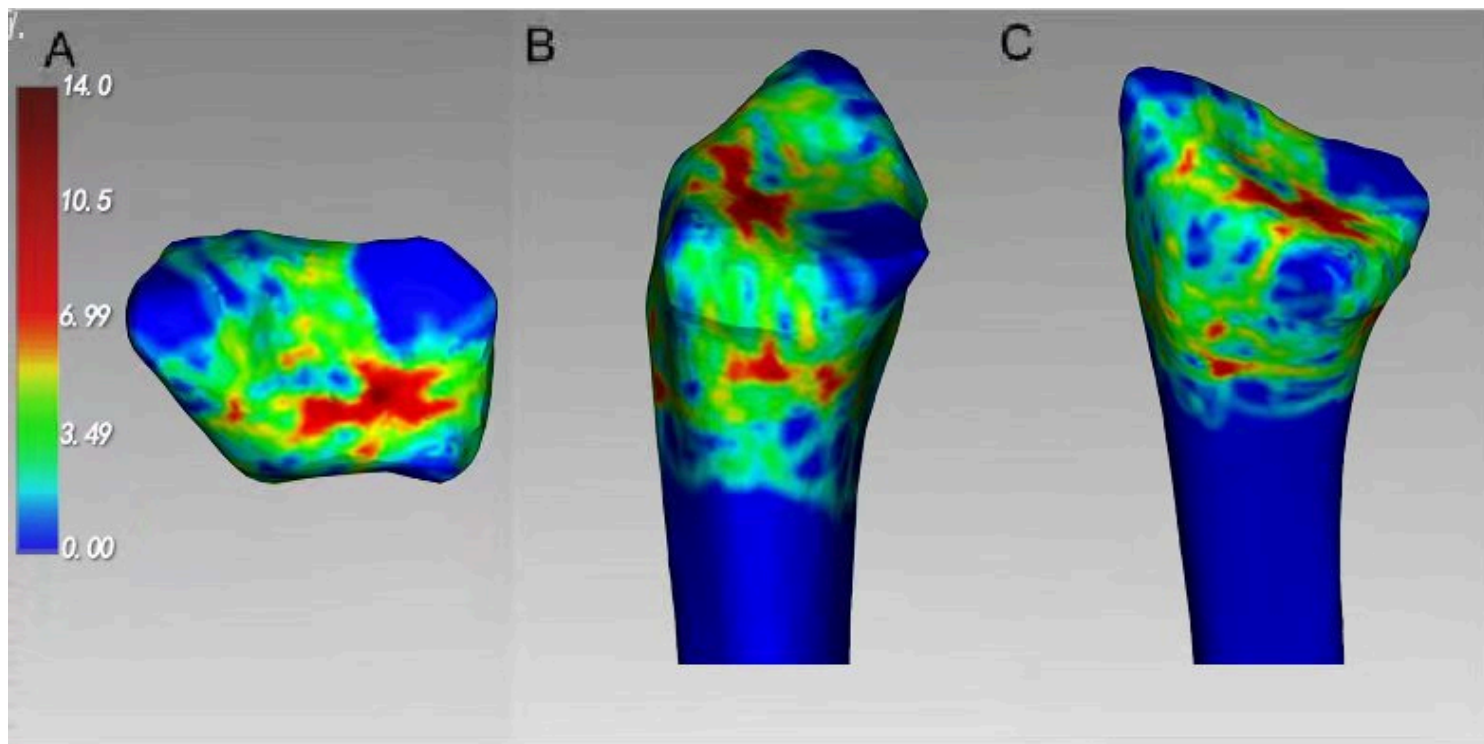


Figure 2

Fracture heat map of a Frykman type VII distal radius fracture, generated using E-3D 21.10 software.

(A)superior view; (B)medial view; (C)anterior view.

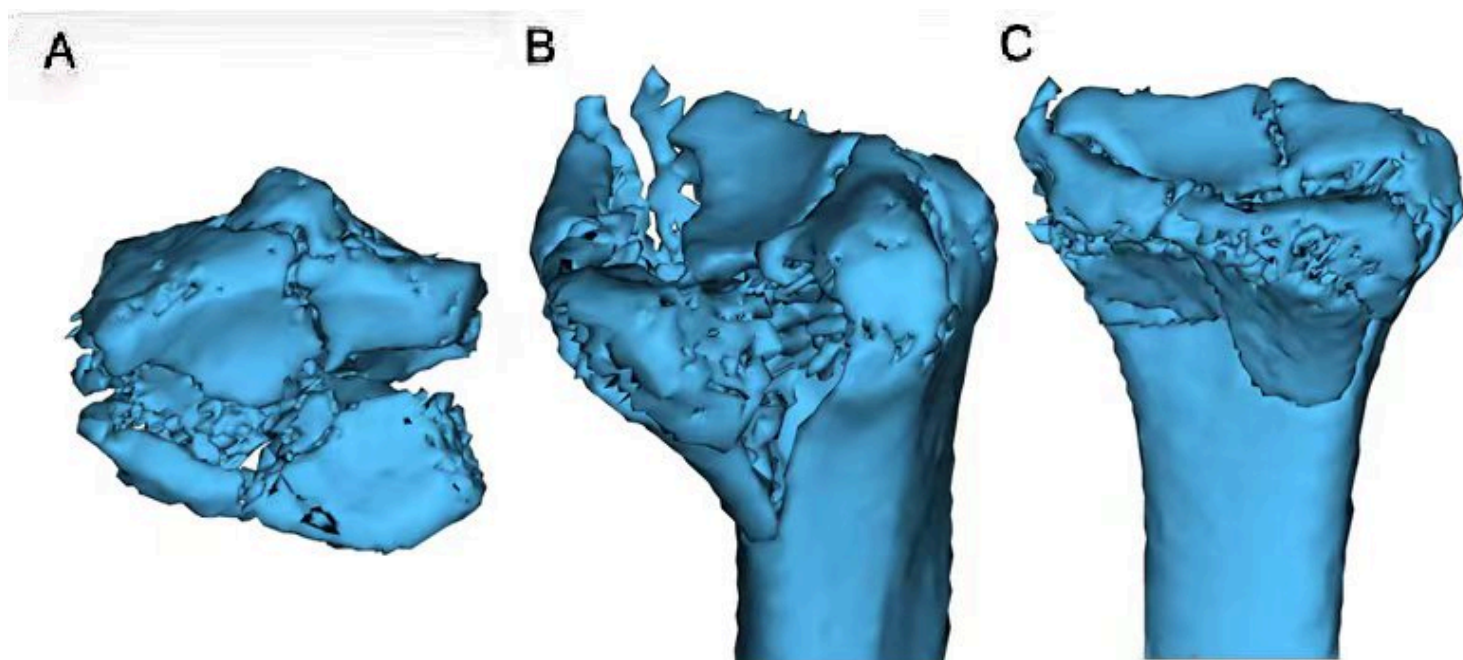


Figure 3

Three-dimensional solid model of a representative Frykman type VII distal radius fracture, generated using E-3D 21.10 software.

(A)superior view; (B)medial view; (C)anterior view.

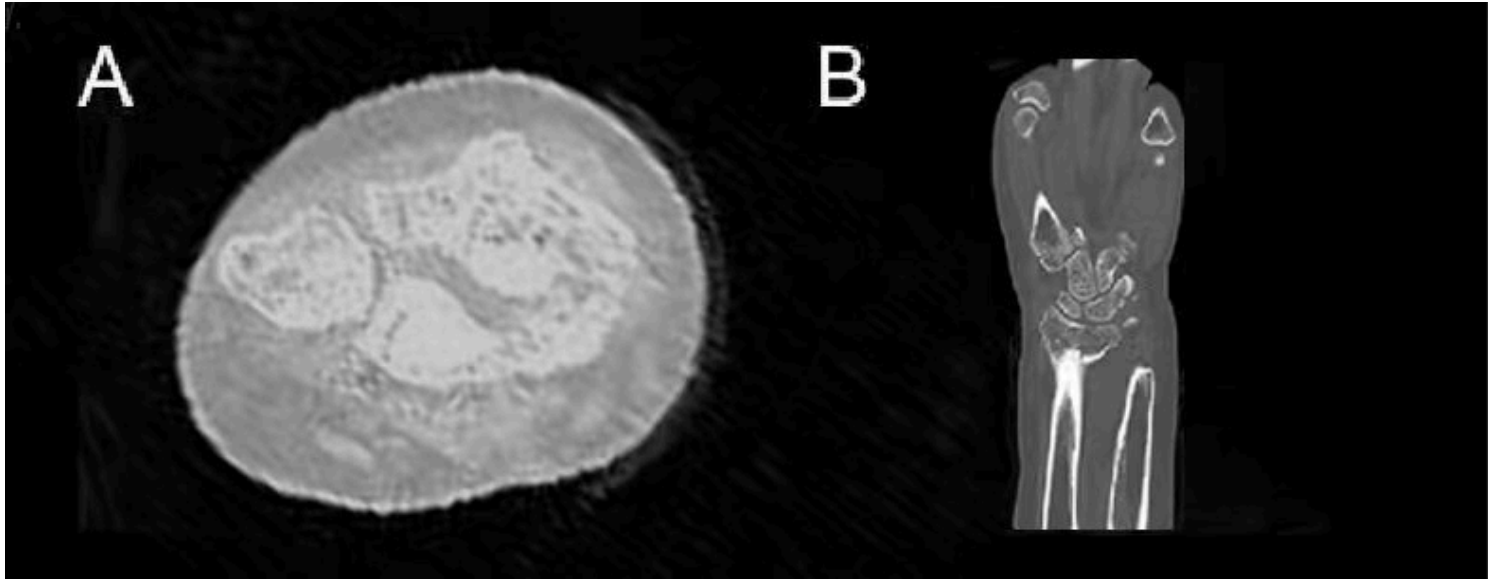


Figure 4

Representative tomographic images of a Frykman type VII distal radius fracture, generated using E-3D 21.10 software.

(A) axial view; (B) coronal view.

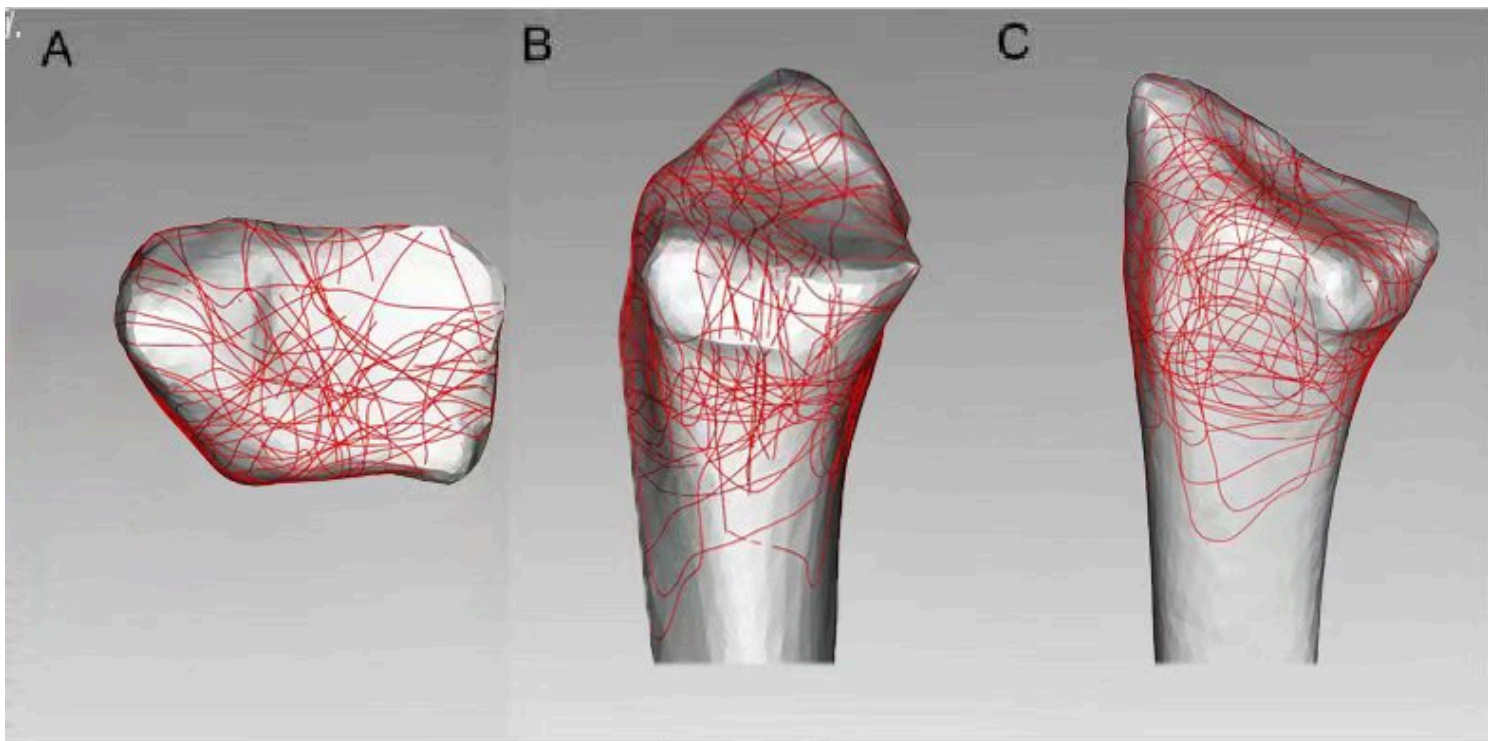


Figure 5

Fracture-line distribution map of a Frykman type VIII distal radius fracture, generated using E-3D 21.10 software.

(A)superior view; (B)medial view; (C)anterior view.

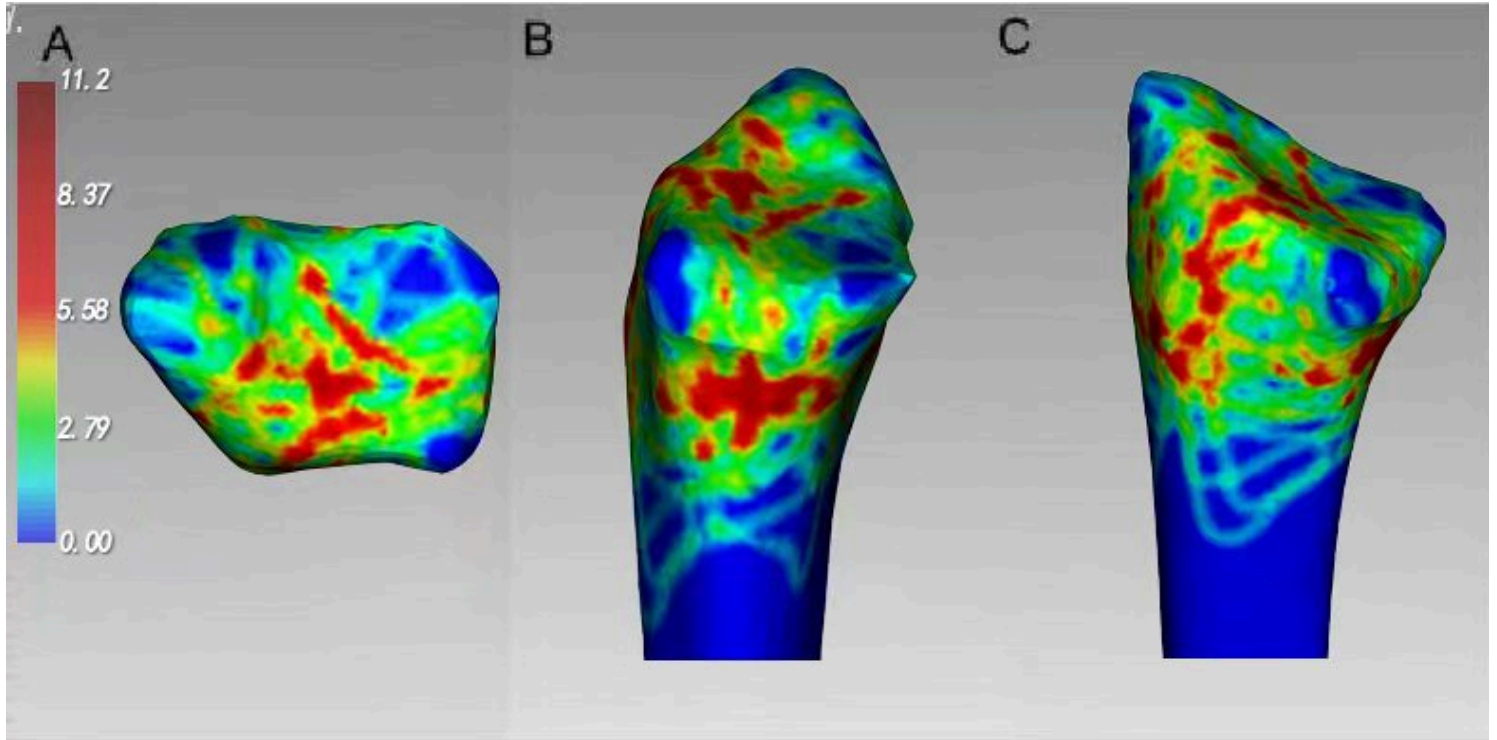


Figure 6

Fracture heat map of a Frykman type VIII distal radius fracture, generated using E-3D 21.10 software.

(A) superior view; (B)medial view; (C)anterior view.

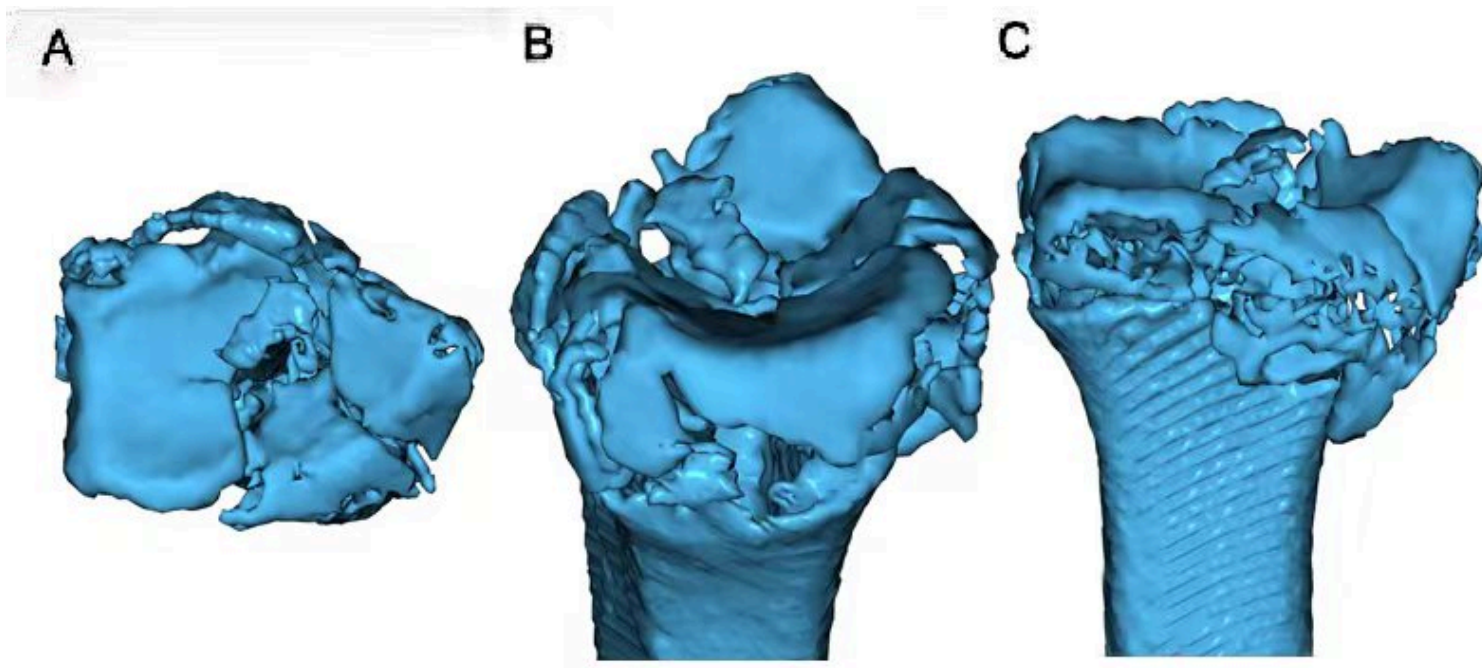


Figure 7

Three-dimensional solid model of a representative Frykman type VIII distal radius fracture, generated using E-3D 21.10 software.

(A)superior view; (B)medial view; (C)anterior view.

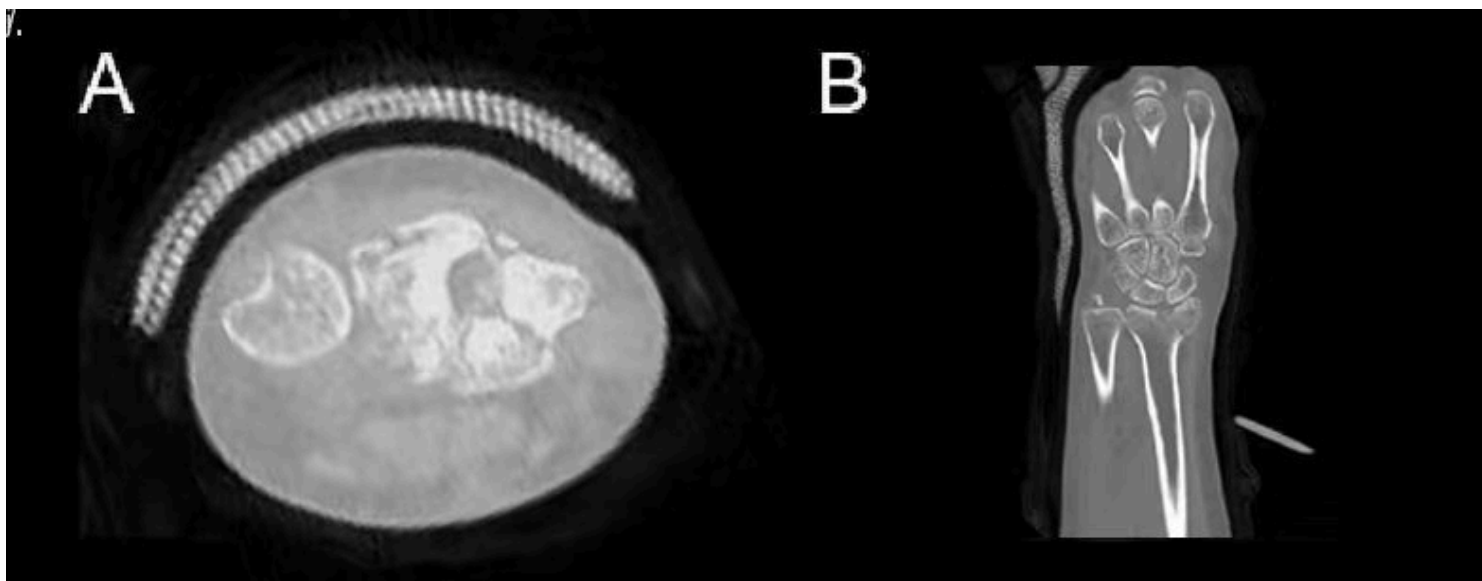


Figure 8

Representative tomographic images of a Frykman type VIII distal radius fracture, generated using E-3D 21.10 software.

(A) axial view; (B) coronal view.