

Navicular Fracture Mapping: A New Perspective on Fracture Patterns and Surgical Strategies

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Research Article

Keywords: Fracture, midfoot, mapping, navicular, tarsal, 3D CT

Posted Date: September 12th, 2025

DOI: <https://doi.org/10.21203/rs.3.rs-7500806/v1>

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Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at European Journal of Orthopaedic Surgery & Traumatology on October 7th, 2025. See the published version at <https://doi.org/10.1007/s00590-025-04550-8>.

Abstract

Background: Navicular fractures are rare and pose significant surgical challenges. This study aimed to define the location and frequency of fracture lines using both two-dimensional (2D) and three-dimensional (3D) computed tomography (CT) mapping. We hypothesized that fracture mapping could reveal constant fragments, as well as patterns of impaction and comminution, to help optimize surgical management.

Methods: A retrospective analysis of CT scans from 44 patients was performed. Fractures were classified according to the Sangeorzan system. Three-dimensional reconstructions were used to identify key fracture patterns, zones of impaction, and the presence of a constant plantar fragment, based on a 360-degree quadrant mapping approach.

Results: Type I fractures (n = 8) were simple transverse fractures with no reproducible pattern. Type II fractures (n = 10) followed an oblique dorsolateral-to-plantar-medial trajectory, with 43% showing impaction in the lateral quadrant. Type III fractures (n = 26) were associated with comminution in 96% of cases and impaction in 81%, with fracture lines converging at the talonavicular joint. A constant plantar fragment was identified in 56% of Type II and 73% of Type III fractures.

Conclusion: 3D navicular fracture mapping may improve understanding of fracture morphology and injury mechanisms. By identifying consistent fracture features, this technique may assist in preoperative planning and inform reduction and fixation strategies.

Level of evidence : IV

Introduction

Fractures of the tarsal navicular are uncommon, accounting for approximately 35.5% of midfoot injuries and 5% of all foot injuries.[1] Motor vehicle collisions (MVCs) are the most common cause, as a high-energy mechanism is typically required to generate the degree of impaction and distraction necessary to disrupt the navicular and adjacent structures. These forces often propagate along the medial column and may also affect the lateral column, leading to a high incidence of associated injuries. Evans et al. reported a 62% incidence of concomitant midfoot and hindfoot injuries on the same side.[2]

This susceptibility is due to the complex network of plantar and dorsal ligaments and the compact nature of the tarsal bones, which together confer significant structural rigidity to the midfoot. The interdependence between the medial and lateral columns of the foot has been likened to the pelvic ring, where injury to one side often implies compromise of the other.[3]

The navicular bone plays a key role in hindfoot motion and gait. Anatomical reduction of this joint is critical for preserving mobility and preventing post-traumatic osteoarthritis. As the keystone of the medial longitudinal arch, the navicular contributes to maintaining the length and alignment of the medial column; shortening following fracture can result in hindfoot varus and forefoot abduction.

Navicular fractures are commonly classified into three types based on fracture pattern and joint involvement.[4] Type I and II fractures tend to preserve medial foot alignment, whereas Type III fractures are frequently associated with lateral comminution and displacement. This classification system has prognostic value for predicting the difficulty of reduction and potential clinical outcomes (Fig. 1).

Talar-navicular fractures remain difficult to manage, particularly in polytrauma patients, due to their association with high-energy trauma and the resulting long-term morbidity.[5] Preoperative planning is essential, and understanding common fracture patterns is crucial to guide open reduction and internal fixation (ORIF). The presence of a constant plantar fragment, as described by Cronier et al., may serve as a reliable landmark for reduction in complex comminuted cases.[6]

Three-dimensional (3D) reconstruction and fracture mapping techniques have already been validated in other anatomical regions, such as the calcaneus and acetabulum, to identify consistent fracture lines and constant fragments.[7, 8] However, such methodologies have not yet been systematically applied to navicular fractures.

The aim of this study was to determine whether 3D fracture mapping of navicular fractures could identify constant fragments, as well as zones of impaction and comminution, to support improved reduction strategies and fixation, while preserving the delicate osseous and vascular anatomy of the navicular.

Materials and Methods

Study Design and Patient Cohort

This was a single-center retrospective study conducted at a trauma center, following approval by the institutional review board. All patients presenting with an acute navicular fracture between 2007 and 2023 were included. Patient demographics including age, mechanism of injury, laterality, presence of an open fracture, and associated fractures of the foot and ankle were recorded.

Exclusion criteria included age under 18 years and incomplete or non-assessable radiographic or CT data. All included CT scans encompassed the entire foot, from forefoot to hindfoot, with a maximum slice thickness of less than 3 mm. Scans were obtained pre- and postoperatively and accessed via the hospital's Picture Archiving and Communication System (PACS). Fractures were classified according to the Sangeorzan classification.[4]

CT Analysis and 3D Modeling

Raw CT data were exported as DICOM (Digital Imaging and Communications in Medicine) files from PACS. Axial-plane data were imported into 3D Slicer (Brigham and Women's Hospital; open-source software) to generate individual project files. Fractures were analyzed in axial, sagittal, and coronal planes simultaneously.

To isolate the navicular bone and its fragments from surrounding tarsal structures, segmentation was performed using two templates: one for the navicular and another for adjacent bones. Articular surfaces and fragment boundaries were highlighted across at least three CT slices per anatomical plane. The segmented navicular was then converted into a 3D model and exported as an STL file for further analysis.

3D Fracture Mapping

Fracture mapping methods followed standardized protocols described by Cole et al. and Xie et al.[9, 10] Each STL file was imported into Blender (Blender Foundation; open-source software), where the main fragments were virtually reduced in three spatial dimensions. Fragment alignment was performed using anatomical landmarks, including the medial tuberosity, the inferior groove for the tibialis posterior tendon, the perforated dorsal cortex, and the lateral cuboid articular surface.

Each reconstructed fracture pattern was superimposed onto a template model of an uninjured navicular using a specific ICP (Iterative Closest Point) alignment add-on, based on the aforementioned landmarks. Left-sided fractures were mirrored to match the right side for standardization. Once proper anatomical alignment was confirmed (after a minimum of 50 iterations), fracture lines were manually traced as smooth curves on the template surface.

Superimposing all individual fracture lines created a frequency-based fracture line map. In addition, zones of impaction and comminution were identified for each case, allowing the generation of corresponding 3D heat maps. These heat maps used a color gradient (from blue to red) to reflect the frequency of involvement. Impaction and comminution zones were analyzed according to four quadrants in a posteroanterior view: superomedial, superolateral, inferomedial, and inferolateral (Fig. 2).

Data Analysis

Statistical analyses were performed using R software (version 3.6.1; R Foundation for Statistical Computing). Qualitative variables were expressed as counts and percentages. Quantitative variables were presented as means with standard deviations (SD). Comparisons of quantitative variables were made using Student's t-test, with statistical significance set at $p < 0.05$. Confidence intervals were reported at the 95% level.

Results

Patient characteristics

A total of 54 navicular fractures were initially identified. Ten patients were excluded due to incomplete radiographic records. The final cohort consisted of 44 patients, of whom 36 (82%) were male and 8 (18%) were female, with a mean age of 34 years (range, 15–74).

According to the Sangeorzan classification, 8 patients (18%) had Type I fractures, 10 (22%) had Type II fractures, and 26 (60%) had Type III fractures. Most injuries occurred during road traffic accidents (63.6%). Four patients (9.1%) had open fractures. One patient presented with a neurovascular injury that led to mid-term amputation.

Associated injuries were common, found in 79.5% of cases, typically involving at least one of the three regions of the foot (forefoot, midfoot, or hindfoot). Patient demographics and fracture characteristics are summarized in Table 1.

Table 1

– Patient demographics and Fracture characteristics (N = 44)*Only one case of a bilateral type 3 navicular fracture is represented here as 1 patient but in both sections into the laterality. **The values are given as the mean, with the range in parentheses.

	TYPE 1	TYPE 2	TYPE 3
Size (nbr. [%]*)	8 (18)	10 (22)	26 (60)
Age (years)**	39 (23–74)	27 (15–45)	33 (16–58)
Sex (nbr. [%])			
Male	5 (62)	9 (90,0)	22 (85)
Female	3 (38)	1 (10,0)	4 (15)
Laterality (nbr. [%])			
Right	6 (75)	4 (40)	14 (52)
Left	2 (25)	6 (60)	13 (48)
Skin coverage (nbr. [%])			
Open	1 (13)	0 (0)	3 (12)
Closed	7 (87)	10 (100)	23 (88)
Concomitant injuries (nbr. [%])			
NO	2 (25)	2 (20)	5 (19)
YES	6 (75)	8 (80)	21 (81)
<i>Forefoot</i>	2	2	6
<i>Midfoot</i>	3	7	12
<i>Hindfoot</i>	4	3	9
<i>Others</i>	5	2	12
Treatments			
Orthopedic	5 (63)	4 (40)	2 (8)
Surgical	3 (37)	6 (60)	24 (92)
<i>Plating</i>	0	4	20
<i>Screw</i>	3	3	5
<i>K-wire</i>	1	0	2
<i>other</i>	1	0	0

Fracture characteristics and management

Type I fractures

Type I fractures accounted for 18% of the cohort ($n = 8$). These were simple transverse fractures without a consistent or reproducible pattern. No impaction or comminution zones were identified. Most cases were managed nonoperatively (5 patients, 62.5%). Surgical fixation was reserved for fractures with large or significantly displaced fragments.

Type II fractures

Type II fractures represented 22% of the cohort ($n = 10$). Fracture lines followed an oblique dorsolateral-to-plantar-medial trajectory. Impaction zones were predominantly located along the lateral aspect of the talonavicular joint. Comminution was primarily concentrated in the superolateral quadrant of the navicular.

Treatment was tailored according to the degree of displacement and comminution. Surgical management was performed in 60% of cases, using screws or plates depending on fragment size and location.

Type III fractures

Type III fractures were the most common, representing 60% of the cohort ($n = 26$). These injuries were frequently associated with additional midfoot (46%) or hindfoot (34%) fractures.

In all Type III cases, a plantar region of the navicular remained intact, corresponding to what we termed the lateral plantar fragment. This constant fragment was present in 73% of Type III and 56% of Type II fractures.

Impaction zones consistently converged at the central portion of the talonavicular joint. Comminution was primarily located along the inferolateral aspect of the navicular and often extended toward the cuboideonavicular joint.

An overview of these findings is presented in Fig. 3.

Discussion

Using 3D fracture mapping techniques, we identified consistent fracture patterns in both Type II and Type III navicular fractures. These included recurrent zones of impaction and comminution, as well as the frequent presence of a constant plantar fragment.

Type I fractures did not demonstrate any reproducible pattern. This may reflect true variability in morphology or could be due to the limited sample size in this subgroup.

In Type II fractures, the predominant fracture line followed a sagittal trajectory from the dorsolateral to the plantar-medial corner, typically resulting in a large medial fragment. This finding reinforces the fracture pathway described in the Sangeorzan classification and supports currently established reduction and fixation strategies.

In Type III fractures, analysis of all fracture lines revealed three primary fragments: a consistent plantar lateral fragment that remained uninvolved, a dorsolateral fragment, and a dorsomedial fragment. Cronier et al. attributed the preservation of the plantar fragment to the strength of the inferior calcaneonavicular (bifurcate) ligament, which anchors the fragment to the anterior process of the calcaneus.[6] This pattern supports the designation of a "constant fragment," analogous to the sustentaculum tali in calcaneal fractures. Rockett et al. also observed this fragment in CT-based analyses and incorporated it into their reduction strategy.[11]

3D mapping of impaction and comminution zones revealed consistent involvement of the dorsolateral quadrant. These areas varied in severity depending on fracture type, with more extensive damage observed in Type III fractures. This distribution appears to support the injury mechanism proposed by Rockett et al., particularly in Type III injuries, where axial loading of the talar head on a pronated hindfoot may exacerbate impaction and comminution.[11]

The potential clinical value of 3D fracture mapping lies in its capacity to improve understanding of navicular fracture morphology, offering a reproducible framework for anticipating fragment configuration and zones of comminution. This is relevant because restoring talonavicular congruity and medial column length is critical for achieving favorable outcomes.[12] Despite applying these principles, secondary osteoarthritis remains common. In the series by Coulibaly et al., 85.4% of patients developed osteoarthritis following surgical treatment.[13]

Fracture mapping may help surgeons anticipate the location of key fragments and tailor the surgical approach accordingly. This information may support decision-making around incision placement and exposure, with the aim of balancing adequate visualization with preservation of vascular integrity. Given the navicular's limited blood supply, protecting its biological environment is essential to reduce the risk of avascular necrosis. DiGiovanni et al. emphasized the importance of an approach that permits simultaneous access to both the talonavicular and naviculo-cuneiform joints, while minimizing periosteal, capsular, or ligamentous stripping.[3] Respectful placement of plates and screws is also recommended to avoid devascularization.

Sangeorzan et al. suggested that at least 60% of the talonavicular joint surface must remain intact to prevent postoperative subluxation.[4] In our series, comminution was consistently located in the dorsolateral quadrant, an area often difficult to anatomically reduce, which may contribute to lateral subluxation of the talar head. Anatomical reduction of the less comminuted medial portion onto the

plantar fragment, anchored to the calcaneal beak, may act as a stabilizing platform and help limit medial displacement of the navicular body. In our practice, the presence of a plantar fragment is taken into consideration during ORIF for Type III, and to some extent Type II fractures, as it may serve as a stable platform for repositioning the main navicular body. (Fig. 5, 6) A prospective clinical study would be required to determine whether this concept results in improved outcomes.

This study has several limitations. It was retrospective and conducted at a single center. The use of the Sangeorzan classification, although widely adopted, may also be questioned, as it does not always capture medial border disruption or forefoot angulation. Schmid et al. have proposed an alternative classification based on the extent of talonavicular joint damage as visualized on preoperative CT scans, which may provide additional clinical relevance.[14]

Conclusion

This study illustrates the potential value of 3D fracture mapping in improving the understanding of navicular fracture morphology and injury mechanisms. By identifying consistent fracture patterns and key fragments, mapping may assist in refining surgical strategies. Optimizing reduction while preserving the bone's biological integrity remains a central goal, in line with established AO principles.

Declarations

Funding Statement

The authors declare that no funding was received for the conduct of this study.

Author Contribution

QDC : redacted the manuscript
VS : carried out data collection
CM : prepared figures and table
LR : carried out statistical analyses
GD : proofread and corrected the manuscript

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Figures

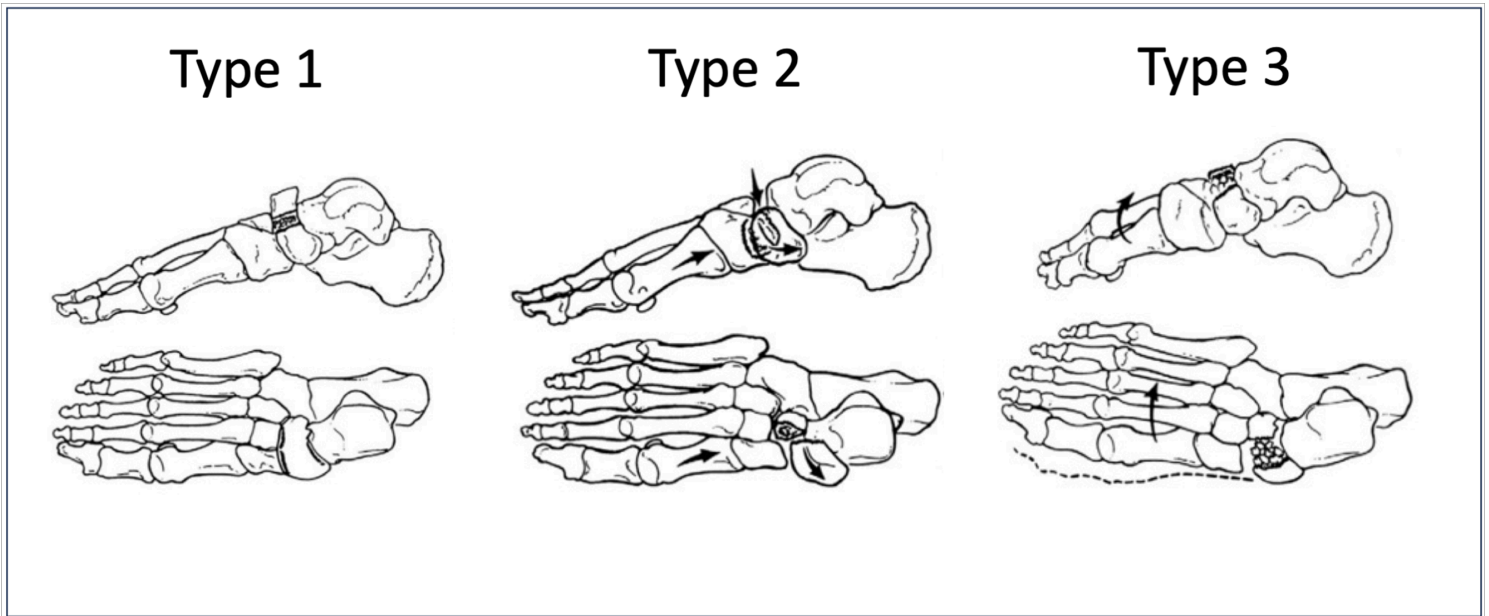


Figure 1

Sangeorzan's classification of navicular fracture. Type 1 = the primary fracture line is transverse in coronal plane. Type 2 = Fractures traverses from dorsolateral to plantar-medial across the navicular body. Type 3 = fracture is essentially with central or lateral comminution, with or without a subluxation or disruption.

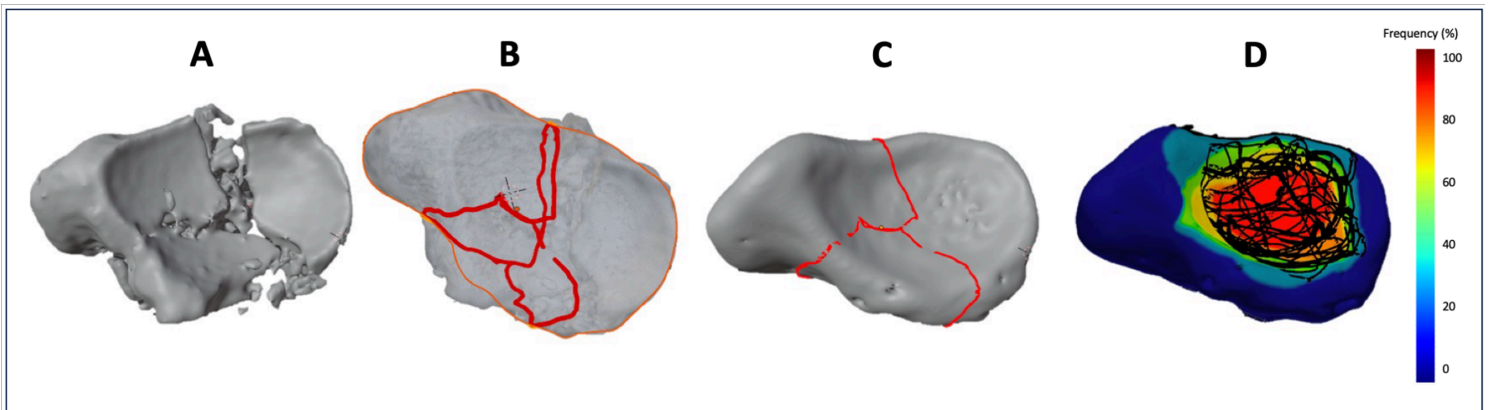


Figure 2

The 3D method of navicular fracture mapping. Here, an example of Sangeorzan's type 3 body navicular fracture, with a partial reduction to maintain the comminution area (**A**). After obtaining the most perfectible overlapping on the template model, the fracture lines was drawn with a red line (**B and C**) and the impactation zone was identified by the same model (black lines) and unified on a heat map (**D**).

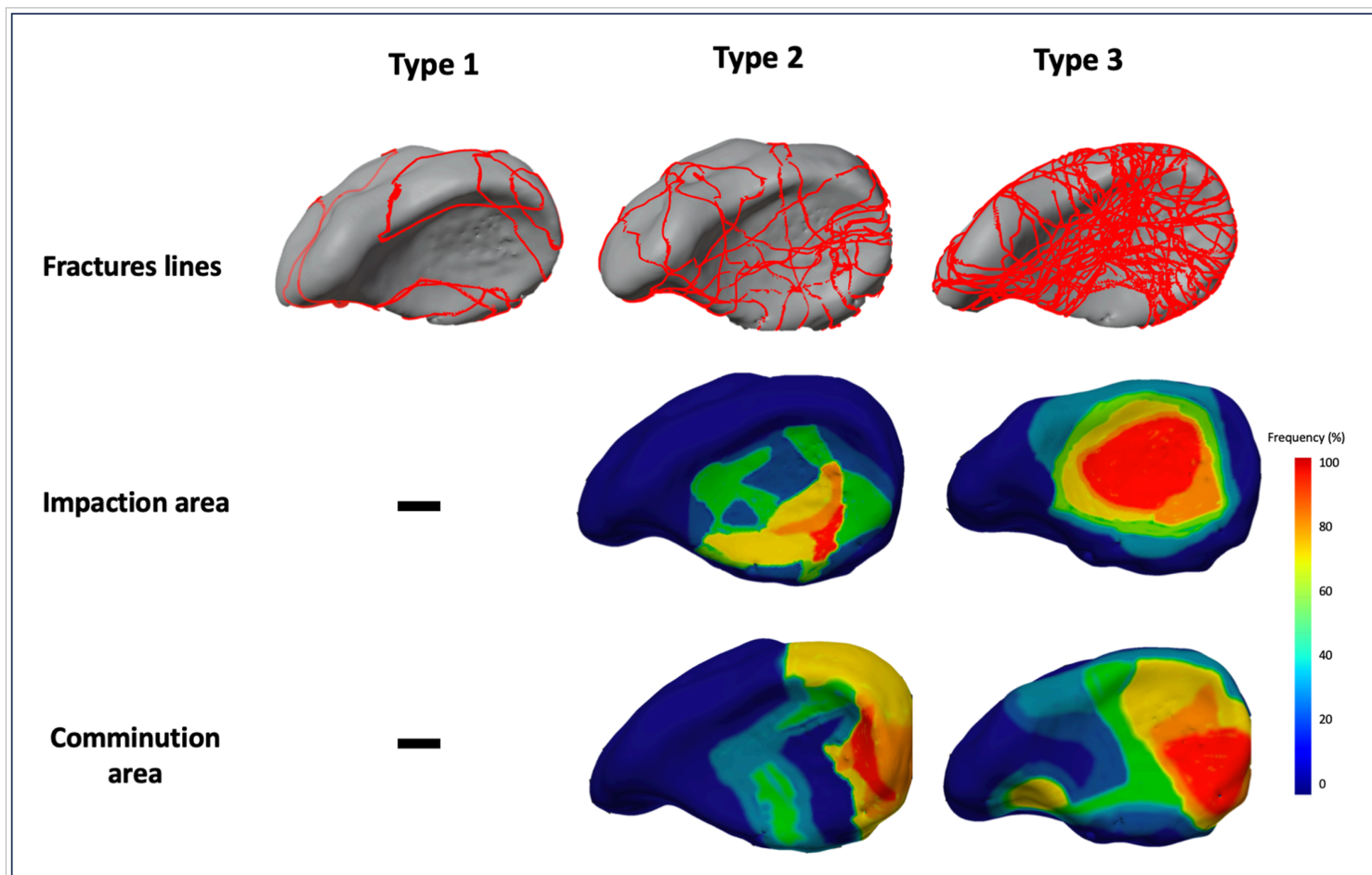


Figure 3

Fracture mapping, impactation and comminution zones for each type. The frequency of impactations and comminutions is represented using a heatmap, with a scale ranging from 0 to 100%.

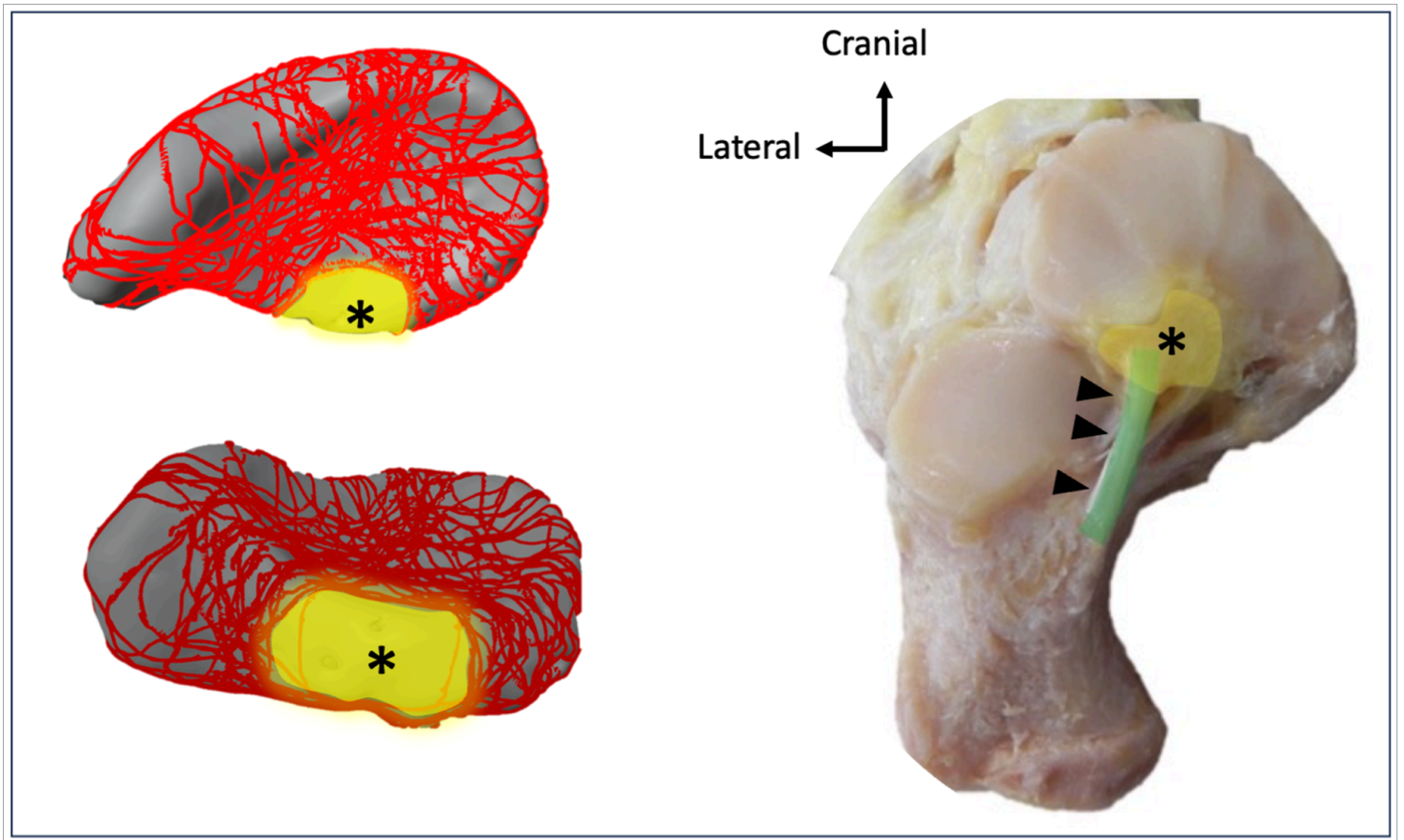


Figure 4

Figure illustrating the constant plantar fragment (*) and the plantar innominate ligament (**black arrows**) on this plastinated anatomical specimen of a right foot.

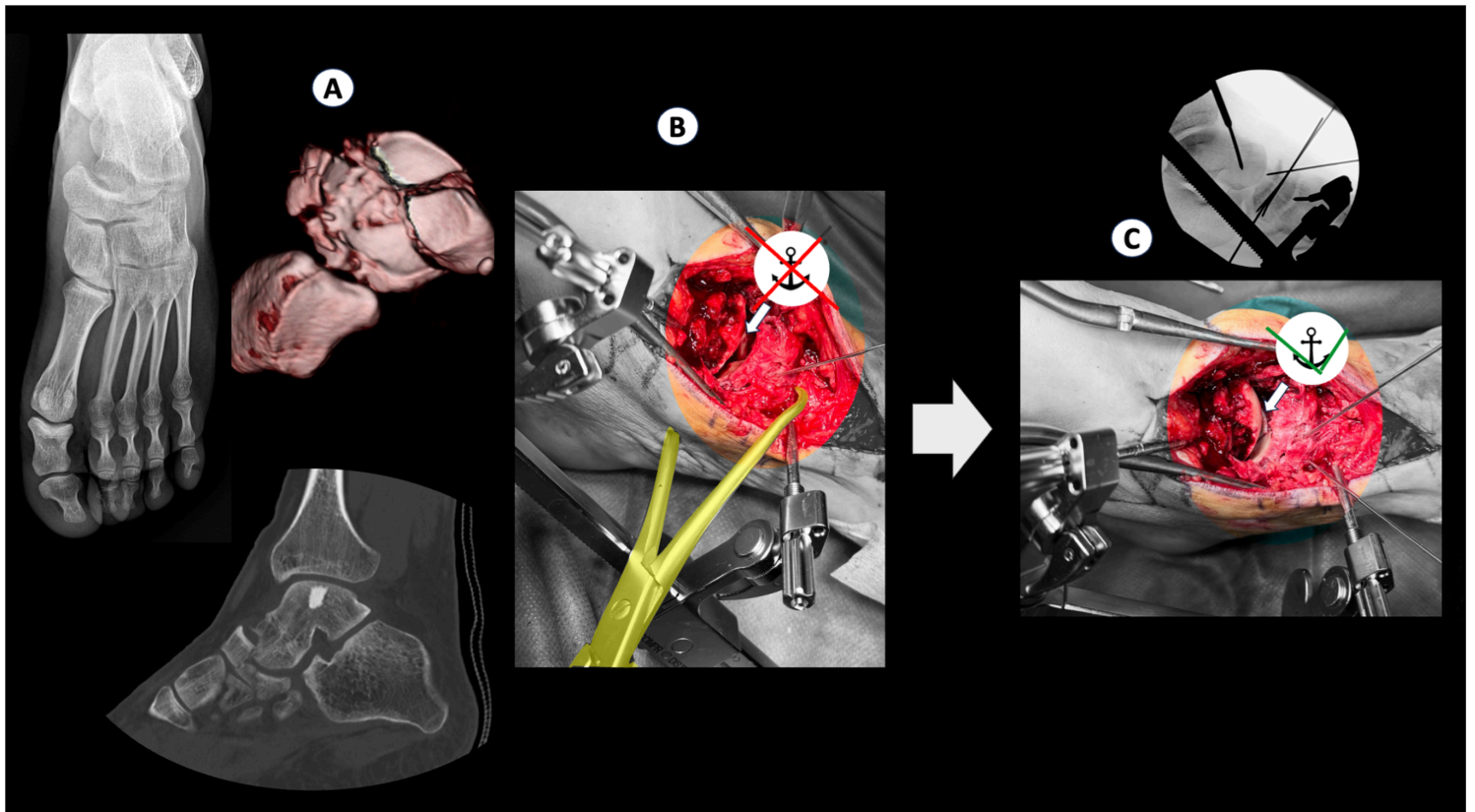


Figure 5

Clinical case example. Imaging and 3D reconstruction of a Type 3 fracture (A). Intraoperative photograph. Initial reduction was incomplete at the level of the constant plantar fragment (white arrow with anchor marking)(B). Using a Weber clamp (yellow), the previously reduced body segment was realigned onto the plantar fragment, ensuring proper positioning of the entire body(C). Note the use of a distractor, which allowed for clear identification of the fragments and facilitated the reduction process.

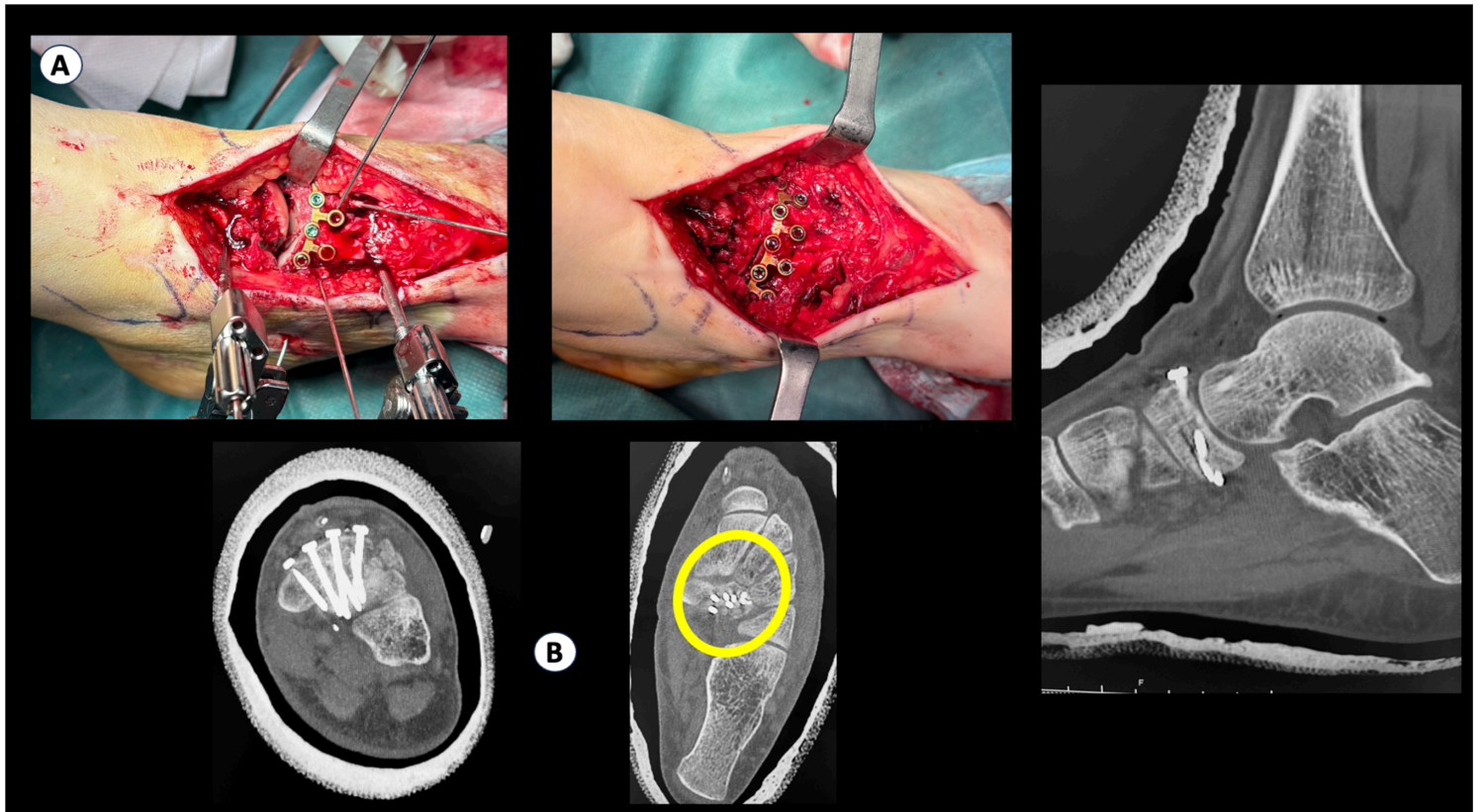


Figure 6

Postoperative images, including stability testing after distractor removal (**A**). Postoperative X-ray and CT scan. Note the convergence of all screws toward the constant plantar fragment (**B**).

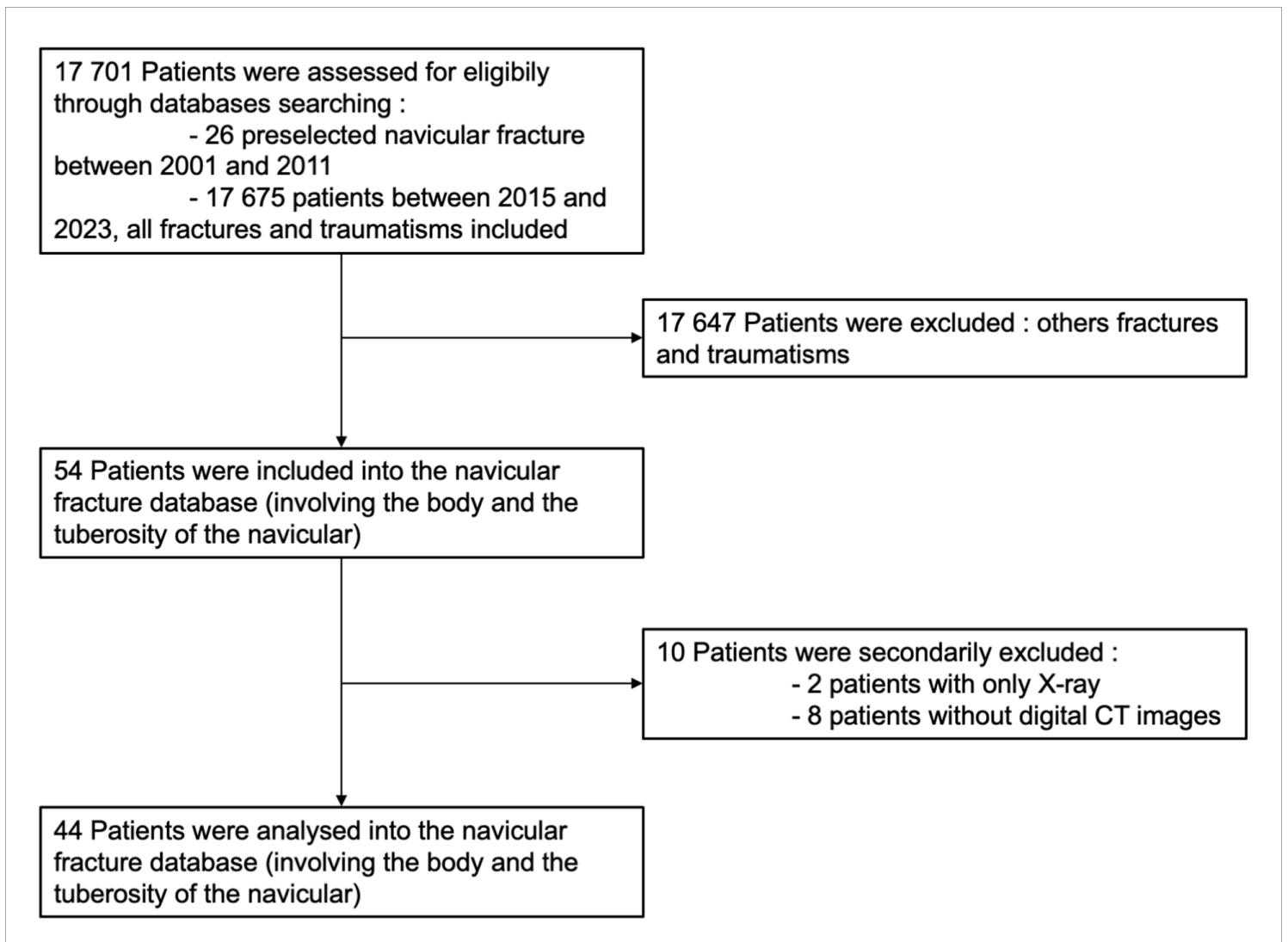


Figure 7

Flowchart