

High-Frequency Ultrasound as a Clinical Tool for Diagnosing Pediatric Anterior Talofibular Ligament Injuries and Guiding Conservative Treatment of Avulsion Fractures

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Abstract

Background Pediatric anterior talofibular ligament (ATFL) injuries differ from those in adults, with avulsion injuries occurring frequently at the ligament attachment sites. Small avulsion fractures may be difficult to detect, while objective imaging parameters for treatment planning and follow-up remain limited. This study evaluated the diagnostic and prognostic utility of high-frequency ultrasound (US) in pediatric ATFL injuries.

Methods We retrospectively analyzed 194 pediatric patients with ATFL injuries who underwent high-frequency US between December 2024 and March 2026. Thirty-two surgically treated patients were included in a diagnostic comparison of US and magnetic resonance imaging (MRI), using intraoperative findings as the reference standard. Forty-two patients with ATFL avulsion fractures treated conservatively and followed by US for 3 months were included in the prognostic analysis. The sensitivity and specificity of US and MRI for complete ATFL tears and avulsion fractures were assessed. The avulsion fracture separation distance was measured on US, and its ability to predict healing was evaluated using receiver operating characteristic (ROC) analysis. Measurement reproducibility was assessed using intraclass correlation coefficients (ICCs).

Results Among the 194 patients, avulsion fracture was the predominant injury pattern, occurring in 129 (66.5%). In the surgical cohort, complete ATFL tears were confirmed in 6 patients and avulsion fractures in 26. For complete tears, US showed a sensitivity of 83.3% compared with 66.7% for MRI. For avulsion fractures, US demonstrated 100% sensitivity versus 80.8% for MRI, with 100% specificity for both modalities. Among the 42 conservatively treated patients, 25 (59.5%) demonstrated healing at 3 months. Avulsion fracture separation distance showed excellent predictive performance for healing (AUC, 0.935; 95% CI, 0.814–0.988; $P < 0.001$). A cutoff of ≤ 0.95 mm yielded 92.0% sensitivity and 82.4% specificity. Interobserver and intraobserver agreement were excellent (ICC, 0.962 and 0.971, respectively).

Conclusions High-frequency US provides sensitive detection of pediatric ATFL avulsion fractures and enables quantitative assessment of avulsion fracture separation. A separation distance of ≤ 0.95 mm was associated with a higher likelihood of healing after conservative treatment. High-frequency US may therefore provide orthopedists with practical diagnostic and prognostic information to support treatment planning and follow-up in pediatric ATFL injuries.

Introduction

Pediatric ankle sprains are common musculoskeletal injuries encountered in orthopedic practice. The anterior talofibular ligament (ATFL) is the most frequently injured component of the lateral ankle ligament complex and plays an important role in lateral ankle stability [1]. Although pediatric ankle sprains are often considered minor injuries, their injury patterns differ from those in adults. In children, lateral ankle injuries may involve not only ligamentous injury but also avulsion fractures at the ligament attachment sites, particularly at the distal fibula [2–4]. Therefore, assessment of pediatric ATFL injuries

should consider not only ligament continuity but also the ligament–bone interface and the presence of small avulsion fragments.

Failure to recognize an ATFL avulsion fracture may lead to underestimation of injury severity and may affect subsequent management [3,4]. Small avulsion fragments can be difficult to detect on conventional radiographs, particularly in the acute setting [5,6]. MRI provides valuable information on ligament and associated osseous injuries; however, high-frequency ultrasound offers complementary visualization of the superficial ligament–bone interface and small cortical or avulsion abnormalities. From an orthopedic perspective, imaging should ideally provide information not only on the presence of injury but also on its severity and potential for healing when conservative treatment is selected. However, quantitative imaging parameters for predicting the healing of pediatric ATFL avulsion fractures have not been well established.

MRI is widely used for evaluating ankle ligament injuries because of its excellent soft-tissue contrast and ability to demonstrate ligament injury and continuity [7]. High-frequency ultrasound (US) provides direct visualization of superficial ligament structures and adjacent cortical bone and allows real-time, dynamic, and multi-angle assessment of the ligament–bone interface. Previous studies have demonstrated the usefulness of US for detecting occult fractures in pediatric ankle injuries [6,8] and evaluating ATFL tears [7,9]. These features may be particularly valuable for identifying small avulsion injuries at the ATFL attachment site in children.

In addition to diagnosis, high-frequency US may allow quantitative assessment of avulsion injuries. Because the avulsion fragment and its original attachment site can be directly visualized, the separation distance between them can be measured and may provide an objective indicator of healing potential during conservative treatment.

Therefore, this study aimed to evaluate the clinical utility of high-frequency US in pediatric ATFL injuries by: (1) characterizing ultrasound injury patterns; (2) comparing the diagnostic performance of US and MRI for complete ATFL tears and avulsion fractures using intraoperative findings as the reference standard; and (3) determining whether ultrasound-measured avulsion fracture separation distance could predict healing during conservative treatment.

Materials and Methods

Study Population

We retrospectively collected data from 194 pediatric patients who presented to our hospital with ankle injuries and were diagnosed with ATFL injury by ultrasound between December 2024 and March 2026. Inclusion criteria were: (1) age ≤ 18 years; (2) ultrasound findings indicative of ATFL injury; and (3) adequate image quality for evaluation. Exclusion criteria included: (1) concomitant systemic diseases affecting bone healing; and (2) incomplete clinical data.

The 194 patients were included in the cross-sectional ultrasound injury pattern analysis. Among them, 32 underwent surgical treatment and were included in the diagnostic efficacy comparison between US and MRI; 42 patients with avulsion fractures who received conservative treatment and completed a 3-month ultrasound follow-up were included in the prognostic analysis. This retrospective study was approved by the Institutional Review Board of Shenzhen Children's Hospital (Approval No. 202609302). The study was conducted in accordance with the Declaration of Helsinki. The requirement for informed consent was waived due to the retrospective design of the study.

Ultrasound Examination

Ultrasound examinations were performed using GE LOGIQ E20/E9, Canon Aplio i900, and Philips EPIQ 7 systems equipped with 5–24 MHz high-frequency linear transducers. Patients were positioned supine or in the lateral decubitus position with the ankle in mild plantar flexion and inversion. The ATFL region was routinely scanned with bilateral comparison. The assessment focused on ATFL thickness, echogenicity, continuity, tension, clarity, and the presence of avulsion fractures or cortical disruption, as shown in Fig. 1.

Ultrasound Injury Pattern Classification

Based on the ultrasound classification described by Cai et al. [10] and adapted for the present study, ATFL injuries were categorized into five types (Fig. 2): Type I, no swelling or ecchymosis with an intact fiber structure; Type II, organized swelling with an intact fiber structure; Type III, tissue swelling with ligament elongation and tearing; Type IV, complete tear with a “free ligament” appearance; and Type V, avulsion fracture at the talar or fibular margin.

At the plane of maximum visualization, the maximum perpendicular distance between the avulsion fragment and the adjacent cortical bone at the original ligament attachment site was measured on ultrasound images. Each measurement was performed twice, and the mean value was recorded. Two musculoskeletal ultrasound specialists with more than 10 years of experience independently performed the measurements and were blinded to each other's results. The mean value of the two measurements obtained by each observer was used for interobserver agreement analysis, and the average value of the two observers' measurements was used as the final avulsion fracture distance for subsequent prognostic analysis.

MRI Examination

MRI and ultrasound examinations were performed during the initial evaluation period, with an interval of no more than 7 days between the two examinations. All MRI examinations were completed before surgical treatment. MRI was performed using 3.0-T scanners (Siemens Skyra and GE Signa HDxt). The

imaging protocols included axial, sagittal, and coronal T1-weighted, T2-weighted, and fat-suppressed sequences.

Image Analysis

Two experienced musculoskeletal radiologists (with more than 8 years of experience in musculoskeletal imaging) independently reviewed the MRI examinations. The radiologists were blinded to the ultrasound findings, surgical results, and clinical outcomes. Similarly, ultrasound images were evaluated independently by two musculoskeletal ultrasound specialists who were blinded to MRI findings and clinical information.

Surgical and Follow-up Criteria

All 32 surgical patients underwent ankle arthroscopy and surgical treatment under general anesthesia. Intraoperative findings of the ATFL, talar and fibular cartilage surfaces, and joint capsule were recorded, including the location and extent of ligament injury and the presence of avulsion fractures. Surgical findings served as the reference standard.

For the 42 non-surgical patients, high-frequency ultrasound was repeated at 3 months after the initial diagnosis to assess ATFL thickness, echogenicity, continuity, and healing at the avulsion fracture site. Healing was classified based on ultrasound findings as: (1) healed—normal ligament structure with callus formation or bone union; or (2) unhealed—no significant improvement in ligament structure with persistent avulsion fracture.

Statistical Analysis

Data were analyzed using SPSS 21.0 and MedCalc 20.0 software. Intraclass correlation coefficients (ICCs) and Bland–Altman analyses were used to assess interobserver and intraobserver agreement for avulsion fracture distance measurements. Using surgical findings as the gold standard, the sensitivity, specificity, and accuracy of US and MRI for diagnosing complete ATFL tears and avulsion fractures were calculated. ROC curve analysis was used to evaluate the predictive value of avulsion fracture distance for healing, and the optimal cutoff value was determined using the maximum Youden index. A P -value < 0.05 was considered statistically significant.

Results

Distribution of Ultrasound Injury Patterns in 194 Pediatric ATFL Injuries

The ultrasound classification results for the 194 patients with ATFL injuries are shown in Table 1. Type V (avulsion fracture) was the most common, identified in 129 cases (66.5%), followed by Type II in 55

cases (28.4%), Type III in 3 cases (1.5%), and Type IV in 7 cases (3.6%). This distribution indicates that avulsion fracture is the predominant pathological type of ATFL injury in children.

Table 1
Distribution of ultrasound injury patterns in pediatric ATFL injuries

Type	Definition	n (%)
II	Organized swelling, intact fiber structure	55 (28.4)
III	Tissue swelling, ligament elongation, and partial tear	3 (1.5)
IV	Complete tear with "free ligament" appearance	7 (3.6)
V	Avulsion fracture at the fibular or talar margin	129 (66.5)
Total		194 (100)

Comparison of Diagnostic Efficacy Between US and MRI (32 Surgical Patients)

Among the 32 surgical patients, intraoperative findings confirmed complete ATFL tear in 6 cases (18.7%) and preserved ligament continuity (partial tear or contusion) in 26 cases (81.3%). Avulsion fractures were present in 26 cases (81.3%) and absent in 6 cases (18.7%). The distribution of avulsion fracture locations was: fibular attachment in 23 cases (88.5%), talar attachment in 2 cases (7.7%), and both attachments in 1 case (3.8%).

Diagnostic Efficacy of US and MRI for Ligament Tears

Among the 6 patients with complete ligament tears, US correctly diagnosed 5 cases and missed 1 case; MRI correctly diagnosed 4 cases and missed 2 cases. The diagnostic efficacy of the two methods for ligament tears is compared in Table 2.

Table 2
Comparison of US and MRI for diagnosing complete ligament tears

Modality	True Positive	False Negative	Sensitivity (%)
US	5	1	83.3
MRI	4	2	66.7

Diagnostic Efficacy of US and MRI for Avulsion Fractures

Among the 26 patients with avulsion fractures (Fig. 3), US correctly diagnosed all 26 cases with no missed diagnoses; MRI correctly diagnosed 21 cases and missed 5 avulsion fractures. The diagnostic efficacy of the two methods for avulsion fractures is compared in Table 3. For the diagnosis of ATFL avulsion fractures, US demonstrated higher sensitivity than MRI (100.0% vs. 80.8%), while both modalities showed a specificity of 100.0%.

Table 3
Comparison of US and MRI for diagnosing avulsion fractures

Modality	TP	FP	TN	FN	Sensitivity (%)	Specificity (%)	Accuracy (%)
US	26	0	6	0	100	100	100
MRI	21	0	6	5	80.8	100	84.4
TP: true positive; FP: false positive; TN: true negative; FN: false negative							

ROC Analysis of Avulsion Fracture Distance for Predicting Healing

In the 42 patients in the follow-up cohort, the avulsion fracture distance ranged from 0.4 to 3.3 mm. At the 3-month ultrasound follow-up, 25 patients (59.5%) showed healing, as shown in Fig. 4, while 17 (40.5%) remained unhealed.

ROC curve analysis demonstrated that the avulsion fracture distance predicted healing with an area under the curve (AUC) of 0.935 (95% CI: 0.814–0.988, $P < 0.001$), indicating excellent predictive value, as shown in Fig. 5. The maximum Youden index was $J = 0.7435$, corresponding to an optimal cutoff value of ≤ 0.95 mm. This threshold yielded a sensitivity of 92.0% and a specificity of 82.4% for predicting healing.

Interobserver and Intraobserver Agreement of Avulsion Fracture Distance Measurements

The intraclass correlation coefficient (ICC) for avulsion fracture distance measurements between the two physicians was 0.962 (95% CI: 0.931–0.979). Bland-Altman analysis showed a mean difference of -0.007 mm (95% CI: -0.084 to $+0.069$ mm) between the two physicians' measurements, with 95% limits of agreement ranging from -0.488 mm to $+0.474$ mm. Only 2 of 42 measurement points (4.8%) fell outside the 95% limits of agreement, below the expected 5%. These results indicate excellent interobserver agreement, with measurement errors within clinically acceptable ranges.

One experienced musculoskeletal ultrasound physician repeated the measurements after a 4-week interval, while being blinded to the initial measurements. The intraobserver ICC was 0.971 (95% CI: 0.948–0.985). Bland-Altman analysis showed that the mean difference between the two measurements was -0.002 mm (95% CI: -0.072 to $+0.067$ mm), with 95% limits of agreement ranging from -0.439 mm to $+0.434$ mm. Only 2 of the 42 measurement points (4.8%) were outside the 95% limits of agreement. These results demonstrate excellent intraobserver agreement, with measurement errors within clinically acceptable limits (Fig. 6).

Discussion

The present study evaluated the clinical utility of high-frequency US in pediatric ATFL injuries from both diagnostic and prognostic perspectives. Three main findings were identified. First, avulsion fracture was the predominant injury pattern. Second, US showed higher sensitivity than MRI for detecting ATFL avulsion fractures, while both modalities demonstrated high specificity. Third, ultrasound-measured avulsion fracture separation distance showed excellent predictive performance for healing after conservative treatment.

Pediatric ATFL injury should not be considered simply as a ligament tear. In the immature ankle, avulsion fractures at the ligament attachment site are relatively common, making pediatric ATFL injury different from an isolated ligament tear [2,3]. Therefore, evaluation should include both ligament continuity and the talar and fibular attachment sites [3,8]. Failure to recognize small avulsion fragments may lead to underestimation of injury severity [3,5,6].

In our surgical cohort, US detected all 26 avulsion fractures, compared with 21 detected by MRI, corresponding to sensitivities of 100% and 80.8%, respectively. Both modalities had 100% specificity. These findings do not suggest that US should replace MRI. Rather, US provides complementary information through direct visualization of superficial ligament structures and the ligament–bone interface [3,7,9]. Its real-time assessment may be particularly useful for identifying small avulsion injuries [3,8,9].

An important finding was that US allowed quantitative measurement of the separation distance between the avulsion fragment and its original attachment site. This provides an objective description of the injury and showed excellent reproducibility, with interobserver and intraobserver ICCs of 0.962 and 0.971, respectively. Reliable quantitative assessment may facilitate communication between imaging specialists and orthopedic surgeons and provide additional information beyond a qualitative diagnosis.

The separation distance also demonstrated strong prognostic value. Among conservatively treated patients, a separation distance of ≤ 0.95 mm showed an AUC of 0.935 for predicting healing, with 92.0% sensitivity and 82.4% specificity. Claes et al. [11] noted that appropriate mechanical stability during fracture healing is essential for callus formation and bone remodeling, and increased fracture gap may affect local stability and bony union. A smaller separation may indicate better maintenance of the fragment–bone relationship and a more favorable local environment for healing. However, the 0.95-mm cutoff should be considered a potential imaging reference rather than an absolute treatment criterion. Clinical symptoms, ankle stability, skeletal maturity, and other imaging findings should remain part of treatment decisions.

From a clinical perspective, these findings suggest that high-frequency US may provide a practical approach encompassing detection of ATFL injury, identification of avulsion fractures, quantitative assessment of fragment separation, and follow-up during conservative treatment.

Limitations

This study has several limitations. First, it is a single-center retrospective study, which may introduce selection bias. Second, the follow-up sample size is relatively limited. Future multicenter, large-sample prospective studies are needed to further validate the conclusions of this study.

Conclusion

High-frequency ultrasound demonstrated high sensitivity for detecting pediatric ATFL avulsion fractures and enabled reliable quantitative measurement of avulsion fracture separation. A separation distance of ≤ 0.95 mm was associated with a higher likelihood of healing after conservative treatment, suggesting that high-frequency ultrasound may provide practical diagnostic and prognostic information to support treatment planning and follow-up.

Abbreviations

ATFL, anterior talofibular ligament;

AUC, area under the curve;

CI, confidence interval;

FN, false negative;

FP, false positive;

ICC, intraclass correlation coefficient;

MRI, magnetic resonance imaging;

ROC, receiver operating characteristic;

TN, true negative;

TP, true positive;

US, ultrasound.

Declarations

Ethics approval and consent to participate

This retrospective study was approved by the Ethics Committee of Affiliated Shenzhen Children's Hospital, College of Medicine, Shantou University (Approval No. 202609302; approved on August 31, 2026). The study was conducted in accordance with the principles of the Declaration of Helsinki. The requirement for informed consent was waived by the ethics committee because of the retrospective nature of the study.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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The authors received no specific funding for this study.

Authors' contributions

BH and ZL designed the study. BH collected and analyzed the data and drafted the manuscript. CY, CD, SX, YL, BT, TW, and ZW contributed to clinical data collection, imaging evaluation, and interpretation of the results. ZL supervised the study and critically revised the manuscript. All authors read and approved the final manuscript.

Data availability statement

The datasets analyzed during the current study are not publicly available because they contain patient-related information and are subject to institutional and ethical restrictions. The data cannot be shared outside the institution in accordance with the applicable institutional and ethical requirements.

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Figures

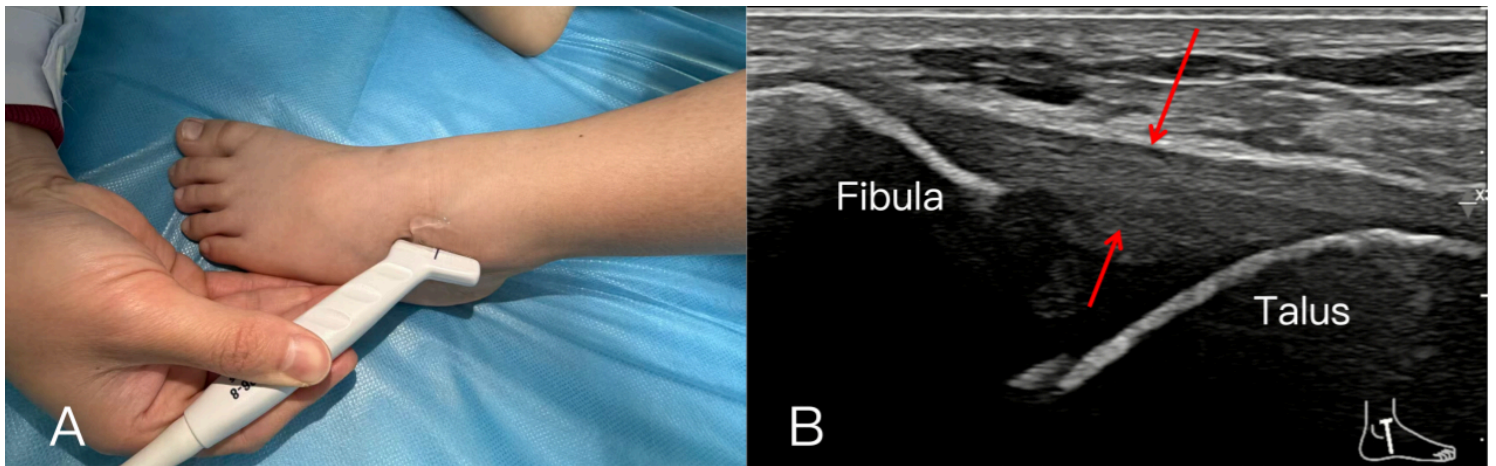


Figure 1

Standard ultrasound examination of the anterior talofibular ligament (ATFL). (A) Patient positioning for ATFL ultrasound examination. (B) Normal ultrasound appearance of the ATFL (red arrow).

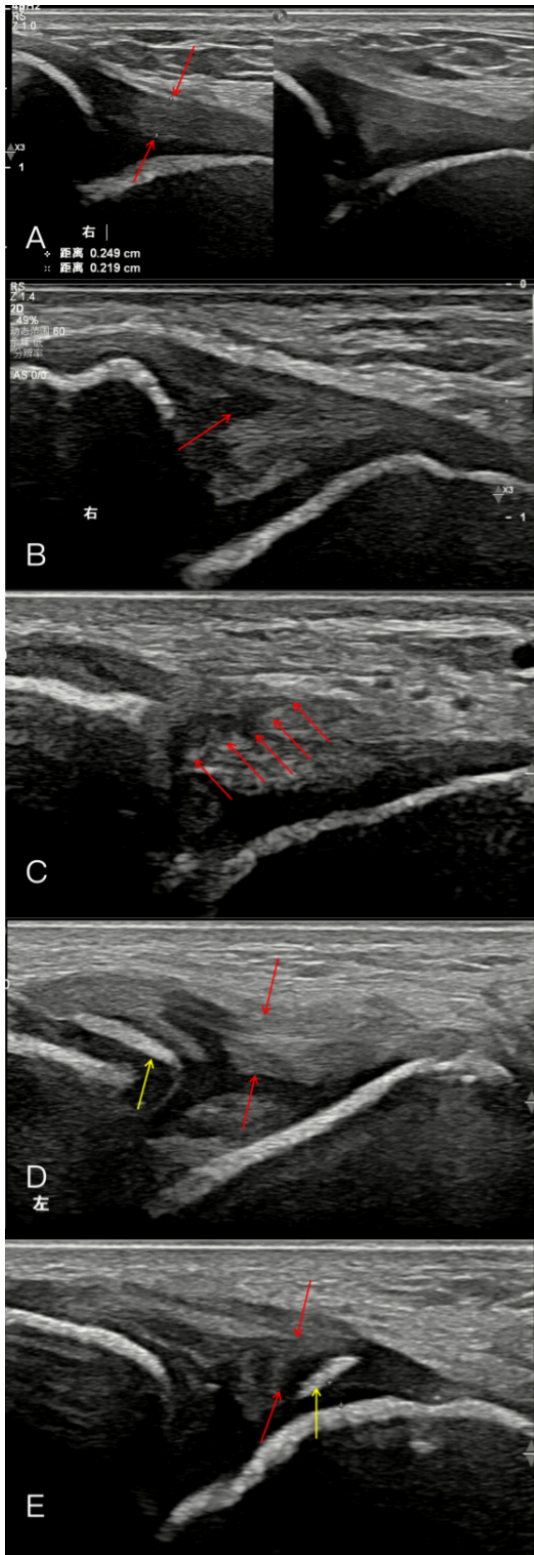


Figure 2

Ultrasonographic classification of ATFL injuries. (A) Type II ATFL injury (left panel), showing ligament thickening (red arrow), compared with a normal Type I ATFL (right panel). (B) Type III ATFL injury, showing partial ligament tear (red arrow). (C) Type IV ATFL injury, showing complete ligament rupture (red arrow). (D) Type V ATFL injury with an avulsion fracture at the fibular attachment (yellow arrow). (E) Type V ATFL injury with an avulsion fracture at the talar attachment (yellow arrow).

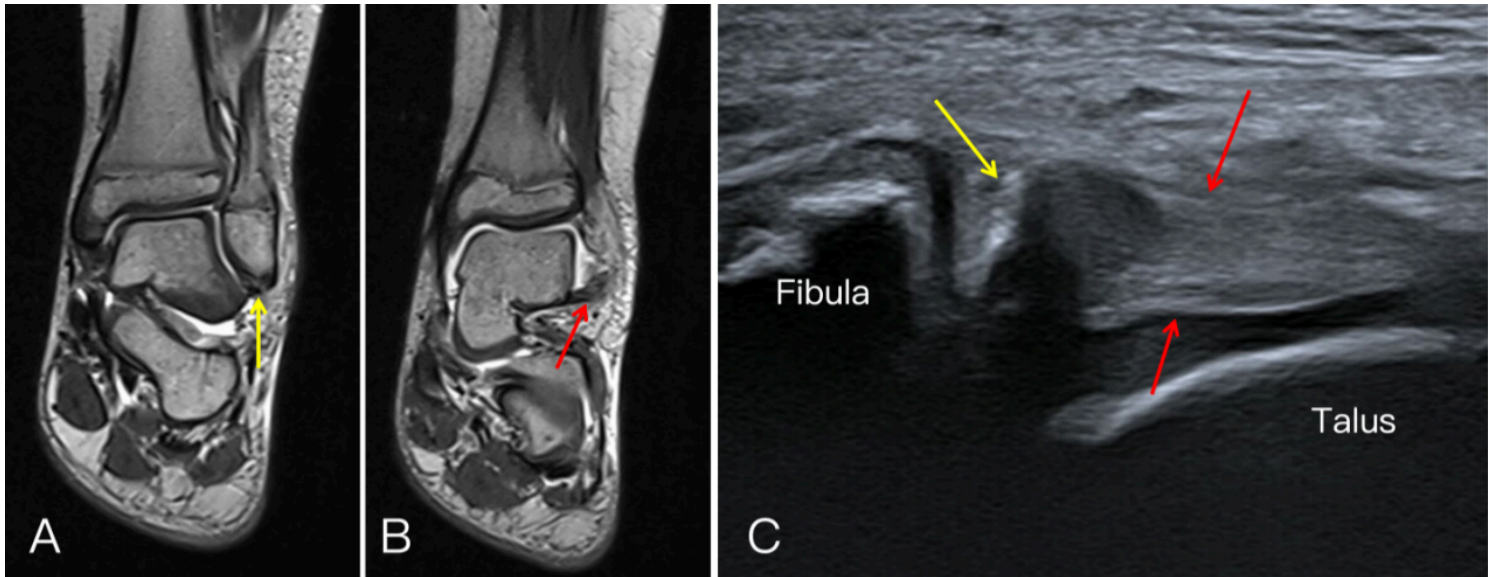


Figure 3

Magnetic resonance imaging and ultrasonographic findings of ATFL injury associated with avulsion fracture. (A) MRI showing a small avulsion fragment at the distal fibula (yellow arrow). (B) Ultrasonography demonstrating swelling of the ATFL (red arrow). (C) Ultrasonography showing thickening of the injured ATFL (red arrow) accompanied by an avulsion fracture of the distal fibula (yellow arrow).

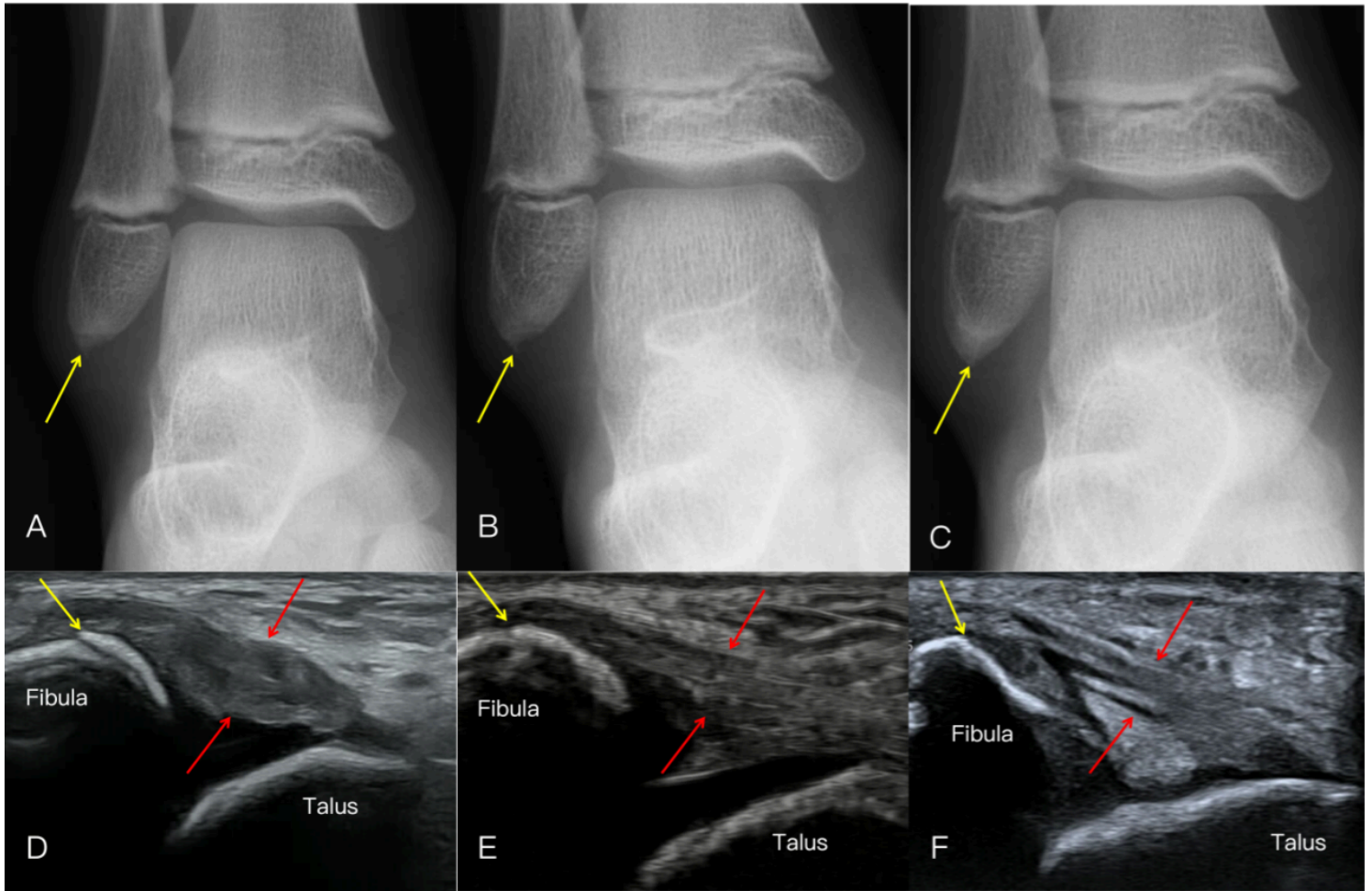


Figure 4

Serial radiographic and ultrasonographic follow-up of ATFL injury with distal fibular avulsion fracture. (A, E) Initial examination on the first day after ankle sprain. Radiography revealed a small avulsion fracture fragment at the distal fibula (yellow arrow), while ultrasonography demonstrated ATFL thickening (red arrow) with an avulsion fracture at the distal fibular attachment site (yellow arrow); the fracture gap measured <0.95 mm. (B, F) One-month follow-up. Radiography showed a blurred fracture line with callus formation (yellow arrow). Ultrasonography demonstrated mild residual ATFL thickening (red arrow), callus formation, and partial resolution of the fracture line (yellow arrow). (C, G) Four-month follow-up. Radiography showed increased bone density at the distal fibula without a visible fracture line (yellow arrow). Ultrasonography demonstrated continuous cortical bone integrity (yellow arrow) and restoration of normal ATFL morphology.

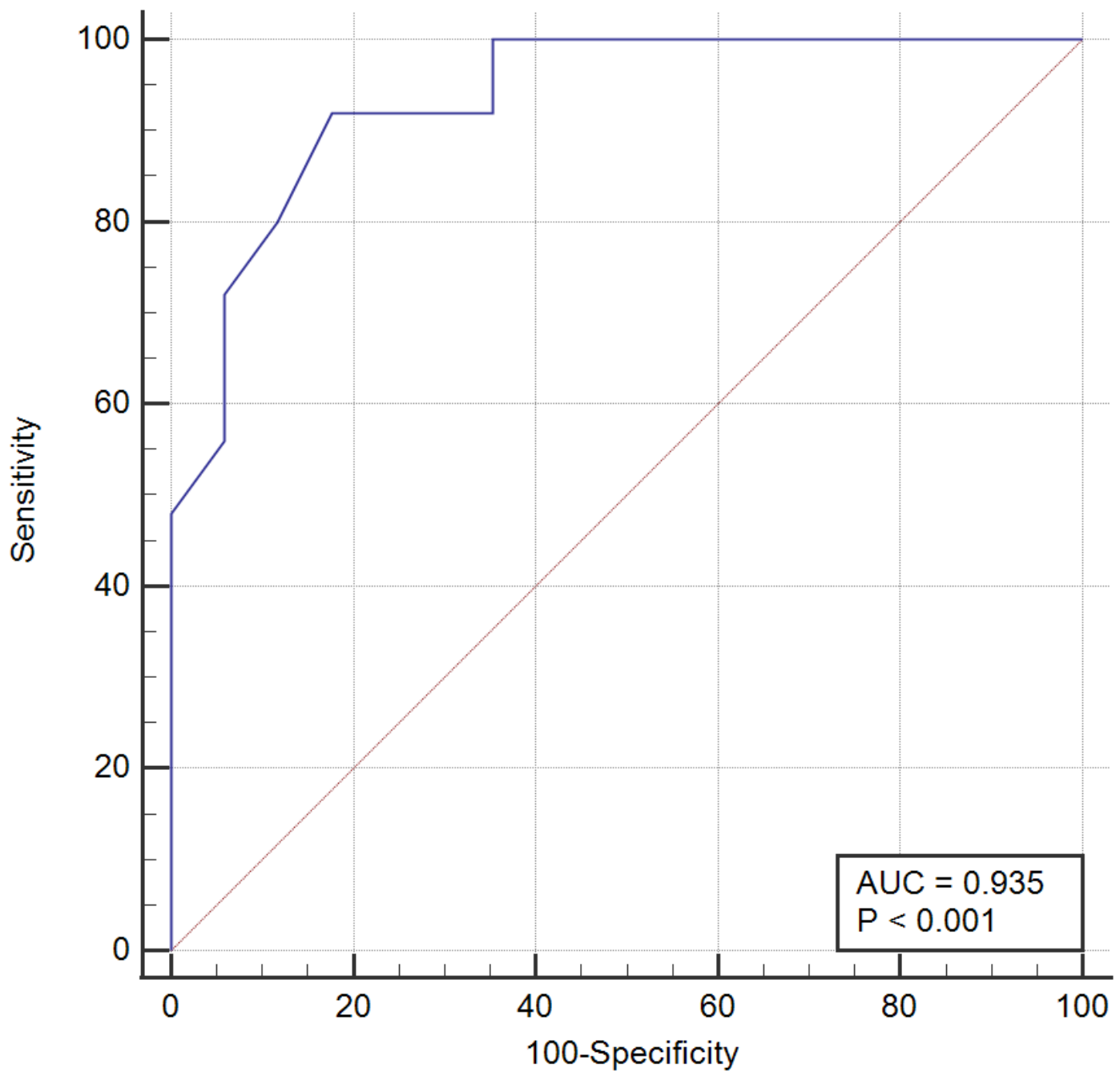


Figure 5

Receiver operating characteristic (ROC) curve analysis of avulsion fracture separation distance for predicting healing after conservative treatment of ATFL injury.

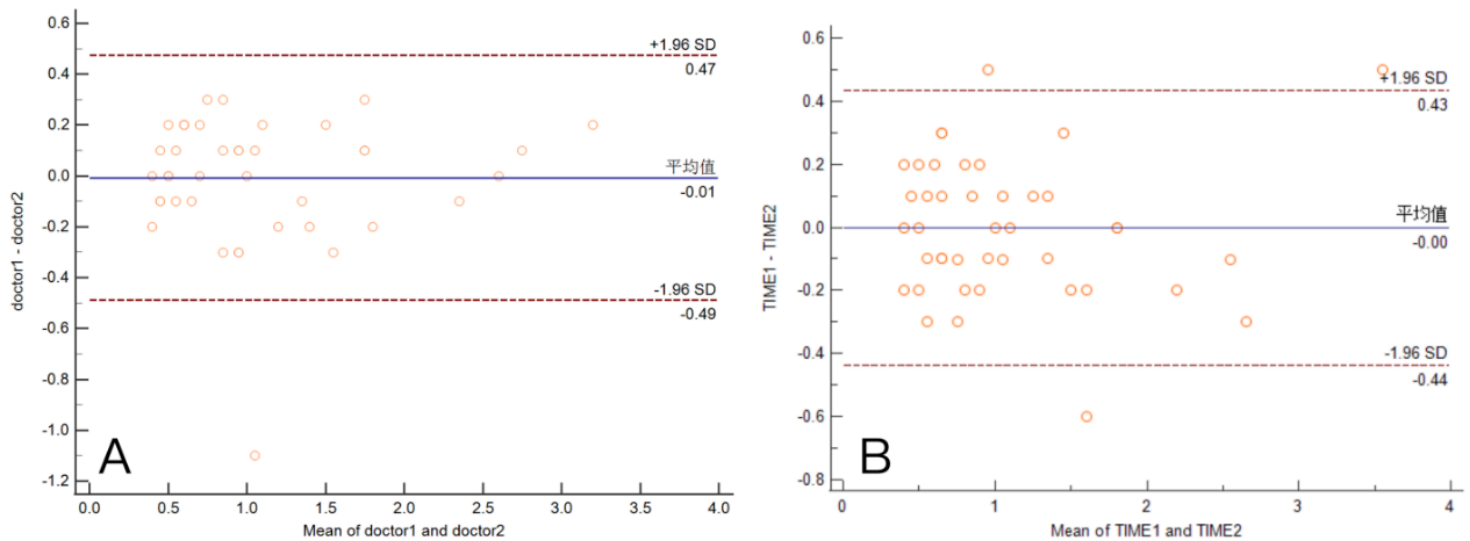


Figure 6

Bland–Altman analysis of interobserver and intraobserver agreement for avulsion fracture separation distance measurements. (A) Interobserver agreement between two physicians. The mean difference was 0.007 mm, with 95% limits of agreement ranging from –0.488 to 0.474 mm. (B) Intraobserver agreement for repeated measurements by the same physician. The mean difference was 0.002 mm, with 95% limits of agreement ranging from –0.439 to 0.434 mm.