

Biomechanical Assessment in Calcaneal Fracture Management: Methods, Clinical Applications, and Future Directions

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This review explores the biomechanical evaluation of calcaneal fractures, utilizing techniques such as computed tomography (CT) imaging and finite element analysis to assess fracture stability, alignment, and load distribution. These evaluations are essential for enhancing treatment approaches and improving patient outcomes. The review underscores the significance of quantitative metrics in linking biomechanical parameters with clinical outcomes, thereby facilitating personalized treatment planning. Future research advancements are anticipated to focus on integrating high-throughput biomechanical approaches, multimodal datasets, and artificial intelligence to enhance the precision of fracture evaluations and develop tailored interventions that foster better recovery and overall quality of life for patients with calcaneal fractures.

Keywords: calcaneal fractures; biomechanical assessment; quantitative metrics; clinical applications; finite element analysis; computed tomography scans

Introduction

Calcaneal fractures, usually resulting from high-energy trauma such as falls from height or vehicle accidents, have a significant impact on health and function, often leading to chronic pain and disability [1]. Despite being unacknowledged for their morbidity, these fractures disrupt normal gait and compromise lower limb stability due to the critical role of calcaneus in weight-bearing and movement. As the foot's largest bone, the calcaneus is crucial for proper gait and overall lower limb balance; its disruption often results in functional impairment, chronic pain, and reduced capability to perform daily activities [2]. Calcaneal fractures account for approximately 1–2% of all tarsal bone fractures, with an incidence of 11.5–13.7 per 100,000 person-years, predominantly affecting young males engaged in manual labor. Prompt and appropriate intervention is crucial to restore function and support patient independence [3]. Biomechanical assessment, which evaluates fracture stability, alignment, and load distribution by applying quantitative metrics, offers valuable insights into injury severity and treatment response [4]. This strategy has become integral part of orthopedic management, aiding in the development of optimized treatment approaches and the assessment of clinical outcomes.

A comprehensive literature search on the biomechanics of calcaneal fractures was conducted across MEDLINE, EMBASE, and Web of Science up to December 2024. Keywords included “calcaneal fracture” and “biomechanical assessment” to identify relevant studies. Peer-reviewed articles reporting biomechanical evaluations of calcaneal fractures with quantitative data were included in this study. However, case reports, non-English articles (those published in other languages), and studies without primary data or a biomechanical focus were excluded. Data were systematically extracted and categorized to examine the relationships between biomechanical indicators and clinical outcomes. This review aims to highlight the relevance of biomechanical parameters to clinical significance, diagnostic tools, and measurement techniques, to support enhanced treatment approaches for calcaneal fractures.

Biomechanical Characteristics of Calcaneal Fractures

Anatomical and Physiological Features

The calcaneus, the largest tarsal bone, plays a critical role in maintaining the structural integrity of the foot by supporting the medial longitudinal arch and facilitating stability and propulsion during gait. It articulates with the navicular, middle cuneiform, and cuboid bones and is supported by a dense ligamentous network that maintains subtalar joint function and overall foot stability. Physiologically, calcaneus absorbs and transmits ground reaction forces, making it particularly vulnerable to high-energy trauma, such as those resulting from falls or motor vehicle accidents [5].

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Table 1. Comparison of different imaging modalities used for calcaneal fracture detection.

Imaging modality	Advantages	Limitations
X-ray	(1) Cost-effective and quick for initial evaluation, providing basic fracture information. (2) Useful for identifying obvious fractures and general fracture patterns. (3) Good for preliminary screening and determining the need for further imaging.	(1) Limited to 2D imaging, making it difficult to show complex fracture lines and joint surface details clearly. (2) Lower sensitivity for intra-articular fractures and subtle fractures, with a higher risk of missed diagnosis. (3) Unable to accurately assess soft tissue injuries and ligament damage.
CT	(1) Capable of 3D imaging to accurately capture fracture lines, displacement, and joint involvement. (2) More precise evaluation of complex fractures (e.g., intra-articular fractures) serves as the basis for calcaneal fracture classification. (3) Multiplanar reconstruction allows viewing fractures from different angles, aiding surgical planning.	(1) Radiation exposure may pose long-term health risks. (2) Limited ability to assess soft tissue injuries, especially ligaments and tendons. (3) Difficulty distinguishing between acute and chronic fractures.
MRI	(1) Superior assessment of soft tissue injuries, including ligaments, tendons, and bone marrow edema. (2) No radiation exposure, safer for long-term patient health. (3) Provides detailed insights on bone marrow edema information, helping to determine the freshness of fracture.	(1) Higher cost and longer examination time. (2) Less intuitive than CT to capture fracture lines, especially subtle ones. (3) Less effective than CT for visualizing calcifications and bony structures and may be affected by metal implants.

Abbreviations: CT, computed tomography; MRI, magnetic resonance imaging.

Types and Classification of Calcaneal Fractures

Calcaneal fractures vary in their location, complexity, and extent of soft tissue involvement. The Sanders classification system is widely used to categorize intra-articular fractures into four types based on fracture patterns: Type I (tongue-type), Type II (joint depression), Type III (tongue-type with joint depression), and Type IV (comminuted) [6]. Accurate classification is critical for guiding appropriate treatment and predicting clinical outcomes, particularly for intra-articular fractures where the integrity of the biomechanically critical subtalar joint is at risk.

Biomechanical Principles of Calcaneal Fractures

These fractures often result from high-energy trauma involving multidirectional forces. Axial loading can produce compressive fractures, whereas shear forces may lead to joint dislocation. For example, a case report using 3D computed tomography (CT) reconstruction revealed articular surface mismatch with a von Mises stress peak of 25 MPa, which correlated with postoperative gait abnormalities [7]. Intra-articular fractures disrupt talocalcaneal congruence, altering the joint's mechanical behavior and reducing stability. Furthermore, displacement, fragmentation, and malalignment impair load-sharing distribution and weight-bearing capacity, potentially increasing the risk of long-term dysfunction if not properly managed.

Biomechanical Assessment Tools

X-ray Imaging and CT Scans

Conventional X-rays and CT scans are the primary imaging approaches for the biomechanical assessment of calcaneal

fractures [8,9]. X-rays provide a rapid and cost-effective tool for initial evaluation, offering two-dimensional views to assess fracture alignment, configuration, and obvious joint involvement. However, their limited ability to depict complex three-dimensional fracture patterns or subtle intra-articular displacements reduces their diagnostic accuracy [10]. Conversely, CT imaging, with its multi-planar reconstruction capabilities, provides superior detail for characterizing fracture lines, fragmentation, and articular step-offs, serving as the basis for classification systems such as the Sanders system [11]. Despite these advantages, CT entails higher radiation exposure and may not be readily accessible in all clinical settings. Notably, the study has demonstrated that CT can identify postoperative articular displacement >2 mm in approximately 16.4% of cases where radiographs suggested of ≤ 2 mm, underscoring its crucial role in precise intra-articular assessment [12]. Magnetic resonance imaging (MRI), while offering excellent soft tissue resolution, is less commonly used for acute fracture assessment due to its limited visualization of bony structure compared to CT. A comparative overview of these imaging modalities is provided in Table 1 [13,14].

Fracture Stability Assessment

The evaluation of fracture stability relies on both a combination of radiographic measures and clinical findings. Key radiographic parameters include Böhler's angle (normal range: 25° – 40° in adults) and Gissane's angle (normal range: 100° – 130° in adults). A reduction in Böhler's angle below 25° indicates elevated tensile stress within the calcaneus and suggests greater injury severity; values approaching 0° significantly increase the likelihood of requiring sub-

Table 2. Comparative analysis of biomechanical testing equipment.

Study	Sample type		Loading conditions	Equipment accuracy	Testing objective	Limitations
Pinzaru <i>et al.</i> [17]	Synthetic models	bone	Static vertical loading (350 N/700 N)	High-precision material testing machine	Fixation system stability, stress distribution	Synthetic models cannot simulate <i>in vivo</i> biological responses
Yu <i>et al.</i> [18]	Cadaveric specimens		Static axial compression (500 N)	Standard material testing machine	Stiffness and strength of titanium plates	Cadaver preservation affects mechanical properties
Jordan <i>et al.</i> [19]	Fresh calcanei	cadaveric	Dynamic cyclic loading (0–1000 N)	Dynamic testing machine (Instron)	Post-fracture fatigue performance	High cost of dynamic testing, small sample size

sequent subtalar arthrodesis [9,14]. Accurate restoration of these angles during surgery is critical for achieving optimal functional outcomes. In pediatric patients, interpretation of these parameters can be more challenging due to developmental variations and incomplete ossification, which may complicate both diagnosis and management planning [15]. While stable fractures in pediatric populations often respond well to conservative treatment, unstable fractures typically necessitate surgical intervention to restore biomechanical integrity and mitigate long-term complications.

Mechanical Testing Equipment

Biomechanical testing systems, including materials testing machines, are widely employed to quantitatively evaluate the structural performance of fractured calcanei and the efficacy of various fixation methods under controlled loading conditions [16]. These tests assess key parameters, including construct stiffness, yield strength, and ultimate load to failure, providing critical data for comparing various osteosynthesis implants and surgical techniques. Different experimental models are generally used, each with inherent advantages and limitations. For example, synthetic bone models subjected to static loads (e.g., 350 N or 700 N) provide uniformity and reproducibility but lack the biological characteristics of living tissue, which may lead to potential overestimations of implant performance [17]. In contrast, cadaveric specimens tested under static axial compression (e.g., 500 N) better mimic *in vivo* conditions; however, repeated freeze-thaw cycles can compromise bone mechanical integrity and underestimate implant strength [18]. Dynamic cyclic loading tests (e.g., 0–1000 N) provide valuable insights into fatigue resistance and long-term performance but are often constrained by high costs and limited sample sizes [19]. A comparative summary of these testing modalities is provided in Table 2 (Ref. [17–19]).

Numerical Simulation Methods

Computational approaches, particularly finite element analysis (FEA), are increasingly used to simulate the biomechanical environment of calcaneal fractures and assess treatment strategies [20]. FEA offers a non-invasive means to estimate stress distribution, deformation, and implant performance under physiologically relevant loading condi-

tions. For instance, a study comparing the C-Nail® system to conventional plating using FEA demonstrated significantly reduced peak von Mises stress (110 MPa vs. 360 MPa) and lower bone-implant interface stresses, suggesting enhanced stability for displaced intra-articular fractures [17]. However, the accuracy and reliability of FEA outcomes are highly dependent on the assumptions made during modeling. Simplified models that treat bones as a homogeneous, isotropic material make computations more efficient but may underestimate localized stress concentrations and associated clinical risks [17,21]. Advanced models incorporating heterogeneous properties of bone and dynamic gait loading improve physiological accuracy but require substantial computational resources and lack extensive clinical validation [22]. The impact of various modeling parameters on predictive accuracy is summarized in Table 3 (Ref. [17,21,22]).

Association of Quantitative Metrics With Clinical Applications

Fracture Healing Time and Functional Recovery

Fracture healing time is closely linked to recovery of function. A study involving 1042 patients with closed calcaneal fractures showed that early weight-bearing within three months post-surgery significantly improved healing and functional outcomes. In contrast, prolonged non-weight-bearing beyond three months was associated with poorer recovery, likely due to reduced fibroblast activity and delayed bone repair processes [23,24].

Fracture Union Rate and Risk of Recurrent Fracture

The union rate reflects the success of bone healing and has a significant influence on long-term functional outcomes. Patients with a Böhler's angle below 10° exhibit a fourfold higher risk of contralateral fracture within five years, often due to compensatory gait changes. Furthermore, malunions can lead to tendinopathy, abnormal load distribution, and the development of subtalar arthritis, thereby elevating the likelihood of requiring revision surgery [17,25,26].

Fracture Displacement and Joint Function

The degree of fracture displacement directly affects subtalar joint function. Significant displacement causes articular

Table 3. Comparative analysis of numerical simulation methods.

Study	Material property assumptions	Boundary conditions	Mesh resolution	Validation method	Limitations
Pinzaru <i>et al.</i> [17]	Homogeneous (isotropic bone)	Fully fixed articular surface	Fine mesh (1 mm)	No experimental validation	Undetectable trabecular structure, overestimates stress uniformity
Qiang <i>et al.</i> [21]	Heterogeneous (regional assignment)	Elastic constraints on ligament attachments	Coarse mesh (3 mm)	Partial validation with cadaver tests	Coarse mesh distorts local stress concentrations
Song <i>et al.</i> [22]	Orthotropic bone	Dynamic gait loading (time-varying forces)	Adaptive mesh	Matched with clinical imaging data	High computational demands, limited accessibility

incongruity, joint instability, and abnormal biomechanics, often resulting in chronic pain and alterations in gait patterns. Accurate preoperative assessment of displacement is essential for predicting functional impairment and guiding surgical realignment to reduce long-term disability.

Biomechanical Performance Parameters and Prognosis

Biomechanical parameters such as stiffness, load-bearing capacity, and deformation under mechanical stress serve as key predictors of functional outcomes. These metrics not only help identify patients who may benefit from targeted interventions, such as specialized physical therapy or orthotics support, but also provide promising insights into overall prognosis [27,28].

Clinical Decision-Making and Treatment Optimization

Quantitative metrics integrate healing time, union rate, displacement, and biomechanical performance to guide the development of personalized treatment strategies. This combined approach supports the development of tailored rehabilitation plans and surgical timing, thereby improving outcomes and reducing complications. By providing objective data, these metrics enhance clinical decision-making and facilitate more targeted and effective patient care [29].

Limitations of Biomechanical Assessment in Calcaneal Fracture Repair

Technical Limitations

Equipment Accessibility

Advanced biomechanical testing and imaging systems are costly and not readily available in many clinical settings, restricting their widespread use. This lack of availability can limit the accuracy and depth of biomechanical evaluations, potentially affecting treatment planning and overall patient outcomes [30].

Patient-Specific Biomechanics

Biomechanical assessments often rely on generalized models that overlook individual factors such as bone quality, age, sex, or comorbidities. This limitation can reduce the accuracy of patient-specific predictions and treatment recommendations [31].

In Vivo vs. In Vitro Studies

Results from *in vitro* tests using cadaveric specimens may not precisely reflect *in vivo* conditions due to differences in tissue response and loading dynamics. As a result, direct application to clinical practice requires careful interpretation and is often limited by the lack of validation under real physiological conditions [21].

Dynamic Load Considerations

Most biomechanical tests use static loading, which do not accurately replicate the dynamic conditions and forces experienced during daily activities such as walking or climbing stairs. The lack of dynamic testing in clinical assessments can lead to underestimating implant fatigue and overlooking patient-specific functional demands [19].

Data Collection Challenges

Ethical Constraints

Ethical considerations limit the collection of invasive biomechanical data from patients, particularly when additional procedures are performed purely for research purposes. As a result, both the quantity and quality of data available for analysis are often limited [21].

Small Sample Sizes

Many studies often involve small, highly selected cohorts, especially complex fractures, which restrict statistical power and reduce the generalizability of their findings [14,19].

Heterogeneous Populations

Variations in age, fracture patterns, and patient comorbidities introduce substantial variability, complicating the interpretation of biomechanical results and making it difficult to establish consistent clinical correlations.

Long-Term Follow-up

Collecting long-term biomechanical data is difficult due to patient dropout, non-compliance, and logistical constraints. Insufficient follow-up limits the ability to fully understand the healing progression and assess the long-term performance of implants.

Table 4. Comparison of biomechanical parameters across different studies.

Research	Stiffness index	Load-bearing capacity	Correlation
Yu <i>et al.</i> [18]	In the biomechanical study of plateable calcaneal titanium plates, the strength and stiffness of the calcaneal fractures fixed with this plate were higher than those of normal feet ($p < 0.05$).	The load-bearing capacity was not directly measured, but the strength and stiffness of the calcaneal fractures fixed with the plate were higher than those of normal feet, sufficient to bear the mechanical load of the foot.	The high strength and stiffness of the plateable calcaneal titanium plate indicate that it may provide good fixation and stability in clinical applications, aiding patient recovery.
Li <i>et al.</i> [37]	In the study on the correlation between ultrasonic parameters of the calcaneus and the biomechanics of the proximal femur in elderly women, the stiffness index of the calcaneus showed a positive correlation with the density of the trabecular bone in the weight-bearing area of the femoral head (QCT-BMD) ($r = 0.490$, $p < 0.01$), and a positive correlation with the Young's modulus of the trabecular bone in the weight-bearing area of the femoral head ($r = 0.418$, $p < 0.05$).	The load-bearing capacity was not directly measured, but the stiffness index of the calcaneus showed a positive correlation with the failure load of the trabecular bone in the weight-bearing area of the femoral head.	The stiffness index of the calcaneus can serve as a reference indicator for predicting the risk of proximal femur fractures in elderly women with osteoporosis.
Dong <i>et al.</i> [38]	In the study on the correlation between spectral CT quantitative parameters and bone biomechanics, the stiffness of the calcaneus was not directly measured. However, a correlation was found between spectral CT parameters and bone density, which is related to stiffness.	The load-bearing capacity was not directly measured, but a correlation was found between spectral CT parameters and bone density, which is related to load-bearing capacity.	The study on the correlation between spectral CT parameters and bone density offers a new method for clinical assessment of osteoporosis and fracture risk. Since bone density is related to fracture risk and stiffness is related to bone density, spectral CT parameters have an indirect correlation with clinical outcomes.

Abbreviation: QCT-BMD, quantitative computed tomography-bone mineral density.

Complexity of Data Interpretation

Multifactorial Nature

Calcaneal fracture healing involves complex interactions among mechanical, biological, and patient-specific factors. Isolating the effects of individual variables is challenging, often leading to oversimplified biomechanical predictions.

Limited Predictive Value

Biomechanical data alone may be inadequate to accurately predict healing outcomes, as biological factors such as blood supply and inflammation also play crucial roles. Therefore, relying only on biomechanical parameters can lead to inaccurate prognoses [32].

Clinical Relevance

Translating biomechanical metrics into practical clinical insights remains difficult. For example, the relationship between joint congruity or stress distribution and patient-reported outcomes, such as pain and mobility, is often unclear [33].

Clinical Variation

Controlled laboratory settings do not fully capture the variability seen in real-world clinical scenarios. As a result, clinicians may be cautious to apply generalized biomechanical findings to individual patients, given the unaccounted anatomical and functional differences [34].

Selecting and Assessing Quantitative Metrics

Key Quantitative Metrics

Fracture Healing Time

Fracture healing time reflects the duration required to achieve both clinical and radiographic union of calcaneal fractures. An extended healing time may indicate greater fracture complexity or delayed recovery. Monitoring these metrics assists in determining the timing of weight-bearing and evaluating treatment efficacy [35,36].

Fracture Union Rate

The union rate denotes the proportion of fractures that show complete bony bridging across the fracture line on radiographic evaluation. It serves as a critical indicator of treatment success, as non-union can lead to significant long-term functional impairments [35,36].

Fracture Displacement and Gap

Quantifying fragment displacement and gap size is essential for assessing fracture alignment and stability. Larger values typically suggest more severe injuries and often necessitate surgical intervention to restore proper biomechanical integrity [35,36].

Biomechanical Performance Parameters

Mechanical parameters such as elastic modulus, strength, and deformation characteristics define the post-fracture mechanical behavior of the calcaneus. Evaluated via biomechanical testing and finite element analysis (FEA), these parameters help predict functional outcomes and complications such as altered gait. They also play a pivotal role in guiding clinical decision-making and planning effective rehabilitation approaches (Table 4, Ref. [18,37,38]).

Measurement Methods and Techniques

Accurate evaluation of these metrics relies on utilizing appropriate methods: (1) Radiographic imaging (X-ray, CT) enables assessment of healing time, displacement, and gap size. (2) Biomechanical testing under controlled loads measures stiffness, strength, and deformation. (3) Clinical evaluations provide qualitative insights into pain and mobility to complement quantitative data [35,36].

Data Collection and Analysis

Standardized procedures are essential for ensuring consistent data collection. Key metrics, such as union rate, displacement, and biomechanical parameters, are systematically recorded. Statistical methods, including *t*-tests, ANOVA, and regression, are applied to identify trends and correlations. Results are then interpreted in a clinical context—considering variables like age, fracture type, and treatment strategy—to guide appropriate treatment selection and help minimize complications.

Future Research Directions

Advanced Biomechanical Assessment Tools and Techniques

Development of Innovative Imaging Methods

Future research should focus on integrating advanced imaging technologies, including 3D motion capture, musculoskeletal modeling, MRI, and ultrasound, to accurately evaluate dynamic biomechanics during fracture healing [39]. Additionally, incorporating artificial intelligence (AI) and machine learning (ML) holds strong potential to improve the accuracy and efficiency of fracture detection and classification. Deep learning models can help identify subtle fractures that are commonly overlooked, while ML algorithms can leverage demographic and clinical data to predict healing trajectories and enable more personalized treatment planning.

Biomechanical Modeling

Finite element analysis (FEA) and computational modeling should be further advanced to simulate complex fracture conditions and compare various fixation techniques. For instance, FEA on proximal tibial fractures has demonstrated that intramedullary nailing offers greater stability under physiological loading compared to plating—though the optimal strategy depends on the specific fracture type.

Fig. 1 illustrates a biomechanically optimized, minimally invasive locked internal fixation model using the sinus tarsi approach, indicating excellent mesh conformity and precise screw positioning, thereby enhancing both simulation accuracy and clinical applicability.

Wearable Sensors

Wearable sensors, including accelerometers and pressure sensors, enable continuous monitoring of gait and weight-bearing, providing real-time data that can be used to guide and adjust rehabilitation approaches.

In Vivo Studies

Furthermore, *in vivo* studies are needed to evaluate real-time biomechanical responses in patients, facilitating the translation of laboratory findings into practical clinical utilities.

Integration of Multimodal Datasets

Data Fusion Techniques

Integrating clinical, biomechanical, imaging, and genetic data using advanced fusion techniques can provide deeper insights into the mechanisms of fracture healing and patient-specific outcomes. For example, genetic profiling, may help identify individuals at risk of delayed union, enabling earlier interventions [40].

ML and AI

Machine learning and AI play an essential role in analyzing complex multimodal datasets, identifying non-obvious patterns, and improving the accuracy of prognostic predictors.

Longitudinal Studies

Long-term studies that monitor biomechanical and clinical parameters over time can provide promising insights into the dynamic changes that occur during the healing process and functional recovery.

Patient-Specific Profiles

Combining genetic, biomechanical, and clinical data can enable the construction of individualized patient profiles, facilitating highly personalized and targeted treatment strategies.

Personalized Healthcare and Treatment Strategies

Genetic and Molecular Profiling

Genetic and molecular markers hold promise for predicting bone healing capacity, allowing for truly personalized prognostic evaluations. Additive manufacturing approaches, such as 3D printing, enable patient-specific implants and fixators that improve stability and reduce surgical time. Additionally, AI-assisted design can optimize implant biomechanics, while the integration of wearable sensors with AI may support real-time monitoring of recovery and rehabilitation progress [38].

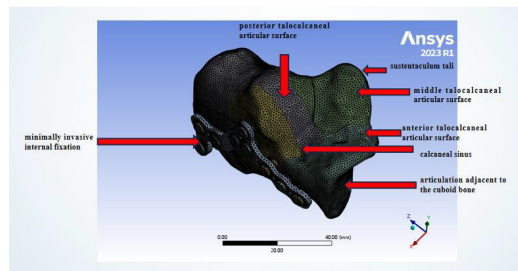
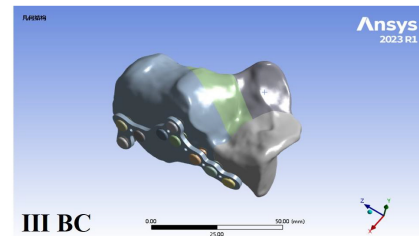
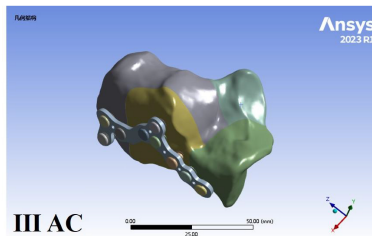
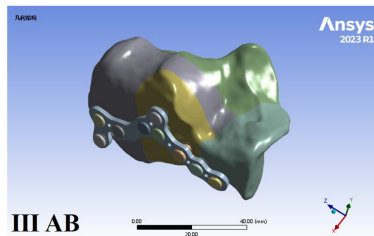
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Fig. 1. Clear and complete mesh of the fracture model, with the plate fitted to the bone surface, indicating no prominent screw damage. With a high level of visual simulation, the structure shows pronounced morphological integrity. (A) Key anatomical structures in a 3D model generated via mesh division after minimally invasive locked internal fixation for calcaneal fractures; (B) Anatomical locked internal fixation via an “L”-shaped incision approach. The Sanders classification of the calcaneus is an imaging-based classification method for describing calcaneal fractures. It is based on the location and number of fracture lines identified in coronal computed tomography (CT) scans. The key points can be summarized as follows: The classification is based on the number of posterior joint surfaces of the calcaneus involved by the fracture lines and the degree of displacement. It is divided into types I to IV. Among them, type III can be further classified into three subtypes: Sanders IIIAB, Sanders IIIAC, and Sanders IIIBC. The ‘IIIAB’ refers to the Sanders IIIAB classification of calcaneal fractures. Here, the letters A and B represent the two fracture lines, with the fracture line located at the junction of yellow, gray, and dark green in the first picture of Figure B. ‘IIIAC’ refers to the 3D model generated from the mesh division of the Sanders IIIAC calcaneal fracture after minimally invasive locked internal fixation, including the reconstruction of the sustentaculum tali fracture. The letters A and C represent the two fracture lines, and the fracture line is located at the junction of yellow, gray, and light green in the second picture of Figure B. ‘IIIBC’ refers to the 3D model generated from the mesh division of the Sanders IIIBC calcaneal fracture after minimally invasive locked internal fixation, including the reconstruction of the sustentaculum tali fracture. The letters B and C represent the two fracture lines, and the fracture line is located at the junction of blue, light green, and dark gray in the third picture of Figure B.

Precision Surgery

Advances in surgical navigation and real-time imaging technologies have improved the accuracy of fracture reduction and fixation while minimizing procedural invasiveness.

Rehabilitation Programs

Rehabilitation should be tailored according to individual’s biomechanical and clinical profiles, with a focus on improving gait, enhancing muscle strength, and reestablishing mobility.

Patient Education and Engagement

Future research should also prioritize approaches to improve patient education and engagement, thereby enhancing adherence to rehabilitation programs and promoting overall recovery outcomes.

Conclusions

Assessing calcaneal fractures through a biomechanical perspective is crucial for optimizing therapeutic strategies and enhancing patient recovery. Evidence underscores factors such as fracture healing time, union rate, displacement patterns, and biomechanical parameters play a significant role in functional recovery, joint stability, and long-term prognosis. The integration of advanced biomechanical testing tools—including high-resolution imaging modalities, computational modeling, and wearable sensors—has significantly enhanced the precision of fracture evaluation and the planning of personalized intervention.

When integrated with multimodal datasets and artificial intelligence-driven analytics, these technologies enable a holistic approach that effectively bridges biomechanical principles with clinical practice. This integration facilitates tailored surgical planning, individualized rehabilitation protocols, and patient-specific care strategies. Biomechanically optimized implants, designed to reduce stress

and stiffness, have demonstrated substantial clinical significance by promoting bone healing and recovery. In the future, advancements in predictive modeling using machine learning which integrates mechanical, genetic, and clinical data, are anticipated to further inform implant selection and treatment planning.

Equally important is emphasizing precise surgical techniques, adaptive rehabilitation, and patient education to support adherence and optimize recovery. The convergence of biomechanics, data analytics, and clinical expertise is paving the way for data-driven, patient-centered treatment programs that address the complex nature of calcaneal injuries. Ultimately, this interdisciplinary synergy holds the promise of delivering safer and more effective orthopedic management, thereby improving both functional outcomes and overall quality of life.

Availability of Data and Materials

Not applicable.

Author Contributions

Conception and design: GST, JZ, KW. Analysis and interpretation: KW, JNS, HFW. Data collection: JNS, HFW. Writing the article: GST. All authors have been involved in revising it critically for important intellectual content. All authors gave final approval of the version to be published. All authors have participated sufficiently in the work to take public responsibility for appropriate portions of the content and agreed to be accountable for all aspects of the work in ensuring that questions related to its accuracy or integrity are addressed.

Ethics Approval and Consent to Participate

Not applicable.

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Conflict of Interest

The authors declare no conflict of interest.

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