

The Research Progress on Minimally Invasive Techniques for Calcaneal Fracture Treatment

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Abstract:

Calcaneal fractures, the most prevalent subtype of tarsal fractures, hold substantial clinical research significance. Epidemiological data indicate that calcaneal fractures account for approximately 2% of all body fractures, with roughly 75% classified as intra-articular fractures—a subtype frequently associated with high disability rates. While traditional open reduction and internal fixation (ORIF) demonstrates distinct superiority in achieving fracture reduction, its inherent limitations, such as elevated wound complication rates and prolonged postoperative recovery cycles, have long posed challenges to clinicians. In recent years, alongside the advancing integration of minimally invasive (MI) principles and innovations in medical technology, the application spectrum of MI techniques in calcaneal fracture management has expanded progressively, with therapeutic outcomes being notably enhanced. Through a systematic review approach, this article elaborates on the latest advancements in MI modalities for calcaneal fractures, including percutaneous reduction and screw fixation, subtalar arthroscopy, and 3D printing-assisted surgery. Furthermore, in-depth discussions are conducted across multiple dimensions, encompassing clinical efficacy, indication selection, and technical essentials. The findings of this review suggest that MI techniques exhibit prominent advantages, such as minimal invasiveness, accelerated recovery, and reduced complications. They are particularly well-suited for Sanders type II and III fractures, as well as patient cohorts with compromised soft tissue conditions.

Keywords:

Calcaneal Fracture, Minimally Invasive Technique, Subtalar Arthroscopy, 3D Printing, Fracture Fixation

1. Introduction

The calcaneus, as the largest tarsal bone in the human foot, plays an irreplaceable role in maintaining normal walking function and weight-bearing balance. Calcaneal fractures are mostly caused by high-energy injuries such as falls from heights or traffic accidents. These injuries are often accompanied by severe functional

impairments, significantly affecting patients' quality of life. Although the traditional lateral "L"-shaped incision surgical approach provides a good operative field of view and facilitates fracture reduction, it has a high incidence of wound complications, reaching 25%–30% [1]. These complications include poor wound healing, skin necrosis, and infection, which severely impact patients' postoperative recovery and final treatment outcomes.

In recent years, with the widespread adoption of minimally invasive concepts in orthopedics and continuous advancements in surgical techniques, minimally invasive treatment of calcaneal fractures has become a major focus of research and clinical interest among orthopedic surgeons. Xu Xiangyang et al. [2] highlighted that minimally invasive surgery not only effectively reduces the risk of soft tissue complications but also better preserves the blood supply system of the calcaneus, creating a more favorable biological environment for fracture healing. This article aims to provide a comprehensive theoretical basis and technical reference for clinical practice by systematically reviewing the latest research progress in minimally invasive techniques for treating calcaneal fractures.

2. The Development History of Minimally Invasive Technology

The minimally invasive treatment of calcaneal fractures has undergone a developmental process from simplicity to complexity, evolving from single techniques to the integration of multiple technologies. In the early stages of minimally invasive technology development, relatively simple techniques such as percutaneous reduction with leverage combined with Kirschner wire fixation were predominantly used. While these methods were straightforward to perform, they had certain limitations in terms of indication selection and reduction accuracy. With advancements in medical technology and improvements in surgical instruments, a variety of minimally invasive internal fixation methods and auxiliary techniques have gradually emerged, significantly expanding the application scope of minimally invasive approaches. Zhong Zhendong [3] made significant discoveries in his digital anatomy research. Through meticulous anatomical studies, he identified multiple safe pathways around the calcaneus, providing crucial anatomical foundations for the selection of minimally invasive surgical approaches. These in-depth basic anatomical studies have established a solid theoretical basis for the development of minimally invasive techniques. Notably, with the introduction and application of new technologies such as subtalar arthroscopy and 3D printing, the precision and safety of minimally invasive treatments for calcaneal fractures have been significantly improved, driving the advancement of minimally invasive techniques toward greater refinement and personalization.

3. The Major Minimally Invasive Techniques and Their Applications

3.1. The Percutaneous Reduction and Screw Fixation

Percutaneous reduction and screw internal fixation is currently the most fundamental and widely used minimally invasive technique for treating calcaneal fractures. It is primarily indicated for Sanders type II fractures and some type III fractures with minimal displacement. This technique involves inserting screws through several small incisions, which effectively stabilizes the fracture fragments

while maximizing the preservation of soft tissue integrity, aligning with the fundamental principles of biological fixation.

Wang Wei et al. [4] demonstrated in their clinical study that using percutaneous reduction and screw internal fixation technique for traumatic calcaneal fractures significantly reduces surgical time, decreases intraoperative blood loss, and accelerates postoperative recovery. The study included 45 patients, and systematic follow-up evaluations revealed an excellent-to-good treatment outcome rate of 88.9%, with no severe postoperative complications observed. It is noteworthy that this technique demands a high level of surgical skill, requiring extensive experience and precise operative ability from the surgeon.

3.2. The Subtalar Arthroscopy-Assisted Technique

The application of subtalar arthroscopy in the treatment of calcaneal fractures represents a significant advancement in the development of minimally invasive techniques in recent years. Yuan Baohua et al. [5], through a systematic review, provided a detailed analysis of the multiple advantages of subtalar arthroscopy in the management of calcaneal fractures. These advantages primarily include: first, the ability to directly visualize the reduction of the articular surface, ensuring its smoothness; second, the accurate assessment of fracture displacement, providing precise references for reduction; and finally, the simultaneous treatment of associated intra-articular injuries, achieving multiple surgical outcomes in a single procedure.

Multiple research findings indicate that subtalar arthroscopy-assisted calcaneal fracture surgery enables precise reduction of the articular surface, with significantly superior reduction quality compared to traditional fluoroscopy-guided reduction techniques. Furthermore, this technique offers a unique advantage: the ability to dynamically assess joint mobility during the procedure, which provides critical assurance for postoperative functional recovery. It is important to note that the learning curve for subtalar arthroscopy is relatively steep, requiring systematic training for surgeons to achieve proficiency.

3.3. The 3D Printing Technology Assisted Surgery

The introduction of 3D printing technology has ushered in a new era of personalized and precise minimally invasive treatment for calcaneal fractures. Research by Jiang Nan et al. shows that using 3D printing technology to create models of calcaneal fractures allows for precise surgical simulations and optimal surgical path planning before the operation, significantly enhancing the accuracy and safety of the procedure.

In their clinical study, the use of 3D printing technology to assist minimally invasive reduction and screw internal fixation for treating elderly patients with Sanders type II–III calcaneal fractures yielded encouraging results. Research data showed that the average surgical time was reduced by approximately 30%, and the excellent and good reduction rate reached 94.4%, significantly higher than that of the traditional surgery group. Particularly for elderly patients with osteoporosis, 3D printing technology helped surgeons select the optimal screw pathways, effectively enhancing fixation stability. This provides a new technological approach to addressing the challenges of fracture treatment in elderly patients.

3.4. Other Minimally Invasive Techniques

In addition to the main techniques mentioned above, several minimally invasive technologies have been applied and promoted in clinical practice in recent years. The minimally invasive plate osteosynthesis technique skillfully combines the stability of traditional plate fixation with the advantages of minimally invasive surgery, reducing surgical trauma while ensuring fixation effectiveness. Balloon osteoplasty is primarily suitable for certain types of compression fractures, where balloon expansion helps restore calcaneal height, offering unique clinical value. Furthermore, navigation-assisted surgery enhances the accuracy of screw placement, further improving the safety and reliability of the procedure (Figure 1). The comprehensive application of these techniques provides more treatment options for patients with calcaneal fractures under varying conditions.

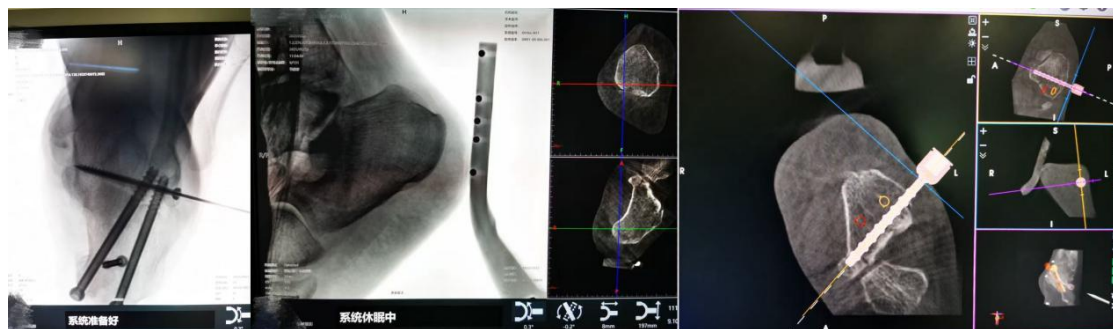


Figure 1. The screw placement for calcaneal fracture under the robot-assisted triage.

4. The Clinical Efficacy Evaluation of Minimally Invasive Techniques

4.1. The comparison of Surgical Outcomes

Zhong Zhendong conducted a targeted study specifically comparing the efficacy differences between minimally invasive techniques and traditional surgical treatments for Sanders type II and III calcaneal fractures. The results showed that the minimally invasive treatment group demonstrated significant advantages in multiple indicators, including operative time, intraoperative blood loss, and hospital stay, all of which were superior to the traditional surgery group. Statistical analysis revealed that these differences were significant ($P < 0.05$). Notably, at the 12-month postoperative follow-up, the excellent and good rate of the Maryland Foot Score in the minimally invasive group reached 90.0%, significantly higher than the 76.7% in the control group, fully demonstrating the superiority of minimally invasive techniques in functional recovery.

4.2. The Analysis of Complications

In terms of complication prevention, minimally invasive techniques demonstrate significant advantages. According to aggregated data from multiple studies, the incidence of wound complications in the minimally invasive treatment group was only 2.5%-5.0%, compared to 15.0%-25.0% in the traditional surgery group. The infection rate was controlled between 0%-2% in the minimally invasive group, while it ranged from 5%-8% in the traditional group. The incidence of nerve injury was 1%-2% in the minimally invasive group, reaching 5%-7% in the traditional group. These data fully illustrate the significant advantages of minimally invasive techniques in reducing surgical complications, which is of great importance for improving patient prognosis.

4.3. The Functional Recovery Assessment

In terms of functional recovery, minimally invasive techniques demonstrate unique advantages. A study by Xu Xiangyang et al. [2] indicated that minimally invasive surgery better preserves the integrity of the soft tissues around the calcaneus, allowing patients to initiate functional exercises earlier, which contributes to enhanced recovery. Clinical observations revealed that at three months post-surgery, patients who underwent minimally invasive treatment exhibited significantly better ankle joint range of motion and walking ability compared to those in the traditional surgery group. Furthermore, the time required for patients receiving minimally invasive surgery to resume normal activities was notably shorter, greatly improving their quality of life and treatment satisfaction.

5. The Indications and Contraindications

5.1. Indications

Based on the latest research evidence and clinical practice experience, minimally invasive techniques are primarily indicated for the following situations: Sanders type I and II intra-articular fractures, as well as some type III fractures with minimal displacement; patients with poor soft tissue conditions, such as those with severe soft tissue swelling or compromised skin integrity; elderly patients and those with multiple underlying medical conditions, who often cannot tolerate traditional open surgery; Gustilo type I and II open fractures, where minimally invasive treatment may be considered after thorough debridement; additionally, for tongue-type fractures with large fragments and significant displacement, minimally invasive techniques may also be employed when technically feasible.

5.2. Contraindications

Minimally invasive techniques, while offering numerous advantages, also have certain limitations. Relative contraindications include: Sanders type IV severely comminuted fractures, which are often difficult to satisfactorily reduce through minimally invasive methods; fractures with significant displacement that cannot be reduced percutaneously; cases where local infection is not effectively controlled; and severe osteoporosis that may compromise the effectiveness of internal fixation. In these situations, clinicians need to carefully evaluate and select the most appropriate treatment plan. When necessary, traditional surgical approaches should still be considered.

6. The Technical Points and Precautions

6.1. Timing of Surgery

The timing of minimally invasive surgery significantly impacts treatment outcomes. Surgery is generally recommended 7-14 days after injury, during which soft tissue edema has largely subsided and bleeding tendencies are under control. This approach effectively reduces surgical risks while ensuring the quality of fracture reduction. For patients with severe soft tissue injuries, the waiting period may be appropriately extended until soft tissue conditions improve before proceeding with surgery.

6.2. Reset Techniques

Accurate reduction is a critical step in ensuring surgical success. Zhang Taiyuan [1] recommends adopting a systematic reduction sequence of "from inside to outside,

from back to front," meaning first reconstructing the articular surface structure, then restoring the calcaneal contour. During the reduction process, auxiliary equipment such as subtalar arthroscopy or C-arm X-ray machines should be fully utilized to monitor the quality of reduction in real time, ensuring that the articular surface step is controlled within 1mm and the Böhler angle is restored to the normal range.

6.3. Fixed Points

The selection of internal fixation devices requires personalized design based on the fracture type. Yuan Baohua et al. [5] particularly emphasize that the screw insertion path must avoid critical structures such as the subtalar joint surface and the neurovascular bundle on the medial side of the calcaneus, strictly adhering to the "safe corridor" principle. For patients with osteoporosis, techniques such as locking screws or bone cement augmentation can be considered to enhance fixation stability.

7. Minimally Invasive Treatment for Special Populations

7.1. The Geriatric Patients

Elderly patients with calcaneal fractures often present with varying degrees of osteoporosis, which poses additional challenges for treatment. The study by Jiang Nan et al. demonstrated that minimally invasive surgery assisted by 3D printing technology allows precise planning of screw trajectories, effectively avoiding areas with severe osteoporosis and significantly improving fixation stability. Meanwhile, minimally invasive surgery causes less physiological disruption to elderly patients, facilitating postoperative recovery and reducing the risk of complications. When treating elderly patients, special attention must also be paid to perioperative management, including pharmacological treatment for osteoporosis and fall prevention measures.

7.2. The Patients with Complex Fractures

For certain type III complex fractures according to Sanders classification, satisfactory therapeutic outcomes can also be achieved through the combined application of subtalar arthroscopy and percutaneous fixation techniques. Zhong Zhendong recommends that when managing such complex fractures, strict adherence to indications and thorough surgical planning are essential. If intraoperative assessment reveals that satisfactory reduction is difficult to achieve through minimally invasive techniques, conversion to open surgery should be promptly performed to avoid compromising treatment outcomes due to excessive pursuit of minimally invasive approaches. This flexible surgical strategy helps strike an optimal balance between the advantages of minimally invasive procedures and treatment efficacy.

8. The Rehabilitation Plan

The rehabilitation protocol for minimally invasive surgery differs significantly from that of traditional surgery, requiring a personalized recovery plan tailored to the characteristics of the minimally invasive approach. In the early rehabilitation phase (0-2 weeks post-surgery), the focus is on active movement, particularly active flexion and extension exercises of the ankle joint, while strictly avoiding weight-bearing. During the mid-term rehabilitation phase (2-6 weeks post-surgery), partial weight-bearing exercises can be initiated, with the load gradually increased in a step-by-step manner based on fracture healing progress. In the late rehabilitation phase (beyond 6

weeks post-surgery), a gradual transition to full weight-bearing should be made according to the fracture healing status shown in imaging studies. Wang Wei and others particularly emphasized that the formulation of a rehabilitation plan must be individualized, taking into comprehensive consideration factors such as the type of fracture, the stability of internal fixation, and the patient's specific condition. A scientific and reasonable rehabilitation plan not only promotes functional recovery but also effectively prevents the occurrence of complications. Throughout the rehabilitation process, regular assessments should be conducted, and the rehabilitation plan should be adjusted promptly based on the recovery progress.

9. Conclusions

With the advancement of technology, the development of minimally invasive techniques will increasingly focus on the integration and innovation of multiple technologies. The deep integration of subtalar arthroscopy with navigation and robotic technologies will further enhance the precision and safety of surgeries. Intelligent surgical navigation systems can provide surgeons with real-time three-dimensional anatomical information, while surgical robots can perform operations with precision beyond human capability. The fusion of these technologies will usher in a new era of minimally invasive treatment for calcaneal fractures. Personalized treatment based on 3D printing will become a key development direction. By using 3D printing technology to customize personalized surgical guides and implants, truly individualized and precise treatment can be achieved. In the future, computer simulation technology can also be integrated to virtually test the effects of different treatment plans before surgery, tailoring the best treatment strategy for each patient. This personalized treatment model is expected to significantly improve therapeutic outcomes and reduce surgical complications. The development of new biodegradable internal fixation materials may address the issue of secondary surgeries for implant removal. Furthermore, significant progress has been made in the research of biodegradable materials, which can safely degrade in the body after fulfilling their fixation function, eliminating the need for secondary surgeries to remove implants. Thus, advancements in materials science will bring revolutionary changes to the minimally invasive treatment of calcaneal fractures.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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