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Optimal Screw Trajectory for Percutaneous Screw Fixation of Sanders Type IIC Calcaneal Fractures: A Finite Element Analysis

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Abstract: ***Background:*** ***Percutaneous screw fixation has been widely used to treat calcaneal fractures, but the optimal screw configuration is still unclear. In this study, finite element analysis was used to explore the optimal screw fixation.*** ***Methods:*** ***Mimics 21.0 software was used to process the ankle CT of a healthy subject and extract a three-dimensional model of the calcaneus. After optimizing the model using Geomagic Wrap 2021, the SandersIIC fracture model was constructed in SolidWorks 2022 and four internal fixation methods with different screw directions were designed to simulate the internal fixation of the fracture. Finally, the finite element analysis was completed in ANSYS Workbench 2022 R1.*** ***Results:*** ***The maximum stress of screw and bone and the maximum displacement of fracture fragment in the study group and control groups 1 were significantly smaller than those in the control groups 2 and 3.*** ***Conclusion:*** ***The screw configuration of study group and control group 1 (two transverse screws to fix the articular surface fracture fragment, one longitudinal screw fixed from the calcaneal tuberosity to the calcaneal anterior process, and one longitudinal screw fixed from the calcaneal tuberosity to the sustentaculum talus) can obtain the best biomechanical fixation effect.***

Keywords: Calcaneal fracture, Percutaneous screw fixation, Finite element analysis.

1. Introduction

Treatment of calcaneal fractures, the most common tarsal fractures, has been controversial [1,2]. The treatment of displaced intra-articular calcaneal fractures has evolved over several years. Initially, scholars favored conservative treatment. Later, it was found that incisional reduction and internal fixation could achieve better functional recovery and more patients could return to normal work and life, so surgical treatment was preferred. However, due to the damage of skin and soft tissues, patients with incision-replacement internal fixation may suffer from poor wound healing, infection and other complications after surgery [3-7].

With orthopedic surgeons' exploration of minimally invasive techniques, percutaneous screw internal fixation for the treatment of intra-articular fractures of the calcaneus has become a relatively mature technique. Numerous studies have demonstrated that percutaneous screw internal fixation can achieve the same results as incisional reduction internal fixation. More and more orthopedic surgeons are inclined to carry out this technique due to its advantages in terms of incisional complications and postoperative incision recovery time [8-12].

However, although percutaneous screw fixation of calcaneal fractures has been shown to be an effective treatment modality for calcaneal fractures, there is no standardization of the optimal fixation path for calcaneal fracture screws. In this study, we used finite element analysis to compare the biomechanical stability of different screw internal fixation modalities for the treatment of displaced calcaneal intra-articular fractures.

2. Materials and Methods

2.1 General Information

A 54-year-old healthy male with a height of 165 cm and a weight of 64 kg was used as the subject, and biomechanical software used included: (1) Medical imaging software: Mimics 21.0 (Materialise Ltd, Belgium); (2) 3D optimization software: Geomagic Wrap 2021 (Rainrrop Ltd, USA); (3) CAD software: SolidWorks 2022 (Dassault Systèmes Ltd, USA); and (4) a computer program for the measurement of the body's weight. optimization software: Geomagic Wrap 2021 (Rainrrop Ltd, USA); (3) CAD software: SolidWorks 2022 (Dassault Systèmes Ltd, USA); (4) finite element analysis software: ANSYS Workbench 2022 R1 (ANSYS Ltd, USA).

2.2 Finite Element Modeling Process

Ankle CT data of a healthy subject was imported into Mimics 21.0 software, and the 3D model of the calcaneus was extracted by the image segmentation function. Then the noise and irregular parts of the calcaneus model were eliminated in Geomagic Wrap 2021 to obtain a smooth surface and complete model of the calcaneus. The 2 mm of the surface of the calcaneus was set as cortical bone, and all the interior was cancellous bone.

2.3 Pre-experimentation

In order to increase the rationality of our screw design, we conducted a pre-experiment before the formal experiment to analyze the stress distribution of the calcaneus in normal human standing. We applied 200N and 420N vertically downward force on the middle subtalar joint surface and the posterior subtalar joint surface, respectively. The part of the calcaneal tubercle in contact with the ground and the calcaneocuboid joint surface were set as fixed supports (Figure 1). The results obtained showed that the stresses in the calcaneus were mainly distributed in the anteromedial aspect of the calcaneus in normal people when standing (Figure 2) [13, 14].

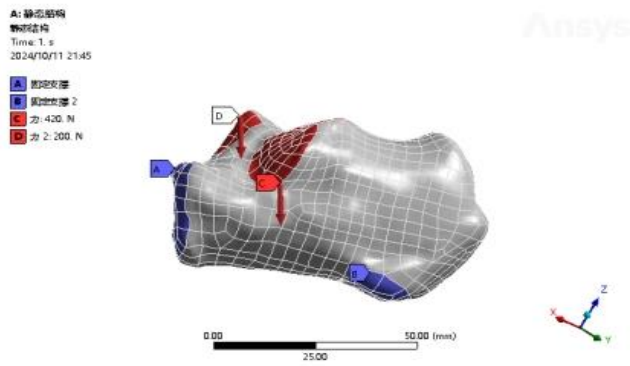

Figure 1: Applied loads and boundaries

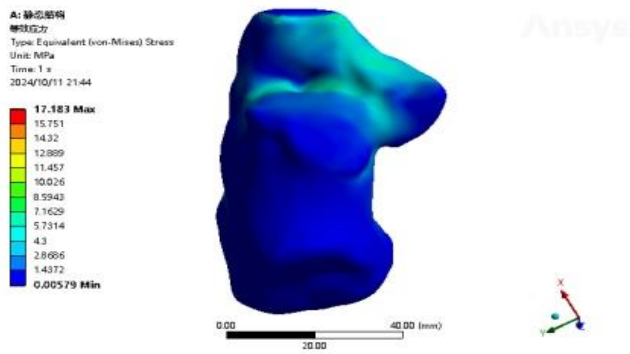

Figure 2: Pre-experimental finite element analysis results: stresses are mainly distributed with the anteromedial side of the calcaneus

2.4 Experimental Design

The calcaneus was then cut into a Sanders Type IIC calcaneal fracture model in SolidWorks 2022 according to the Sanders calcaneal fracture typing criteria [15, 16]. According to the anatomical structure of the calcaneus, the mechanism of injury of the fracture and the results of our pre-experiment, four types of screw internal fixation were designed and named as study group, control group 1, control group 2 and control group 3 in that order. In all four fracture models, we used two 3.5-mm screws placed from the calcaneal thalamic portion into the sustentaculum tali and ensured that the spatial position of these two screws remained absolutely identical in all four groups. What is not the same in all four groups is the direction in which we fix our longitudinal screws. In the study group one screw was placed longitudinally from the calcaneal tubercle into the anterior process; the other screw was placed from the calcaneal tubercle into the calcaneal sustentaculum tali (Figure 3a, e). The two longitudinal screws in control group 1 were fixed in the same way as in the study group, but the two screws were placed crosswise (Figure 3 b、f). In control group 2, two longitudinal screws were placed parallel to the anterior calcaneal process from the calcaneal tuberosity (Figure 3 c、g). In control group 3, the two longitudinal screws were crossed from the calcaneal tuberosity and inserted into the anterior calcaneal process (Figure 3 d、h). Finally, the material properties are assigned and the contact joints are set in ANSYS Workbench 2022 R1 (Table 1) [13, 14]. The mesh size was set to 1 mm. the loads and boundary conditions applied were consistent with our pre-experiments.

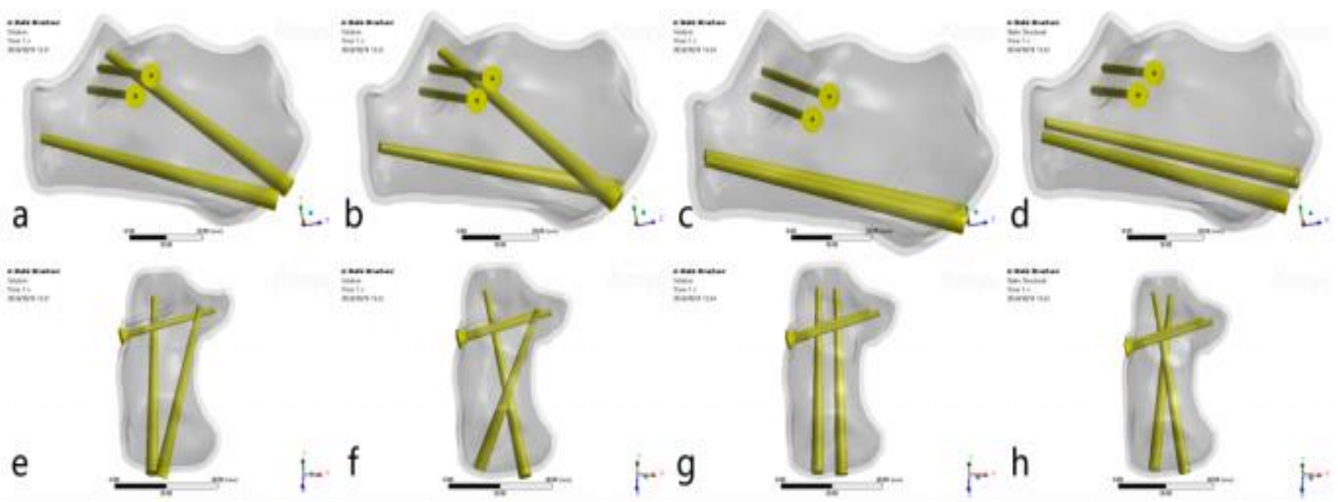

Figure 3: Four percutaneous screw internal fixation models: a, e: study group; b, f: control group 1; c, g: control group 2; d, h: control group 3

Table 1: Finite element analysis material properties

Materials	Young's modulus (MPa)	Poisson's ratio
Screw	200000	0.28
Cortical bone	7300	0.3
Cancellous bone	100	0.3

3. Results

The finite element results of interest in this study include the maximum stresses in the calcaneus (Figure 4), the maximum stresses in the screws (Figure 5), and the maximum displacement of the fracture block (Figure 6), as shown in Table 2. The maximum stresses in the calcaneus, the maximum stresses in the transverse and longitudinal screws, and the maximum displacement of the fracture block were similar in the study and control groups 1. And all of them were significantly lower than control group 2 and control group 3, except for the maximum stress of longitudinal screws. The maximum stress of the longitudinal screws in the study group and control group 1 was significantly higher than that in control group 2 and control group 3. According to previous finite element studies, when the stress on the metal endoprosthesis exceeds 600 mPa, it is likely to lead to failure of the endoprosthesis, and the screw stresses in all of our groups did not exceed this value, so our internal fixation models were all stable [17].

Table 2: Finite element analysis results

	Study group	Control group 1	Control group 2	Control group 3
Maximum stress in the calcaneus (MPa)	39.385	38.884	46.429	45.583
Maximum stress of transverse screws (MPa)	129.08	125.48	177.11	158.65
Maximum stress of longitudinal screws (MPa)	124.77	119.69	44.96	76.357
Maximum displacement of the fracture block (mm)	0.35164	0.34582	0.4633	0.44227

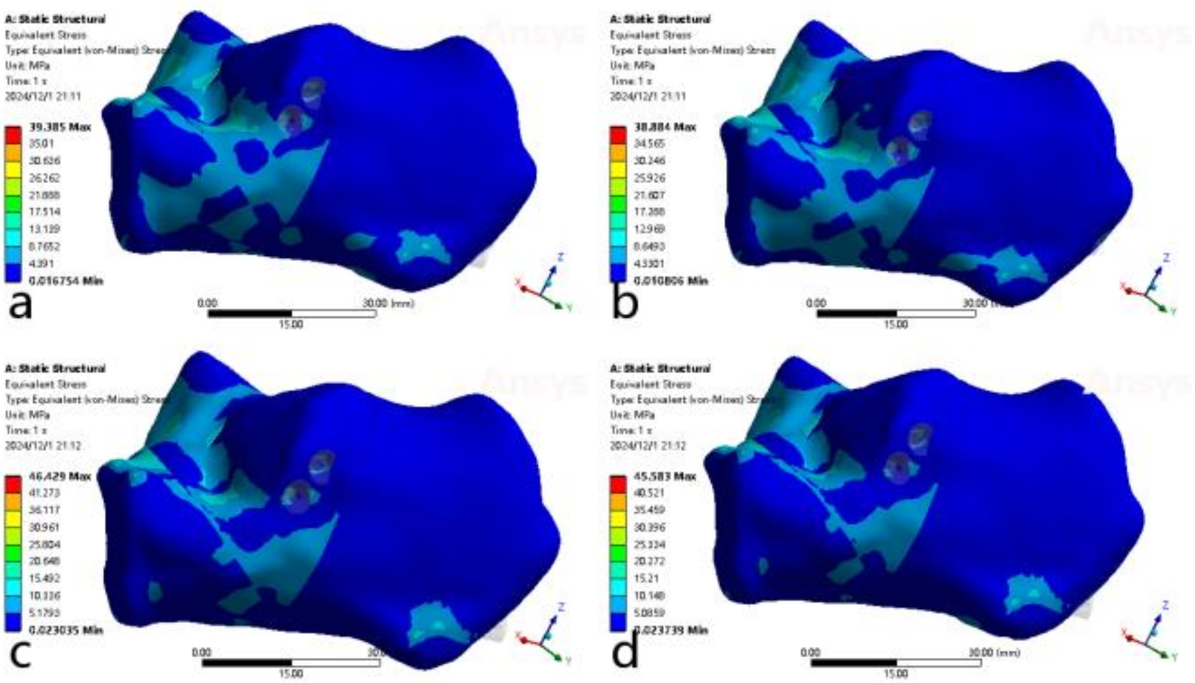

Figure 4: Maximum equivalent force of the calcaneus in each model 4a: the maximum equivalent force of the calcaneus in the study group was 39.385 MPa; 4b: the maximum equivalent force of the calcaneus in the control 1 group was 38.884 MPa; 4c: the maximum equivalent force of the calcaneus in the control 2 group was 46.429 MPa; 4d: the maximum equivalent force of the calcaneus in the control 3 group was 45.583 MPa.

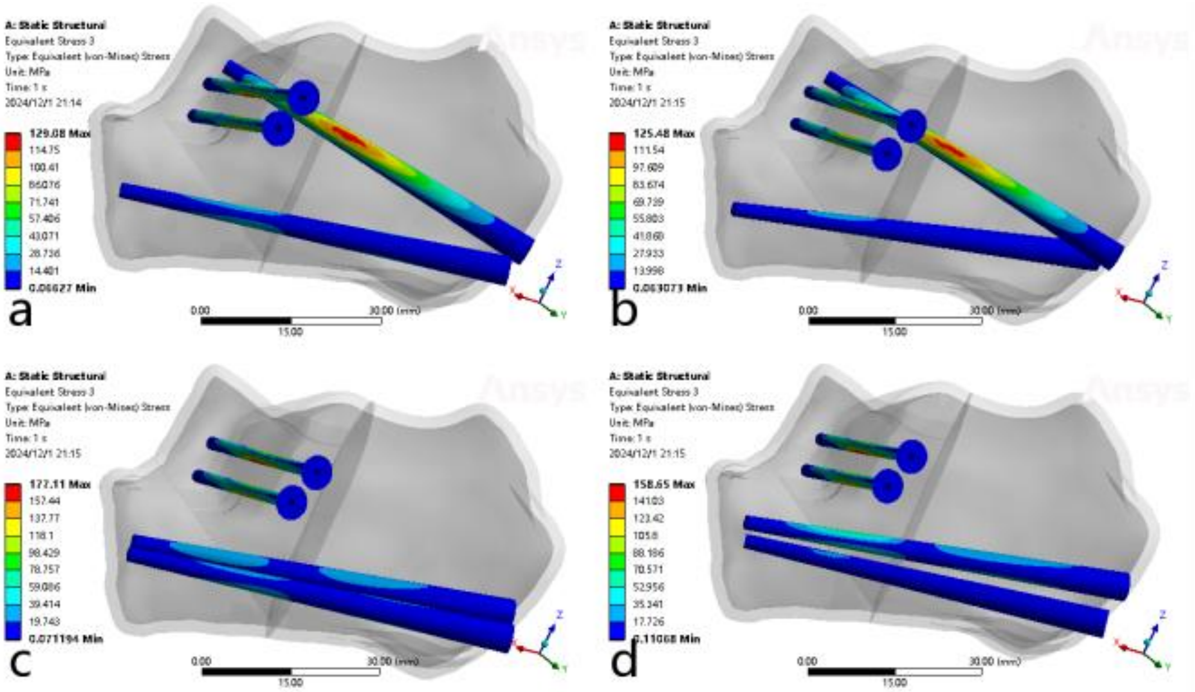

Figure 5: Maximum stress of screws in each model 5a: Maximum stress of screws in the study group is 129.08; 5b: Maximum stress of screws in control 1 group is 125.48 MPa; 5c: Maximum stress of screws in control 2 group is 177.11 MPa; 5d: Maximum stress of

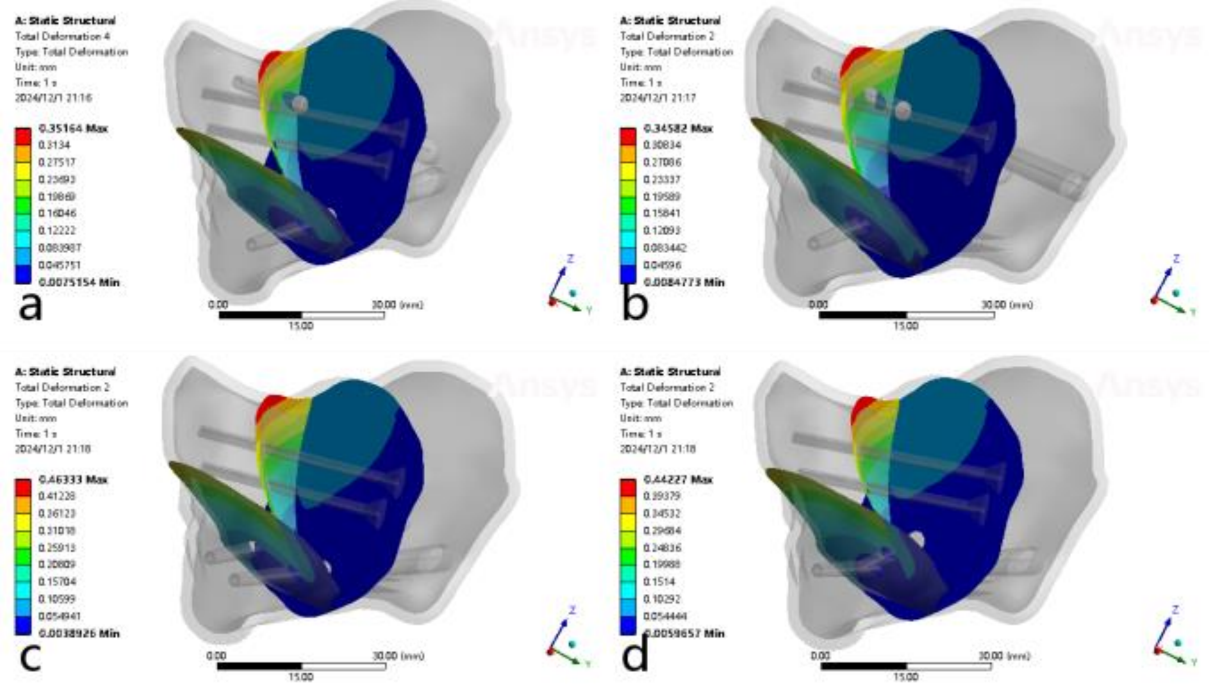

Figure 6: Maximum displacement of the fracture block in each model: the maximum displacement of the fracture block in the study group was 0.35164 mm; 6b: the maximum displacement of the fracture block in control 1 group was 0.34582 mm; 6c: the maximum displacement of the fracture block in control 2 group was 0.46333 mm; 6d: the maximum displacement of the fracture block in control 3 group was 0.44227 mm.

4. Discussion

In the treatment of calcaneal fractures, percutaneous screw internal fixation has been widely proven to be effective. Several studies have shown that percutaneous screw fixation is not only comparable to plate fixation in terms of fixation strength and stability, but also has the advantages of less trauma, shorter operative time, and faster postoperative recovery [8, 9, 12, 18-20]. The effectiveness of screw fixation versus locking plate fixation of calcaneal fractures compared with finite element analysis by Ming Ni. Fixation of calcaneal fractures with screws only resulted in a similar movement of the fracture block as with locking plate fixation, and both fixation modalities resulted in adequate stability [20]. Cheng Long et al. used three-step closed reduction percutaneous screw fixation to treat 33 cases of displaced intra-articular calcaneal fractures with no postoperative incisional complications and significant improvement in Böhler angle and height and width of the calcaneus [10]. Ye Peng in comparing incisional reduction internal fixation and closed reduction percutaneous internal fixation for the treatment of displaced intra-articular calcaneal fracture with a mean follow-up time of 16.533±3.95 months, they found that the two methods had the same restoration effect in terms of length, width, height, Böhler angle, gissane angle of the calcaneus, and that the postoperative period of closed reduction percutaneous distraction fixation pain and incisional complications were significantly lower than those of incisional reduction and internal fixation [21]. Therefore, we did not compare with plate fixation in this study, but focused on optimizing the screw direction of percutaneous screw fixation in order to further improve its fixation effect. We also did not pursue the use of more screws to increase the stability of fixation. We combined the results of the pilot experiment with the injury mechanism of the calcaneus to ensure that the screw design was scientific and reasonable.

In our preexperiment, we simulated the force on a normal human standing and found that the stress was mainly concentrated on the anterior medial aspect of the calcaneus. In the mechanism of injury of calcaneal fracture, the force is transmitted from the talus to the calcaneus through the middle and posterior talar articular surfaces, and the calcaneus forms a primary fracture line under the action of the shear force, and the primary fracture line divides the calcaneus into two main fracture blocks, anteromedial and posterolateral [15, 22]. And the most important screws connecting the two main fracture blocks, anterior medial and posterior lateral. In control group 2 and control group 3, two longitudinal screws were placed from the calcaneal tubercle into the calcaneus process. In study and control group 1, we had one longitudinal screw placed to the calcaneal sustentaculum tali and one longitudinal screw placed in the calcaneus anterior process, so that our longitudinal screws were oriented more anteromedially than anteriorly. In our results, the study group and control group 1 showed a significant advantage over control group 2 and control group 3 in terms of maximum stress on the bone and transverse screws, and maximum displacement of the fracture block. The longitudinal screws were higher than control group 2 and control group 3, which is an indication that longitudinal screw placement in the calcaneal sustentaculum tali can take more stress than placement in the calcaneal anterior process. It also proves that the screw orientation we designed for the study group and control group 1 can obtain better biomechanical results.

In addition, this study used a finite element analysis approach and during the experiments we had to reduce the calcaneus to an internally homogeneous model and we did not take into account the ligaments surrounding the calcaneus. However, this is not the case. The cancellous bone inside the calcaneus is distributed inhomogeneously. The calcaneal tubercle, the sustentaculum tali, and the anterior process of the calcaneus are areas of trabecular convergence, which are hard and strong, and therefore provide a good biomechanical basis for screw fixation of calcaneal fractures. The calcaneal sustentaculum tubercle, together with the medial wall of the calcaneus, constitutes a strong medial load-bearing column. Therefore, the placement of screws from the calcaneal sustentaculum tubercle to the calcaneal sustentaculum tali in the direction of the medial wall can effectively support the medial load-bearing column, maintain the height of the calcaneus, and resist the internal and external rotation of the calcaneal sustentaculum tubercle. The sustentaculum talus is connected to the tibia and talus by the deltoid ligament and the interosseous ligament, respectively. The strength of both bundles of ligaments provides a robust stabilizing effect on the sustentaculum fracture fragment [23, 24]. Therefore, we believe that longitudinal screw fixation from the posterior calcaneal tuberosity to the sustentaculum talus is more suitable for the anatomical structure and mechanical requirements.

5. Innovation and Deficiency of This Study

The innovation of this study is that we considered the anatomical structure of the calcaneus and the injury mechanism of calcaneus fracture when designing the internal fixation of screws; and we conducted a pre-experiment to analyse the stress distribution inside the calcaneus when a normal person is standing up, which makes the design of our screws more scientific and reasonable. Shortcomings: we only designed Sanders type IIC calcaneus fracture and did not evaluate other types of fracture in Sanders' typing; also as a finite element analysis, we simplified the model of the calcaneus to a uniform elastic model, and also ignored the ligaments around the calcaneus, so the results may be affected to a certain extent.

6. Conclusion

For the treatment of Sanders type IIC calcaneal fractures, the best biomechanical results can be obtained by using two transverse screws to fix the articular surface fracture fragment, one longitudinal screw from the calcaneal tuberosity to the sustentaculum talus, and one longitudinal screw from the calcaneal tuberosity to the calcaneal anterior process.

References

[1] Potter, M.Q. and J.A. Nunley, *Long-term functional outcomes after operative treatment for intra-articular fractures of the calcaneus*. J Bone Joint Surg Am, 2009. **91**(8): p. 1854-60.1854-60.10.2106/jbjs.H.01475

[2] Snoap, T., M. Jaykel, C. Williams, et al., *Calcaneus Fractures: A Possible Musculoskeletal Emergency*. J Emerg Med, 2017. **52**(1): p. 28-33.28-33. 10.1016/ j.jemermed.2016.07.085

[3] Rammelt, S. and M.P. Swords, *Calcaneal Fractures-Which Approach for Which Fracture?* Orthop Clin North Am, 2021. **52**(4): p. 433-450.433-450. 10.1016/j.ocl.2021.05.012

[4] Razik, A., M. Harris, and A. Trompeter, *Calcaneal fractures: Where are we now?* Strategies Trauma Limb Reconstr, 2018. **13**(1): p. 1-11.1-11. 10.1007/ s11751-017-0297-3

[5] Jiang, N., Q.R. Lin, X.C. Diao, et al., *Surgical versus nonsurgical treatment of displaced intra-articular calcaneal fracture: a meta-analysis of current evidence base*. Int Orthop, 2012. **36**(8): p. 1615-22.1615-22. 10.1007/s00264-012-1563-0

[6] Zhang, W., F. Lin, E. Chen, et al., *Operative Versus Nonoperative Treatment of Displaced Intra-Articular Calcaneal Fractures*: A Meta-Analysis of Randomized Controlled Trials. J Orthop Trauma, 2016. **30**(3): p. e75-81.e75-81.10.1097/bot.0000000000000446

[7] Hsu, A.R., R.B. Anderson, and B.E. Cohen, *Advances in Surgical Management of Intra-articular Calcaneus Fractures*. J Am Acad Orthop Surg, 2015. **23**(7): p. 399-407.399-407.10.5435/jaaos-d-14-00287

[8] Jin, C., D. Weng, W. Yang, et al., *Minimally invasive percutaneous osteosynthesis versus ORIF for Sanders type II and III calcaneal fractures: a prospective, randomized intervention trial*. J Orthop Surg Res, 2017. **12**(1): p. 10.10.10.1186/s13018-017-0511-5

[9] Nosewicz, T., M. Knupp, A. Barg, et al., *Mini-open sinus tarsi approach with percutaneous screw fixation of displaced calcaneal fractures: a prospective computed tomography-based study*. Foot Ankle Int, 2012. **33**(11): p. 925-33.925-33.10.3113/fai.2012.0925

[10] Long, C., K. Li, J. Zhu, et al., *Three-step closed reduction and percutaneous screw fixation: A reliable and reproducible protocol in managing displaced intra-articular calcaneal fractures*. Injury, 2023. **54 Suppl 2**: p. S49-s55.S49-s55. 10.1016/ j.injury. 2022.02.017

[11] Nelson, J.D., T.E. McIff, P.G. Moodie, et al., *Biomechanical stability of intramedullary technique for fixation of joint depressed calcaneus fracture*. Foot Ankle Int, 2010. **31**(3): p. 229-35.229-35. 10.3113/ fai.2010.0229

[12] Luo, G., C. Fan, P. Gao, et al., *An evaluation of the efficacy of percutaneous reduction and screw fixation without bone grafting in Sanders Type-II and Type-III displaced intra-articular calcaneal fractures*. BMC Musculoskelet Disord, 2022. **23**(1): p. 562. 562. 10.1186/s12891-022-05515-2

[13] Pang, Q.J., X. Yu, and Z.H. Guo, *The sustentaculum tali screw fixation for the treatment of Sanders type II calcaneal fracture: A finite element analysis*. Pak J Med Sci, 2014. **30**(5): p. 1099-103.1099-103. 10.12669/ pjms.305.5301

[14] Yu, B., W.C. Chen, P.Y. Lee, et al., *Biomechanical comparison of conventional and anatomical calcaneal plates for the treatment of intraarticular calcaneal fractures - a finite element study*. Comput Methods Biomech Biomed Engin, 2016. **19**(13): p. 1363-70. 1363-70.10.1080/10255842.2016.1142534

[15] Sanders, R., *Intra-articular fractures of the calcaneus: present state of the art*. J Orthop Trauma, 1992. **6**(2): p. 252-65.252-65.10.1097/00005131-199206000-00022

[16] Sanders, R., P. Fortin, T. DiPasquale, et al., *Operative treatment in 120 displaced intraarticular calcaneal fractures. Results using a prognostic computed tomography scan classification*. Clin Orthop Relat Res, 1993(290): p. 87-95.87-95.

[17] He, K., S. Fu, S. Liu, et al., *Comparisons in finite element analysis of minimally invasive, locking, and non-locking plates systems used in treating calcaneal*

fractures of Sanders type II and type III. Chin Med J (Engl), 2014. **127**(22): p. 3894-901.3894-901.

[18] de Vroome, S.W. and F.M. van der Linden, *Cohort study on the percutaneous treatment of displaced intra-articular fractures of the calcaneus*. Foot Ankle Int, 2014. **35**(2): p. 156-62. 156-62. 10.1177/ 1071100713509804

[19] Chen, Z., C. Fan, J. Zhang, et al., *A novel minimally invasive percutaneous treatment for Essex-Lopresti joint depression-type DIACFs by ligamentotaxis*. BMC Surg, 2022. **22**(1): p. 431.431.10.1186/s12893-022-01868-6

[20] Ni, M., D.W. Wong, J. Mei, et al., *Biomechanical comparison of locking plate and crossing metallic and absorbable screws fixations for intra-articular calcaneal fractures*. Sci China Life Sci, 2016. **59**(9): p. 958-64.958-64.10.1007/s11427-016-0010-9

[21] Peng, Y., J. Liu, G. Zhang, et al., *Reduction and functional outcome of open reduction plate fixation versus minimally invasive reduction with percutaneous screw fixation for displaced calcaneus fracture: a retrospective study*. J Orthop Surg Res, 2019. **14**(1): p. 124.124.10.1186/s13018-019-1162-5

[22] Lowery, R.B. and J.H. Calhoun, *Fractures of the calcaneus. Part I: Anatomy, injury mechanism, and classification*. Foot Ankle Int, 1996. **17**(4): p. 230-5.230-5.10.1177/107110079601700409

[23] Cain, J.D. and M. Dalmau-Pastor, *Anatomy of the Deltoid-Spring Ligament Complex*. Foot Ankle Clin, 2021. **26**(2): p. 237-247. 237-247. 10.1016/ j.fcl. 2021.03.001

[24] Carr, J.B., *Mechanism and pathoanatomy of the intraarticular calcaneal fracture*. Clin Orthop Relat Res, 1993(290): p. 36-40.36-40.