Non-Profit Joint-Stock Company "Astana Medical University"

IBN:616.718.72-001.513-089.23

ZHANASPAYEV TIMUR MARATOVICH

Improvement of the treatment of intra-articular comminuted depressed calcaneal fractures using a device for intraoperative reduction

Dissertation for the degree of Doctor of Philosophy (PhD)

8D10102– Medicine

Scientific consultant:
Doctor of Medical Sciences
M.T. Abilmazhinov

Foreign scientific consultant:
Doctor of Medical Sciences,
Professor A.B. Bondarenko

Republic of Kazakhstan
Astana 2026

Introduction

Relevance of the research topic

Calcaneal fractures are the most common traumatic injuries to the hindfoot and can lead to severe disability with social and economic consequences [1]. Their incidence ranges from 11.5 to 13.5 cases per 100,000 population per year and accounts for 2% to 5.1% of all bone fractures [2-5]. Among calcaneal fractures, intra-articular injuries occur in 75% of cases and are often accompanied by significant displacement of bone fragments [6-9].

Intra-articular impression fractures are characterized by depression of the posterior articular facet into the calcaneal shaft, a decrease in its height, an increase in the width and shortening of the shaft, and the formation of varus or valgus deformities. These changes lead to a decrease in the Böhler angle and an increase in the Hissan angle, reflecting a disruption in the anatomical configuration of the hindfoot. Failure to adequately reduce the fracture leads to the development of longitudinal flatfoot, subtalar arthrosis, talotibial and fibular-calcaneal impingement syndrome, decreased weight-bearing ability of the foot, and chronic pain, which significantly impairs patients' quality of life and ability to work [7, 10-14].

The anatomical complexity of the subtalar joint, which is concave in the horizontal plane and convex in the sagittal plane, significantly complicates intraoperative repositioning and objective assessment of its adequacy. Even when using the extended lateral approach (ELA), the surgeon has limited visualization of the articular surface. With a minimally invasive approach through the sinus tarsi (STA), the risk of underreposition of the posterior articular facet is even higher [15-18]. According to the literature, after X-ray control with intraoperative assessment using 3D visualization with an O-arm arch, residual displacement of fragments remains in 35-47% of patients [19-22], which in 29-42% of cases leads to the development of post-traumatic arthrosis of the subtalar joint [5,13,23,24].

The treatment strategy for intra-articular impression fracture of the calcaneus is determined by the severity of the injury, assessed according to the R. Sanders classification [23]. For type II–III fractures, satisfactory results have been achieved using percutaneous or minimally invasive methods of repositioning and fixation [13, 25–34].

However, the treatment of the most severe multi-comminuted intra-articular impression fractures of the calcaneus type Sanders IV remains controversial. Some researchers recommend primary subtalar arthrodesis [35-37], while others use open reduction and internal fixation (ORIF) [38-39]. Despite comparable functional results in individual studies [40], arthrodesis inevitably leads to ankylosis of the subtalar joint and limitation of motion, whereas with anatomical reduction and stable fixation, it is possible to preserve joint function and achieve higher scores on the AOFAS scale [38-39].

Achieving anatomical reposition of the posterior articular facet and restoring the spatial configuration of the calcaneus remains a key factor in improving long-term treatment outcomes.

Restoration of the calcaneus's overall configuration is best achieved through intraoperative distraction using external fixation devices and a ligamentotaxis mechanism [41]. However, currently used devices provide distraction primarily along one axis–either the tibia or the calcaneus axis–which limits the potential for complete restoration of the anatomy.

There are no data in the literature on the use of an intraoperative device capable of providing controlled distraction simultaneously along the tibia and calcaneus axis, which could facilitate more effective bone restoration through uniform ligamentotaxis along the entire perimeter. Furthermore, the need for an extended lateral approach when installing angularly stable plates is associated with a high rate of wound complications (up to 30–37%), necessitating improvements in both repositioning techniques and postoperative wound management.

Thus, the problem of choosing the optimal surgical approach for multi-fragment Sanders IV impression fractures of the calcaneus remains unresolved. Improving intraoperative repositioning techniques using a modernized external fixation device that provides multi-axial distraction and more precise restoration of calcaneal anatomy is a pressing issue in modern traumatology and meets the needs of practical healthcare in the Republic of Kazakhstan.

Goal of the study

Improving the efficiency of surgical treatment of patients with transarticular multi-fragmentary impression fracture of the calcaneus by modernizing the external fixation device for intraoperative reposition of bone fragments.

Research objectives:

1. To evaluate the stress-strain state of a device for intraoperative reposition of bone fragments in transarticular multi-fragmentary impression fractures of the calcaneus, modernized with a repositioning unit using a mathematical model of *device – lower leg – foot*.

2. To conduct a radiographic assessment of the restoration of the anatomical parameters of the calcaneus using a device for intraoperative repositioning of bone fragments in transarticular multi-comminuted impression fractures of the calcaneus, modernized with a repositioning unit, under conditions of two-vector distraction.

3. To evaluate the clinical and functional results of treatment of patients with transarticular multi-comminuted impression fractures of the calcaneus after using the two-vector distraction method with a device modernized with a repositioning node.

Scientific novelty:

1. A new method of two-vector distraction has been developed, using a device modernized with a repositioning unit, for intraoperative repositioning of bone fragments in transarticular multi-comminuted impression fractures of the calcaneus.

2. For the first time, a comparative study has established the clinical, functional and radiological effectiveness of the use of two-vector intraoperative repositioning using a device modernized with a repositioning unit for transarticular multi-comminuted impression fractures of the Sanders IV type.

The main points submitted for defense:

1. Based on the results of mathematical modeling of the *device – lower leg – foot* system, it was established that the device for intraoperative repositioning of bone fragments, modernized with a repositioning unit, has a sufficient safety margin (up to 720 MPa) and provides two-vector intraoperative distraction along the axis of the lower leg and the axis of the calcaneus, which creates conditions for restoring the spatial configuration of the calcaneus in transarticular multi-comminuted impression fractures of the Sanders IV type;

2. The use of two-vector intraoperative distraction using a device modernized with a repositioning unit ensures the restoration of the three-dimensional configuration of the calcaneus, which is expressed in a reliable decrease in its width, an increase in height and length ($p<0.001$), confirming the effectiveness of anatomical correction in transarticular multi-comminuted impression fractures of the Sanders IV type.

3. The use of the proposed device with two-vector intraoperative distraction, compared with traditional repositioning methods, significantly reduces the incidence of postoperative complications (from 43.3% to 5.9%) and increases the proportion of excellent and good functional outcomes according to the AOFAS scale (from 55.9% to 88.2%) ($p<0.001$).

Practical significance:

1. The developed method of two-vector distraction, using a device modernized with a repositioning unit, allows for the restoration of the anatomical configuration of the calcaneus and articular facet in transarticular multi-comminuted impression fractures of the Sanders IV type.

2. The use of the proposed method of two-vector distraction, using a device modernized with a repositioning unit, reduces the incidence of postoperative complications, thereby improving the long-term functional results of treatment.

3. The introduction of the developed technology into the practice of trauma departments allows for the standardization of surgical tactics for the most severe intra-articular fractures of the calcaneus, increases the predictability of treatment outcomes, and reduces the need for repeated reconstructive interventions.

Implementation of research results

During the work, the reposition of bone fragments in transarticular multi-comminuted impression fractures of the calcaneus by means of two-vector distraction with the proposed device was introduced into clinical practice in the trauma departments of the City Hospital No. 1 of Astana and the N.D. Batpenov National Scientific Center of Traumatology and Orthopedics; two implementation certificates were issued.

Personal contribution of a doctoral student:

Under the guidance of scientific consultants, an analysis and statistical processing of clinical and instrumental data was conducted on patients with Sanders IV calcaneal fractures treated inpatients at the Astana City Hospital No. 1, the N.D. Batpenov National Scientific Center of Traumatology and Orthopedics, and the Professor Kh.Zh. Makazhan Multidisciplinary Hospital in Karaganda.

I participated in the treatment of patients at the City Hospital No. 1 during the collection of clinical data. A literature review of existing methods for repositioning and treating calcaneal fractures was conducted. Patients were recruited for the study. All data were systematized, documented, and presented as a dissertation by the author.

I co-authored a two-vector distraction method for intraoperative repositioning of bone fragments in calcaneal fractures.

Validation of the research findings

The results of the research work were discussed at the

- International Scientific and Practical Conference "Horizons of Traumatology and Orthopedics" (Turkestan, 2022) - Young Scientists Competition
- IV Congress of Traumatologists and Orthopedists of the Republic of Kazakhstan (Astana, August 28-29, 2024).

Publications on the topic of the dissertation

Based on the dissertation research materials, 4 scientific papers were published, including 3 articles in publications recommended by the Committee for Control in the Sphere of Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan:

1. Абильмажинов М.Т., Жанаспаев Т.М., Жанаспаева Г.А. Эволюция метода репозиции внутрисуставного компрессионного перелома пяточной кости // Science & Healthcare. – 2022. – Vol. 24, № 5. - P. 188-195. DOI10.34689/SH.2022.24.5.023
2. Жанаспаев Т.М., Мухаметжанов Х.М., Жанаспаева Г.А. Нерешенные аспекты и достижения лечения внутрисуставных переломов пяточной кости // ВЕСТНИК КАЗНМУ. – 2022. - Т. 4, № 63. - Стр. 122-140. DOI:10.53065/m5784-36160791-h
3. Жанаспаев А.М., Жанаспаев Т.М., Горбунов Б.Н., Бондаренко А.В. Биомеханика репонирующего воздействия, оцененная методом конечных элементов и рентгенологические результаты двухвекторной дистракции аппаратом внешней фиксации при оперативном лечении перелома пяточной кости типа Sanders IV // Traumatology and Orthopaedics of Kazakhstan. – 2024. – Vol. 3, № 74. – P. 17-25. DOI:10.52889/1684-9280-2024-3-74-17-25

1 publication in an international scientific journal included in the Scopus database:

1. Zhanaspayev T.M., Zhanspayeva G.A., Abilmazhinov M.T. Evaluation of the result of articular facet reduction and intraoperative distraction for sanders type calcaneal fracture in polytraumatized patients // Pol Merkur Lek. – 2024. – Vol. 52, №5. - P. 512-521. DOI:10.36740/Merkur202405106

1 patent issued by the Eurasian Patent Organization:

1. Патент на изобретение №037877 от 31.05.2021 г. Жанаспаев А.М., Жанаспаев М.А., Жанаспаев Т.М. Устройство для интраоперационной репозиции внутрисуставного компрессионного перелома пяточной кости.

An application for a patent has been filed for the invention “A method of two-vector distraction for intraoperative repositioning of bone fragments in transarticular multi-comminuted impression fractures of the calcaneus”

Volume and structure of the dissertation

The dissertation is written in Russian and is presented on 95 pages of computer-typeset text. It consists of an introduction, a review of literary sources, four sections, a conclusion, findings, practical recommendations, and a list of 120 references (12 in Russian, 108 in foreign languages). The dissertation includes 17 tables, six graphs, and is illustrated with 37 figures..

Materials and methods of research

Object and subject of research:

The study involved 59 patients with 68 intra-articular multi-comminuted impression fractures of the calcaneus (Sanders IV type). Surgical treatment was performed in the trauma departments of the N.D. Batpenov National Scientific Center of Traumatology and Orthopedics, the First Multidisciplinary City Hospital No. 1 in Astana, and the Kh.Zh. Makazhan Multidisciplinary Hospital in Karaganda from 2016 to 2023.

We formed two groups: a study group and a control group. In the study group, three-dimensional restoration of the calcaneus structure was performed intraoperatively using two-vector distraction with the proposed modernized external fixation device, open reduction of the depressed articular facet, and osteosynthesis with an angularly stable plate. In the control group, reduction was performed using single-vector axial traction according to H. Westhues using surgical instruments and external fixation devices, and osteosynthesis with a plate, screws, and pins.

A comparison of patients in both groups revealed no statistically significant differences in age, injury mechanism, or severity of calcaneal deformity. Treatment assessments for patients in the study and control groups were based on complaints, general condition, wound healing, and radiographic data. Functional outcome was assessed using the AOFAS scale and VAS pain intensity scores. Treatment outcomes were assessed 3, 6, and 12 months after surgery.

Comparison of the two study groups was carried out according to the following criteria:

- restoration of Böhler’s angle;
- restoration of Gissane’s angle;
- restoration of the inclination angle of the posterior articular facet;
- restoration of calcaneal width, length, and height;
- functional treatment outcome according to the AOFAS hindfoot and ankle scale;
- pain intensity according to the VAS;
- development of postoperative complications.

The study design is presented in Figure 1

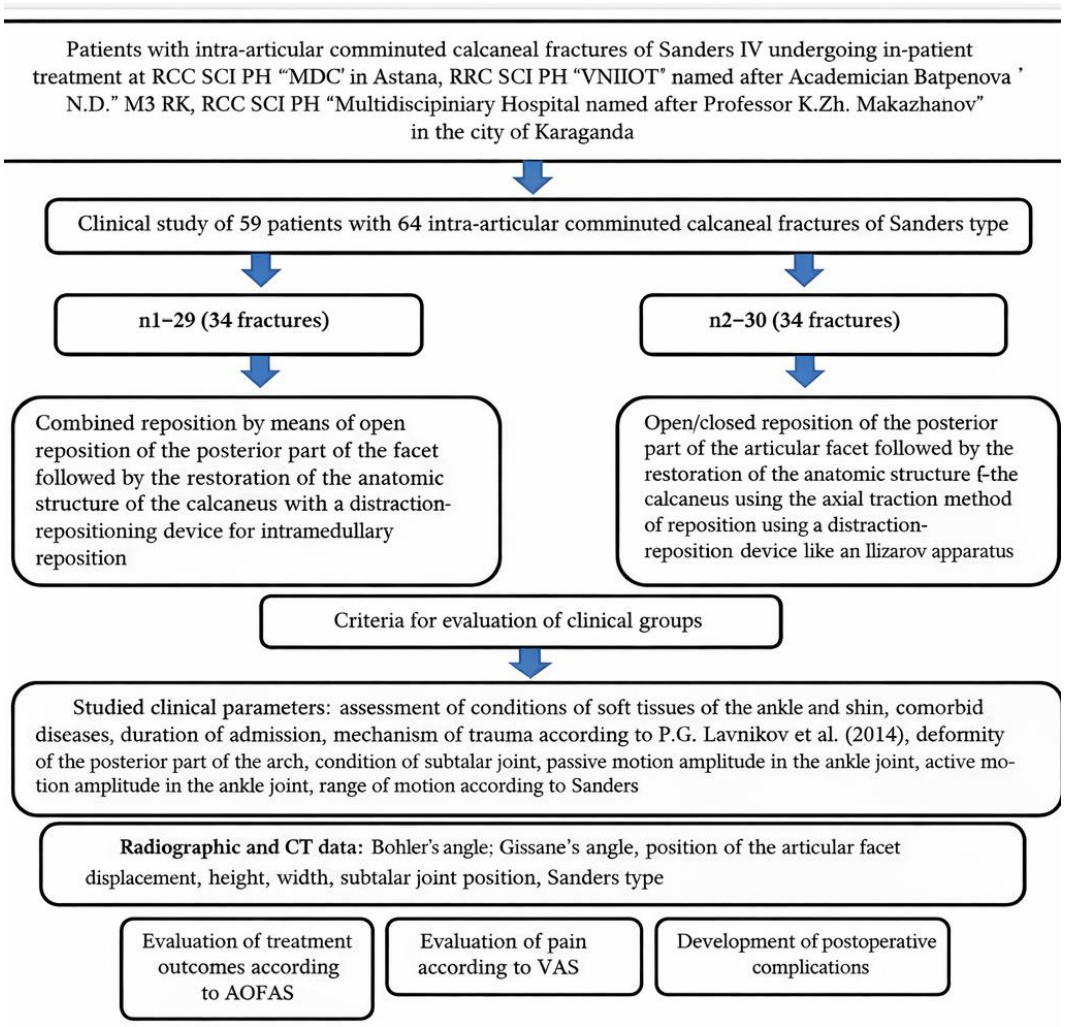

Figure 1 – study design

Methods of statistical processing of the obtained data

Statistical data processing was performed using the Statistica software package. Sample size calculation was performed using G*Power 3.1. At a significance level of $\alpha = 0.05$, study power of $1–\beta = 0.80$, and the expected average effect (Cohen's $d = 0.8$), the minimum required sample size was at least 26 patients in each group. The actual sample size (29 patients in the study group and 30 patients in the control group) is sufficient to conduct a statistically correct comparative analysis.

Before selecting the analysis methods, the distribution of quantitative variables was assessed using the Shapiro–Wilk test. Due to the asymmetric distribution of most clinical and X-ray anthropometric parameters, as well as the presence of extreme values, nonparametric methods were predominantly used for statistical analysis.

Descriptive statistics of quantitative clinical and radiological parameters are presented as median and interquartile range (IQ1; Q3). The term "range" refers to the range of values from minimum to maximum (Min–Max).

The Mann–Whitney U test was used to assess differences between quantitative parameters in two independent clinical groups. Analysis of intragroup dynamics of parameters during repeated measurements (preoperatively, postoperatively, and at the final examination) was performed using the Friedman test, and for pairwise comparisons, the Wilcoxon test.

Fisher's exact test was used to analyze qualitative characteristics and complication rates. Differences were considered statistically significant at a significance level of $p \leq 0.05$.

Results and conclusion

The dissertation includes biomechanical and clinical phases. In the biomechanical section, a finite element analysis of the stress-strain state of the device-tibia-foot system was performed. It was found that with two-vector distraction, the resulting stress (maximum 665 MPa in the pin fixation area) does not exceed the tensile strength of the structure (720 MPa), confirming the device's sufficient safety margin and reliability. Virtual modeling demonstrated the feasibility of controlled movement of the repositioning unit and restoration of the three-dimensional structure of the calcaneus through combined distraction along the tibia and calcaneus axes.

The clinical portion of the study is based on an analysis of the treatment outcomes of 59 patients (68 with Sanders IV fractures). The study group underwent posterior facet repositioning combined with intraoperative dual-vector distraction using the developed device and fixation with an angularly stable heel plate. The control group utilized traditional repositioning techniques.

In the main and control groups, the increase in the Beller angle was 37.5°±5.2° and 19.4°±5.5°, respectively; the Gissan angle was 115.5°±4.8° and 104.1°±49.8°, respectively; the posterior articular facet angle was up to 54.3°±7.2° and 33.9°±19.7°, respectively ($p < 0.001$). The restoration of the spatial parameters of the calcaneus was also more pronounced in the main group compared to the control group: the width decreased to 34.3±2.5 mm and 48.3±8.9 mm, respectively ($p < 0.001$); the height increased to 45.5±5.2 mm and 42.9±5.7 mm, respectively; the length has been increased to 81.7±5.4 mm and 80.1±7.4 mm, respectively.

The proposed method was associated with a significant reduction in the incidence of postoperative complications compared to traditional treatment methods. Functional treatment outcomes, as measured by the AOFAS scale, were statistically significantly higher in the study group, while pain severity, as measured by the VAS scale, was lower than in the control group. The proportion of "excellent" and "good" outcomes significantly exceeded that in the comparison group.

The obtained results indicate that the combination of open anatomical facet repositioning with intraoperative dual-vector distraction ensures comprehensive restoration of calcaneal anatomy. Formation of ligamentotaxis along the entire bone perimeter creates conditions for correcting deformity and preventing secondary loss of correction. Stable osteosynthesis with a calcaneal plate with angular stability ensures the maintenance of the achieved result and the possibility of early functional rehabilitation.

Thus, the results of the conducted biomechanical modeling, radiographic analysis and clinical and functional assessment indicate the feasibility and effectiveness of using the developed device for intraoperative two-vector distraction in the treatment of transarticular multi-comminuted impression fractures of the calcaneus type Sanders IV.

Based on the above, the following conclusions can be drawn:

Conclusion:

1. The developed method of dual-vector distraction using a device upgraded with a reduction unit for transarticular multi-comminuted impression fractures of the calcaneus has a sufficient safety margin based on stress-strain state assessment: maximum stresses in the pin area reach 665 MPa, with a structural tensile strength of 720 MPa. The design enables controlled dual-vector distraction along the tibia and calcaneus axis.

2. Radiographic evaluation showed a statistically significant difference in the correction of the anatomical parameters of the calcaneus in the main group compared to the control group: Behler angle - 40° [35; 45] and 20° [0; 30], respectively ($U = 138.5$; $p < 0.001$); Gissan angle - 116° [113; 120] and 105° [0; 130], respectively ($U = 367.0$; $p < 0.05$); the angle of inclination of the posterior articular facet - 55° [50; 60] and 30° [0; 50], respectively ($U = 153.5$; $p < 0.001$).

A comparative analysis of the clinical and functional effectiveness of the developed method for treating transarticular comminuted impression fractures of the calcaneus in the study groups showed that the proportion of patients with “excellent” and “good” outcomes in the main group was 88.2%, which is 1.6 times higher compared to the control group (55.9%) ($p < 0.001$). The frequency of “satisfactory” and “unsatisfactory” outcomes was lower in the main group ($p < 0.001$). In the main group, a 1.8-fold decrease in pain intensity was noted (2.2 ± 1.3 points [1; 5]), compared to the control group (4 ± 1.4 points [1; 7]). The average score on the AOFAS scale in the main group reached 88.5 ± 5.6 points [49;97], in the control group – 71.5 ± 17.9 points [20;92] ($U = 152.5$; $p < 0.001$).

Practical recommendations

To improve the effectiveness of intraoperative repositioning of intra-articular multi-fragmentary impression fracture of the calcaneus type Sanders IV, it is recommended to use the proposed external fixation device, which, when used clinically, provided higher rates of restoration of the angle of Bohler, Gissan, inclination of the posterior articular facet, width, height, length of the calcaneus than the methods used by H. Westhues and external fixation devices.

Reference

1. Leigheb M., Codori F. et al. Current Concepts about Calcaneal Fracture Management: A Review of Metanalysis and Systematic Reviews // Applied Sciences (Basel). – 2023. – Vol. 13, Is. 22. – Art. 12311. DOI: https://doi.org/10.3390/app132212311

2. Бодня А.И. Лечебная тактика при сочетанной травме заднего отдела стопы // Травма. – 2019. – № 4. – С. 119–124. DOI: https://doi.org/10.22141/1608-1706.4.20.2019.178756

3. Haapasalo H., Laine H.J., Mäenpää H., Wretenberg P., Kannus P., Mattila V.M. Epidemiology of calcaneal fractures in Finland // Foot and Ankle Surgery. – 2017. – Vol. 23. – P. 321–324. DOI: https://doi.org/10.1016/j.fas.2016.10.004

4. Симаков А.Ю. Хирургическое лечение внутрисуставных переломов пяточной кости: автореф. дис. … канд. мед. наук: 04.03.15. – М.: Московский областной научно-исследовательский клинический институт им. М.Ф. Владимирского, 2018. – 24 с.

5. Zhu Y. et al. Socioeconomic factors and lifestyles influencing of calcaneal fractures, a national population-based survey in China // Journal of Orthopaedic Surgery and Research. – 2019. – Vol. 14. – P. 423. DOI: https://doi.org/10.1186/s13018-019-1493-2

6. Yan H.F., Na H.D., Park J.J., Park C.H. Study on sustentaculum tali fragment constancy in intraarticular calcaneus fracture // Journal of Orthopaedic Trauma. – 2023. – Vol. 37, № 11. – P. E422–E427. DOI: https://doi.org/10.1097/BOT.0000000000002657

7. Cianni L., Vitiello R., Greco T. et al. Predictive factors of poor outcome in Sanders type III and IV calcaneal fractures treated with an open reduction and internal fixation with plate: a medium-term follow-up // Journal of Clinical Medicine. – 2022. – Vol. 11, № 19. – Art. 5660. DOI: https://doi.org/10.3390/jcm11195660

8. Zhang G., Ding S., Ruan Z. Minimally invasive treatment of calcaneal fractures // Journal of International Medical Research. – 2019. – Vol. 47. – P. 3946–3954.

9. Vosoughi A.R. et al. Different types and epidemiological patterns of calcaneal fractures based on reviewing CT images of 957 fractures // Foot and Ankle Surgery. – 2020. – Vol. 28, № 1. – P. 88–92.

10. Knight J.R., Gross E.A., Bradley G.H., Bay C., LoVecchio F. Boehler's angle and the critical angle of Gissane are of limited use in diagnosing calcaneus fractures in the ED // American Journal of Emergency Medicine. – 2006. – Vol. 24, № 4. – P. 423–427.

11. Пахомов И.А. Хирургическая тактика и организация специализированной помощи пациентам с ортопедической патологией стопы и голеностопного сустава: автореф. дис. … д-ра мед. наук: 14.01.15. – Новосибирск: Новосибирский НИИ травматологии и ортопедии, 2012. – 55 с.

12. Gonzalez T.A., Lucas R.C., Miller T.J., Gitajn I.L., Zurakowski D., Kwon J.Y. Posterior facet settling and changes in Bohler's angle in operatively and nonoperatively treated calcaneus fractures // Foot & Ankle International. – 2015. – Vol. 36, № 11. – P. 1297–1309.

13. Tantavisut S., Phisitkul P., Westerlind B.O., Gao Y., Karam M.D., Marsh J.L. Percutaneous reduction and screw fixation of displaced intra-articular fractures of the calcaneus // Foot & Ankle International. – 2017. – Vol. 38, № 4. – P. 367–374.

14. Day M.A. et al. Correlation of 3D joint space width from weightbearing CT with outcomes after intra-articular calcaneal fracture // Foot and Ankle International. – 2020. – Vol. 41, № 9. – P. 1106–1116.

15. Gwak H.-C., Kim J.-G., Kim J.-H., Roh S.-M. Intraoperative three-dimensional imaging in calcaneal fracture treatment *// Clinics in Orthopedic Surgery*. – 2015. – Vol. 7, № 4. – P. 483–489. – DOI: 10.4055/cios.2015.7.4.483.

16. Nosewicz T.L., Knupp M., Bolliger L. et al. The reliability and validity of radiographic measurements for determining the three-dimensional position of the talus in varus and valgus osteoarthritic ankles // Skeletal Radiology. – 2012. – Vol. 41, № 12. – P. 1567–1573.

17. Woon C.Y.L., Chong K.W., Yeo W., Yeo N.E.M., Wong M.K. Subtalar arthroscopy and fluoroscopy in percutaneous fixation of intra-articular calcaneal fractures: the best of both worlds // Journal of Trauma. – 2011. – Vol. 71. – P. 917–925.

18. Park C.H., Yoon D.H. Role of subtalar arthroscopy in operative treatment of Sanders type 2 calcaneal fractures using a sinus tarsi approach // Foot & Ankle International. – 2018. – Vol. 39, № 4. – P. 443–449.

19. Pires R.E., Giordano V., Boni G. et al. Expanding the indications for calcaneal plates beyond foot fractures: a technical trick and case series // European Journal of Orthopaedic Surgery and Traumatology. – 2021. – Vol. 31, № 2. – P. 275–282. DOI: https://doi.org/10.1007/s00590-020-02757-5

20. Franke J., von Recum J., Wendl K., Grutzner P.A. Intraoperative 3-dimensional imaging–beneficial or necessary? // Unfallchirurg. – 2013. – Vol. 116. – P. 185–190.

21. Neumaier M., Kohring J., Ciufo D., Ketz J.P. Technique and early outcomes for high-energy calcaneus fractures treated with staged external fixation to combined open reduction internal fixation and subtalar arthrodesis // Journal of Orthopaedic Trauma. – 2023. – Vol. 36, № 11. – P. E412–E417. DOI: https://doi.org/10.1097/BOT.0000000000002424

22. Eckardt H., Lind M. Effect of intraoperative three-dimensional imaging during the reduction and fixation of displaced calcaneal fractures on articular congruence and implant fixation // Foot & Ankle International. – 2015. – Vol. 36, № 7. – P. 764–773.

23. Sanders R., Vaupel Z.M., Erdogan M., Downes K. Operative treatment of displaced intraarticular calcaneal fractures: long-term (10-20 Years) results in 108 fractures using a prognostic CT classification // Journal of Orthopaedic Trauma. – 2014. – Vol. 28, № 10. – P. 551–563. - doi: 10.1097/BOT.0000000000000169.

24. Buzzi R., Sermi N., Soviero F., Bianco S., Campanacci D.A. Displaced intra-articular fractures of the calcaneus: ORIF through an extended lateral approach // Injury. – 2019. – Vol. 50, № 2. – P. 2–7.

25. Gil Monzo E.R., Liew I., Tadikonda P. et al. Optimal posterior screw placement configuration in Sanders 2B calcaneal fractures: a biomechanical study // Revista Espanola de Cirugia Ortopedica y Traumatologia. – 2023. – Vol. 67, № 2. – P. 144–152. DOI: https://doi.org/10.1016/j.recot.2022.06.007

26. Pastides P.S., Milnes L., Rosenfeld P.F. Percutaneous arthroscopic calcaneal osteosynthesis: a minimally invasive technique for displaced intra-articular calcaneal fractures // Journal of Foot and Ankle Surgery. – 2015. – Vol. 54, № 5. – P. 798–804.

27. Shi G., Lin Z., Liu W. et al. 3D mapping of intra-articular calcaneal fractures // Scientific Reports. – 2023. – Vol. 13, № 1. – Art. 8827. DOI: https://doi.org/10.1038/s41598-023-34711-w

28. Grun W. et al. Results after percutaneous and arthroscopically assisted osteosynthesis of calcaneal fractures // Foot & Ankle International. – 2020. – Vol. 41, № 6. – P. 689–697.

29. Marouby S. et al. Percutaneous arthroscopic calcaneal osteosynthesis for displaced intra-articular calcaneal fractures: systematic review and surgical technique // Foot and Ankle Surgery. – 2020. – Vol. 26, № 5. – P. 503–508.

30. Clement R.C., Lang P.J., Pettett B.J., Overman R.A., Ostrum R.F., Tennant J.N. Cost and cost-effectiveness analysis of treatment options for Sanders II and III calcaneus fractures in laborers // Journal of Orthopaedic Trauma. – 2017. – Vol. 31, № 6. – P. 299–304.

31. Pitts C.C. et al. Radiographic and postoperative outcomes of plate versus screw constructs in open reduction and internal fixation of calcaneus fractures via the sinus tarsi // Foot & Ankle International. – 2019. – Vol. 40, № 8. – P. 929–935.

32. Bremer A.K. et al. Limited open reduction and internal fixation of calcaneal fractures // Foot & Ankle International. – 2020. – Vol. 41, № 1. – P. 57–62. - doi: 10.1177/1071100719873273

33. Dai F. et al. Percutaneous prodding reduction and K-wire fixation via sinus tarsi approach versus ORIF for Sanders Type III calcaneal fractures: a prospective case-controlled trial // Foot and Ankle Surgery. – 2022. – Vol. 41, № 1. – P. 37–42.

34. Zhou H.C., Yu T., Ren H.Y. et al. Clinical comparison of extensile lateral approach and sinus tarsi approach combined with medial distraction technique for intra-articular calcaneal fractures // Orthopaedic Surgery. – 2017. – Vol. 9, № 1. – P. 77–85.

35. Giuliani A., Calori S., Singlitico A., Forconi F., Maccauro G., Vitiello R. Primary subtalar arthrodesis in displaced intra-articular calcaneal fracture: a systematic review // Musculoskeletal Surgery. – 2025. – Vol. 100. – P. 11-20. – DOI: 10.1007/s12306-025-00901-0.

36. Potenza V., Caterini R., Farsetti P., Bisicchia S., Ippolito E. Primary subtalar arthrodesis for the treatment of comminuted intra-articular calcaneal fractures // Injury. – 2010. – Vol. 41, № 7. – P. 702–706.

37. Holm J.L., Laxson S.E., Schuberth J.M. Primary subtalar joint arthrodesis for comminuted fractures of the calcaneus // Journal of Foot and Ankle Surgery. – 2015. – Vol. 54, № 1. – P. 61–65.

38. Lin J. et al. Comparison of sinus tarsi approach versus extensive lateral approach for displaced intra-articular calcaneal fractures Sanders type IV // International Orthopaedics. – 2019. – Vol. 43, № 9. – P. 2141–2149.

39. Akalin Y., Cansabuncu G., Çevik N., Avci Ö., Akinci O., Öztürk A. An evaluation of the results of locked plate osteosynthesis applied without the use of bone graft in Sanders type III and IV intra-articular calcaneus fractures // International Orthopaedics. – 2020. – Vol. 44, № 12. – P. 2753–2760.

40. Buckley R., Leighton R., Sanders D., Poon J., Coles C.P., Stephen D. et al. Open reduction and internal fixation compared with ORIF and primary subtalar arthrodesis for the treatment of Sanders type IV calcaneal fractures: a randomized, multicenter trial // Journal of Orthopaedic Trauma. – 2014. – Vol. 28, № 10. – P. 577–583.

41. Абильмажинов М. Т., Жанаспаев Т. М., Жанаспаева Г. А. Эволюция метода репозиции внутрисуставных импрессионных переломов пяточной кости // Science & Healthcare. – 2022. – Т. 24, № 5. – С. 188–195.