Clinical Biomechanics 62 (2019) 23–27

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

Distal fibula osteotomies improve tibiotalar joint compression: A biomechanical study in a cadaveric model

Christopher B. Arena[a], Evan P. Roush[a], Allen R. Kunselman[b], Paul J. Juliano[a], Umur Aydogan[a], Gregory S. Lewis[a,*]

[a] Department of Orthopaedics and Rehabilitation, Penn State College of Medicine, Hershey Medical Center, 500 University Drive, Mail Code H089, Hershey, PA 17033, USA

[b] Department of Public Health Sciences, Penn State College of Medicine, 500 University Drive, Hershey, PA 17033, USA

ARTICLE INFO

Keywords:
Ankle arthrodesis
Osteotomy
Tibiotalar arthrodesis
Osteoarthritis
Biomechanics

ABSTRACT

Background: Successful tibiotalar joint fusion relies on adequate compression. Compression following joint preparation may be affected by the extent to which the fibula holds the joint out to anatomical length. The purpose of this study was to evaluate the effect of various distal fibula osteotomies on tibiotalar joint compression.

Methods: Eight adult cadaveric lower extremity specimens with an intact ankle joint and syndesmotic complex were evaluated. The ankle joint cartilage was denuded to subchondral bone. The fibula was surgically modified with three progressing procedures including an oblique fibula osteotomy, 1 cm resection, and distal fibula resection. A transducer was utilized to measure tibiotalar joint force, contact area, and peak pressure values while compressive forces of 30 N, 50 N, and 100 N were applied to the proximal tibia/fibula.

Findings: Distal fibula resection significantly increased tibiotalar joint force, contact area, and peak pressure the most of all fibula conditions tested compared to intact fibula control ($p < .05$). Tibiotalar joint force and peak pressures were significantly increased with a distal fibula oblique osteotomy, 1 cm resection, and complete resection under both 30 and 50 N applied compressive force ($p < .05$).

Interpretation: Complete distal fibular resection results in higher tibiotalar joint force, contact area, and peak pressure which may improve clinical rates of successful ankle fusion.

1. Introduction

End stage ankle arthritis with significant functional limitations is a frequent pathology treated by foot and ankle surgeons (Segal et al., 2012). Although total ankle arthroplasty is becoming more widely accepted as a treatment option for select patients suffering from ankle arthritis, tibiotalar arthrodesis has long been considered the gold standard for treatment of this disease (Lawton et al., 2017; Mehdi et al., 2017; SooHoo et al., 2007). Many techniques have been described in performing ankle arthrodesis including fibular sparing, transfibular, miniarthrotomy, and arthroscopic techniques (Miller et al., 1996; Gougoulias et al., 2007; Sung et al., 2010; Smith et al., 2013). Ankle arthroplasty options following tibiotalar fusion may be compromised in the setting of complete distal fibular resection, thus some surgeons advocate only removing the medial third of the fibula for bone autograft while leaving the lateral fibula strut and malleolus intact (Kline and Wukich, 2011).

Regardless of the approach to ankle arthrodesis, the keys to obtaining successful fusion are to restore alignment, perform adequate joint preparation, and obtain joint stability, surface compression and contact area (Frey et al., 1994). The bone loss associated with adequate tibiotalar joint preparation creates separation between the talus and tibial plafond. Joint surface contact area and compression may be impeded by leaving the fibula completely intact. In the authors' clinical observations, it can be difficult to impose contact between these surfaces and apply adequate compression while the full length fibula remains intact, potentially strutting the tibiotalar joint out to anatomic length.

Tibiotalar joint compression, and rates of fusion, may be improved by distal fibular osteotomies. Fusion rates have been described in the transfibular approach to ankle arthrodesis where the fibula is osteotomized and utilized as allograft. A fibular shortening osteotomy

* Corresponding author at: Department of Orthopaedics & Rehabilitation, Penn State College of Medicine, 500 University Drive, Mail Code H089, Hershey, PA 17033, USA.

E-mail address: glewis1@pennstatehealth.psu.edu (G.S. Lewis).

https://doi.org/10.1016/j.clinbiomech.2019.01.001
Received 29 June 2018; Accepted 7 January 2019

technique for ankle arthrodesis has also recently been described by Mehdi et al. (Mehdi et al., 2017) with promising clinical results for time to fusion and non-union rate. Although clinical reports of longer-term effects of this relatively new procedure are lacking, the clinical benefits of compression have been better established and are widely recognized (Hamid et al., 2018; Jeng et al., 2011). Compression is a fundamental technique in fracture fixation for promoting primary bone healing. Taylor et al. reported more rapid ankle fusion and lower nonunion rates when using tibiotalocalcaneal fusion nail systems with internal compression compared to ones without. (Taylor et al., 2016) To our knowledge no biomechanical analysis has been performed to specifically evaluate the effects of distal fibular osteotomies on tibiotalar joint compression (Mehdi et al., 2017; Sung et al., 2010). In this study, we evaluated the effects three different distal fibula osteotomies had on tibiotalar joint force, contact area, and peak pressures under three loading conditions. Our hypothesis was that distal fibula osteotomies would increase tibiotalar joint forces and contact areas.

2. Materials and methods

This study was determined by our institutional IRB board as exempt from IRB review.

2.1. Specimens

Eight fresh frozen cadaveric lower extremity specimens, mid-tibia to toes, from four donors were tested (Medcure, Portland OR). There were one male and three female donors, aged 43–58 years with a mean age of 50 years. The specimens had an intact tibiotalar joint and syndesmotic complex, and were free of any known preexisting abnormalities, trauma, fractures, or previous surgeries. This was verified by donors' prior medical history obtained from the cadaver supply company, gross visual inspection, and fluoroscopic evaluation prior to specimen selection.

2.2. Setup & exposure

Each specimen was brought to room temperature prior to any testing. All specimens were prepared by exposing the proximal tibia and fibula and potting together into a section of PVC (polyvinyl chloride) pipe. A custom jig was constructed to secure the specimen in a neutral, vertical position while allowing free axial loading and vertical translation. A standard anterior ankle approach was performed on the specimens between the tibialis anterior and extensor hallucis longus tendons. The anterior ankle joint was exposed and tibiotalar cartilage was denuded to subchondral bone with the use of an osteotome.

2.3. Distal fibula osteotomies

Next the fibula was exposed through a direct lateral approach with care to maintain syndesmotic attachments. Following tibiotalar joint force, contact area, and peak pressure measurement as described below with the fibula intact, the osteotomies were performed by the first author under the direction of a senior author (U.A.), a foot and ankle fellowship-trained orthopaedic surgeon. The fibula was surgically modified using a microsaggital saw with the following three progressing procedures: (1) an oblique fibular osteotomy was first performed 3 cm proximal to the ankle joint line at a 45° angle which was measured by a goniometer; (2) an additional paralleled osteotomy 1 cm proximal to the oblique cut was performed and the segment excised; and (3) the remaining distal fibula was completely resected. (Fig. 1).

2.4. Measuring tibiotalar joint force, contact area, and peak pressures

A Tekscan articular pressure transducer (K-scan sensor 4205–300; Tekscan, Boston, MA) was custom trimmed to fit and cover the tibiotalar joint surfaces with minimal interference from the surrounding soft tissue. The thin pressure sensor was inserted anteriorly into the tibiotalar joint. The sensor's flexibility conformed to the joint surfaces once inserted. Field calibrations using three static weights were performed on each sensor. The pressure sensor readings were recorded using lower sensor sensitivity for enhanced pressure magnitude measurements. The potted proximal tibia and fibula were increasingly loaded with 30, 50, and 100 N static weights, with tibiotalar joint force, contact area, and peak pressure measurements repeated for each load (Fig. 1). Known static loads were applied because surgical devices for applying joint compression are implant-specific and according to our pilot testing, can give highly variable results across surgeons and test sessions. The experimenter applying the loads to the proximal tibia was blinded to the tibiotalar joint force, contact area, and peak pressure results to ensure unbiased and consistent load applications.

Each sensor was checked between specimens for any damage. If the sensor was suspected of any damage, a new calibrated sensor was then used. Repeatability of measurements was confirmed by three repeated trials for all conditions in half of the tested specimens.

2.5. Statistical methods

The tibiotalar total joint force, contact area, and peak pressure values were determined using Tekscan software and compared across conditions using general linear models with correlated errors (Diggle et al., 2002) to account for two repeated factors per specimen (fibula condition and applied compression force). The general linear model with correlated errors is fit using restricted maximum likelihood. We used the Kronecker product of an unstructured matrix and compound symmetric matrix (Galecki, 1994) as the variance-covariance matrix. Residual diagnostics from the models were examined to ensure the validity of the parametric modeling assumptions. Statistical significance was set at $p < .05$. All hypothesis tests were two-sided and all analyses were performed using SAS software, version 9.4 (SAS Institute Inc., Cary, NC).

3. Results

Compared to intact fibula control, an oblique distal fibula osteotomy performed and 30 N applied compression force resulted in a mean tibiotalar joint force increase of 10.0 N ($p = .002$). A 1 cm excisional fibula osteotomy and 30 N applied compression significantly increased the tibiotalar joint force by 8.6 N ($p = .006$). A complete distal fibula resection and 30 N applied load significantly increased the tibiotalar joint force compared to control by 15.8 N ($p < .001$). Similar trends were seen for the 50 N and 100 N applied compression forces with significance detected (*) in most comparisons to intact fibula as represented in Table 1 & Fig. 2 (error bar = standard error). Increased tibiotalar contact area measured across the ankle joint under all three applied compression conditions was most significant in the group with complete distal fibular resections as represented in Fig. 2 (30 N, $p < .001$; 50 N, $p < .001$; 100 N, $p = .008$). Increased tibiotalar joint peak pressures were significantly higher in 8 out of 9 fibula surgical osteotomy and loading groups ($p < .05$) as demonstrated in Table 1.

4. Discussion

To our knowledge no biomechanical analysis has been reported to evaluate the effects of distal fibular osteotomies on tibiotalar joint compression. The purpose of this study was to evaluate the effect a distal fibula oblique osteotomy, 1 cm distal fibula shortening osteotomy, and distal fibula excision had on tibiotalar joint force, contact area, and peak pressure during proximal tibia/fibula loading. Our results suggest that distal fibula osteotomies may increase tibiotalar joint force, contact area, and peak pressure under similar loading conditions where distal fibula resection resulted in the most number of significant

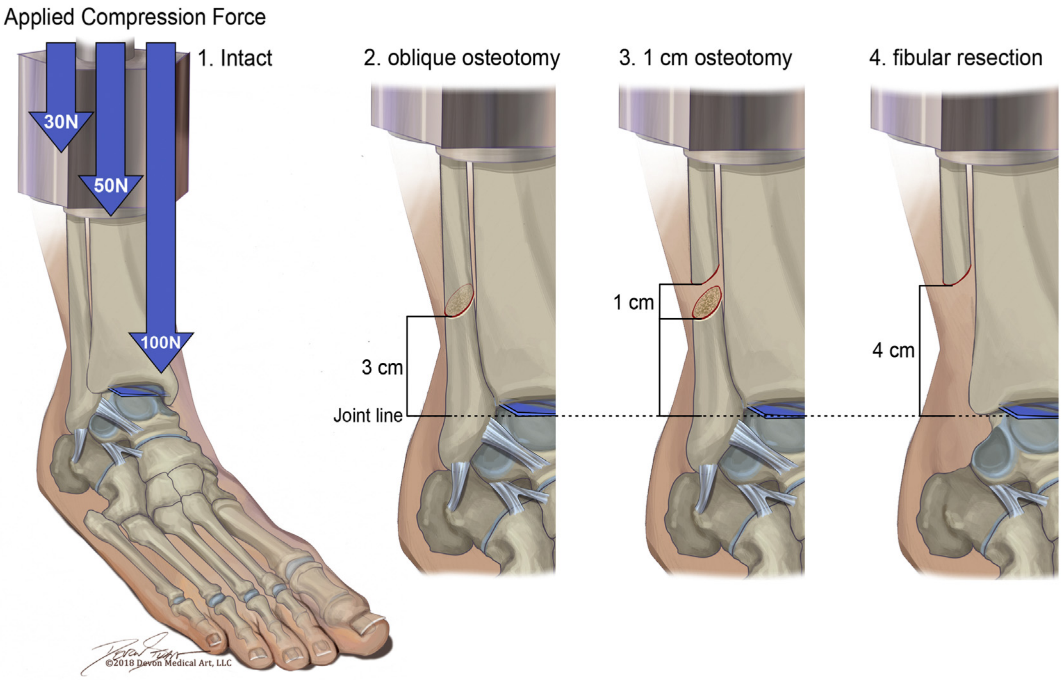

Fig. 1. Schematics showing osteotomy conditions and applied loadings. A custom jig was constructed to secure the cadaver specimen in a neutral, vertical position. The proximal tibia and fibula was potted in PVC pipe and the tibiotalar joint was denuded to subchondral bone where Tekscan contact pressure measurements (sensor shown in blue) were obtained under applied compression forces of 30 N, 50 N, and 100 N. Conditions sequentially tested in each specimen included 1) intact fibula; (2) oblique osteotomy; (3) 1 cm osteotomy; and (4) fibular resection. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

increases in comparison to intact control.

Mehdi et al. recently described a fibular shortening osteotomy technique in tibiotalar arthrodesis with fusion rates approaching 98% and a mean fusion time of five months (Mehdi et al., 2017). These results have a lower non-union rate than previously described in the literature (10–40%), however, no work to our knowledge has been done to quantify the mechanical effects distal fibula osteotomies have on the tibiotalar joint during loading (Frey et al., 1994; Goetzmann et al., 2016; Haddad et al., 2007). Biomechanical and basic science data supporting the clinical findings represented by Mehdi et al. may support further clinical research in optimizing tibiotalar compression and higher successful fusion rate techniques. Applied compression forces of 30, 50, and 100 N were used following preliminary testing using multiple surgeons with multiple fusion hardware and compressive techniques. Results using surgical compression tools were both highly user and technique dependent and were thought to be unreliable in testing the effects fibula osteotomies would have on tibiotalar joint compression. These preliminary results, however, were used to establish the range of applied loads tested to best approximate clinically relevant values.

The largest number of significant increases in tibiotalar joint forces, contact area, and peak pressure was obtained through distal fibular resection. Clinically, this procedure may limit subsequent options for revision surgery to total ankle arthroplasty and should be considered by the treating surgeon (Kline and Wukich, 2011). The syndesmosis and soft tissue attachments were also never released independent of fibula osteotomies. This may help to distinguish if the underlying improvement in ankle joint compression with distal fibula resection was primarily related to bony versus syndesmotic restraints. Oblique and 1 cm fibular shortening osteotomies did provide statistically significant increases in applied tibiotalar joint forces for 30 N and 50 N loads. These were not significant in the 100 N applied loads and had little significant effect on tibiotalar contact area. These mixed results likely contribute to the combined bony and syndesmotic stability of the ankle joint as

Table 1
Means and (standard deviations) of tibiotalar joint pressure results, as well as p-values (bold indicates significance $p < .05$) for comparison to corresponding Intact (control) condition.

Applied Compression Force (N)	Intact	Oblique osteotomy	1 cm osteotomy	Fibular resection
Tibiotalar joint force (N)				
30	8.3 (7.4)	18.3 (8.0) **p = .002**	16.9 (6.9) **p = .006**	24.1 (3.8) **p < .001**
50	14.3 (10.7)	26.7 (11.4) **p = .007**	23.5 (11.3) **p = .037**	38.1 (6.5) **p < .001**
100	32.6 (17.1)	45.5 (19.2) p = .081	43.6 (19.3) p = .135	64.9 (15.0) **p < .001**
Tibiotalar joint contact area (mm^2)				
30	42.8 (32.7)	74.5 (37.4) **p = .035**	66.0 (36.1) p = .114	99.1 (28.7) **p < .001**
50	67.0 (40.7)	93.2 (41.5) p = .116	78.9 (46.1) p = .462	138.5 (41.5) **p < .001**
100	110.8 (64.5)	121.7 (53.4) p = .629	109.4 (56.7) p = .951	178.1 (69.8) **p = .008**
Tibiotalar joint peak pressure (kPa)				
30	260.3 (136.4)	431.7 (126.2) **p = .006**	479.8 (66.2) **p < .001**	498.8 (138.4) **p < .001**
50	367.3 (153.5)	613.3 (202.9) **p = .004**	617.8 (159.1) **p = .004**	596.1 (159.5) **p = .007**
100	676.3 (180.8)	916.4 (316.5) p = .057	970.8 (288.2) **p = .022**	944.0 (298.8) **p = .036**

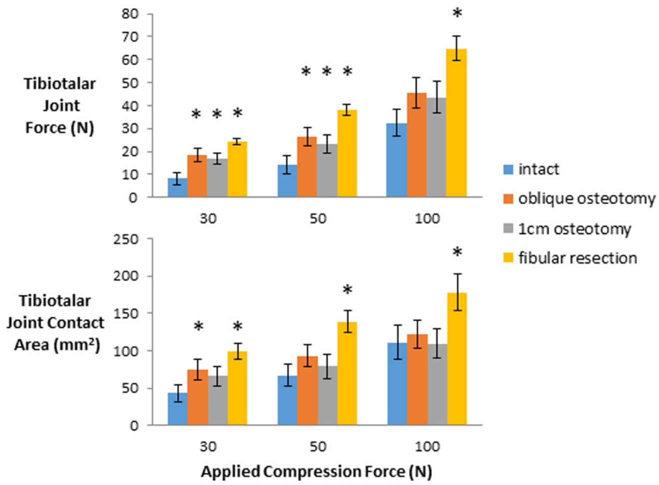

Fig. 2. Effects of three different fibular osteotomies on tibiotalar joint force and contact area under 30 N, 50 N, and 100 N applied compression force. Error bars indicate standard error and statistical significant difference compared to intact control is indicated by "*".

oblique and 1 cm fibular shortening osteotomies address bony stability and not the syndesmosis. Distal fibula resection was the only procedure that addressed both bony and syndesmotic stability and produced statistically significant results in all applied loads for both tibiotalar joint force and contact area. Oblique distal fibula osteotomy, shortening osteotomies, and possibly syndesmotic only releases may provide the benefit of increased ankle joint compression during arthrodesis without limiting arthroplasty revision options.

A limitation of the study was in its design as a "time-zero" biomechanics cadaveric study. No measurements of ankle joint force or contact pressure were obtained under prolonged loading which would be present clinically in ankle arthrodesis. Loads did not include physiologic weightbearing loads with muscle reaction forces, as the early postoperative period typically involves non-weightbearing and no active range of motion in our patient population. Additionally, proximal tibiofibular motion is not accounted for in our experimental design, however, only limited mobility has been described in the proximal tibiofibular joint relative to ankle position (Soavi et al., 2000). Surgical conditions were not randomized in order to enable a more statistically powerful repeated measures design; the order of the surgical conditions was such that cuts to the fibula were made in a progressive manner. Lastly, we are extrapolating that higher ankle joint forces and contact area obtained during fibular osteotomies in our cadaveric model may translate to clinically higher successful ankle fusion rates. Compression is a known fundamental component of primary bone healing and thus likely critical for successful arthrodesis (Frey et al., 1994; Scranton Jr., 1985; Colton and Selikson, 2008).

Proximal fibular osteotomies have been shown to alter gate mechanics about the knee and have been described as a treatment modality of medial compartment knee osteoarthritis (Huang et al., 2017; Qin et al., 2018). Effects distal fibular osteotomies performed in the setting of tibiotalar arthrodesis may have on long term clinical outcomes such as gait alterations and adjacent joint disease (i.e. knee osteoarthritis) are currently lacking. Although distal fibular osteotomies demonstrated favorable short term fusion rates, long term clinical outcomes should be followed to better guide surgical decision making.

5. Conclusion

Our findings suggest a distal fibula oblique osteotomy, 1 cm excisional osteotomy, or complete distal fibula excision may increase the amount of force transmitted to the ankle joint under loading. Complete distal fibular resection resulted in the highest tibiotalar joint force, contact area, and peak pressure of the surgical options tested. Leaving the fibula intact may decrease tibiotalar compression during ankle arthrodesis. We recommend further clinical exploration of this technique through clinical testing to ultimately determine the effects on rates of successful ankle arthrodesis, as well as long term clinical outcomes to evaluate possible long term alterations in gate mechanics and adjacent joint osteoarthritis.

Disclosures

Declarations of interest: Dr. Lewis reports non-financial support from Depuy-Synthes outside the submitted work, and grants and non-financial support from Arthrex outside the submitted work. Other authors have nothing to disclose.

All authors have approved the final article.

Contributions

Christopher Arena, MD: study conception and design, data acquisition, analysis and interpretation, drafting and revising article.

Evan Roush: experimental setup fabrication, data acquisition, drafting article methods.

Allen Kunselman, MA: data analysis (statistical).

Paul Juliano, MD: study conception, revising article.

Umur Aydogan, MD: study conception and design, revising article.

Gregory Lewis, PhD: study design, data acquisition performed in his lab, data analysis and interpretation, drafting and revising article.

References

Colton, C., Selikson, D., 2008. The history of fracture treatment. In: Browner, B.D. (Ed.), Skeletal Trauma: Basic Science, Management and Reconstruction. 1 1. Saunders, pp. 24–25 (9781437721706).
Diggle, P.J., Heagerty, P., Liang, K.Y., Zeger, S.L., 2002. Analysis of Longitudinal Data. Oxford University Press, Oxford, UK.
Frey, C., Halikus, N.M., Vu-Rose, T., Ebramzadeh, E., 1994. A review of ankle arthrodesis: predisposing factors to nonunion. Foot Ankle Int. 15 (11), 581–584. https://doi.org/10.1177/107110079401501102.
Galecki, A.T., 1994. General class of covariance structures for two or more repeated factors in longitudinal data analysis. Commun. Stat. Theory Methods 23, 3105–3109.
Goetzmann, T., Mole, D., Jullion, S., et al., 2016. Influence of fixation with two vs. three screws on union of arthroscopic tibio-talar arthrodesis: comparative radiographic study of 111 cases. Orthop. Traumatol. Surg. Res. 102 (5), 651–656. https://doi.org/10.1016/j.otsr.2016.03.015.
Gougoulias, N.E., Agathangelidis, F.G., Parsons, S.W., 2007. Arthroscopic ankle arthrodesis. Foot Ankle Int. 28 (6), 695–706. https://doi.org/10.3113/FAI.2007.0695.
Haddad, S.L., Coetzee, J.C., Estok, R., et al., 2007. Intermediate and long-term outcomes of total ankle arthroplasty and ankle arthrodesis. A systematic review of the literature. J. Bone Joint Surg. Am. 89 (9), 1899–1905. https://doi.org/10.2106/JBJS.F.01149.
Hamid, K.S., Glisson, R.R., Morash, J.G., Matson, A.P., DeOrio, J.K., 2018. Simultaneous intraoperative measurement of cadaver ankle and subtalar joint compression during arthrodesis with intramedullary nail, screws, and tibiotalocalcaneal plate. Foot Ankle Int. 39 (9), 1128–1132. https://doi.org/10.1177/1071100718774271.
Huang, W., Lin, Z., Zeng, X., et al., 2017. Kinematic characteristics of an osteotomy of the proximal aspect of the fibula during walking: a case report. J. Bone Joint Surg. 7e (43).
Jeng, C.L., Baumbach, S.F., Campbell, J., Kalesan, B., Myerson, M.S., 2011. Comparison of initial compression of the medial, lateral, and posterior screws in an ankle fusion construct. Foot Ankle Int. 32 (1), 71–76. https://doi.org/10.3113/FAI.2011.0071.
Kline, A.J., Wukich, D.K., 2011. Transfibular approach for ankle arthrodesis. In: Operative Techniques in Orthopedic Surgery. 4 (78). pp. 4140–4145.
Lawton, C.D., Butler, B.A., Dekker, R.G., 2017. Total ankle arthroplasty versus ankle arthrodesis-a comparison of outcomes over the last decade. J. Orthop. Surg. Res. 12 (1), 76. https://doi.org/10.1186/s13018-017-0576-1.
Mehdi, N., Bernasconi, A., Laborde, J., Lintz, F., 2017. An original fibular shortening osteotomy technique in tibiotalar arthrodesis. Orthop. Traumatol. Surg. Res. 103 (5), 717–720. https://doi.org/10.1016/j.otsr.2017.03.023.
Miller, S.D., Paremain, G.P., Myerson, M.S., 1996. The miniarthrotomy technique of ankle arthrodesis: a cadaver study of operative vascular compromise and early clinical results. Orthopedics 19 (5), 425–430.
Qin, D., Chen, W., Wang, J., et al., 2018. Mechanism and influencing factors of proximal fibular osteotomy for treatment of medial compartment knee osteoarthritis: a prospective study. J. Int. Med. Res. 46 (8), 3114–3123. https://doi.org/10.1177/0300060518772715.
Scranton Jr., P.E., 1985. Use of internal compression in arthrodesis of the ankle. J. Bone

Joint Surg. Am 67 (4), 550–555.
Segal, A.D., Shofer, J., Hahn, M.E., et al., 2012. Functional limitations associated with end-stage ankle arthritis. J. Bone Joint Surg. Am. 94 (9), 777–783. https://doi.org/10.2106/JBJS.K.01177.
Smith, J.T., Chiodo, C.P., Singh, S.K., Wilson, M.G., 2013. Open ankle arthrodesis with a fibular-sparing technique. Foot Ankle Int. 34 (4), 557–562. https://doi.org/10.1177/1071100713477617.
Soavi, R., Girolami, M., Loreti, I., et al., 2000. The mobility of the proximal tibio-fibular joint. A Roentgen stereophotogrammetric analysis on six cadaver specimens. Foot Ankle Int. 21 (4), 336–342. https://doi.org/10.1177/107110070002100411.
SooHoo, N.F., Zingmond, D.S., Ko, C.Y., 2007. Comparison of reoperation rates following ankle arthrodesis and total ankle arthroplasty. J. Bone Joint Surg. Am. 89 (10), 2143–2149. https://doi.org/10.2106/JBJS.F.01611.
Sung, W., Greenhagen, R.M., Hobizal, K.B., Burns, P.R., Wukich, D.K., 2010. Technical guide: transfibular ankle arthrodesis with fibular-onlay strut graft. J. Foot Ankle Surg. 49 (6), 566–570. https://doi.org/10.1053/j.jfas.2010.07.005.
Taylor, J., Lucas, D.E., Riley, A., Simpson, G.A., Philbin, T.M., 2016. Tibiotalocalcaneal arthrodesis nails: a comparison of nails with and without internal compression. Foot Ankle Int. 37 (3), 294–299. https://doi.org/10.1177/1071100715611891.