Topical Review

AMERICAN ORTHOPAEDIC FOOT & ANKLE SOCIETY.

Foot & Ankle International®
1–10

DOI: 10.1177/1071100716679190
fai.sagepub.com

The Use of Osteotomies in the Treatment of Asymmetric Ankle Joint Arthritis

Markus Knupp, MD[1]

Keywords: supramalleolar osteotomy, calcaneus osteotomy, ankle arthritis, ankle replacement, ankle fusion, hindfoot deformity, dome osteotomy, subtalar joint

Introduction

Osteoarthrosis (OA) of the ankle joint is common and found in 1% of the world's population.[68] In contrast to OA of the hip or knee (mainly primary arthritis), the etiology at the ankle is posttraumatic in a large majority of patients.[12,68] As a result, they become symptomatic 12 to 15 years earlier than arthritic hip or knee patients.[25] This underlines the importance of long-lasting treatment options for this patient group. Surgical treatments for ankle joint arthritis are divided into 2 categories: procedures that preserve the joint and those that do not.[*]

Although ankle arthrodesis and total ankle replacement (TAR) show good short- and mid-term results, several complications have been reported in long-term data.[9,13,39] For arthrodesis, this may include OA of adjacent joints.[9] The overall survival rate after TAR is around 80% after 10 years,[18,28,29] and therefore ankle replacement in many cases does not present a lifelong solution.

Two-thirds of the patients with ankle joint arthritis present with an asymmetric wear pattern, for example, more wear on either the medial or the lateral side of their tibiotalar joint.[67] As the ankle is part of a kinematic chain, the intra-articular load distribution is not only influenced by the alignment of the tibiotalar joint itself but is highly dependent on extrinsic forces that are present because of the alignment of the subtalar (ST) joint, the medial column of the foot, and soft tissue balance.

The present review provides an overview of the joint-preserving possibilities to balance the forces in the ankle joint by performing osteotomies around the ankle joint.

Anatomic and Biomechanical Background

The load distribution within the joint is influenced by the alignment (static component) and the joint-crossing tendons (dynamic component). While standing, the center of force transmission is medialized in a varus deformity and lateralized in a valgus deformity. The forces within the joint are amplified by the activation of the triceps surae; the Achilles tendon acts as an additional deforming force on the hindfoot, specifically as an invertor in varus deformities and an evertor in valgus deformities respectively.

Location of the deformity

As the hindfoot is composed of 4 bones (fibula, tibia, talus, calcaneus), localization of the apex may be difficult, even more if there is a multiplanar deformity. In a large majority, the apex of a supramalleolar deformity lies close to the ankle joint or even within the joint. Therefore, correction through the apex may not be possible in all cases, particularly with opening or closing wedge osteotomies. If the correction is not performed at the level of the apex, translation of the distal fragment occurs (Figure 1). Wedge osteotomies proximal to the apex lead to medialization of the ankle joint if a valgus ankle is corrected (Figure 1) and to lateralization of the ankle if a varus ankle is corrected. This may maintain a lateral overload in valgus arthritic ankles and a medial overload in varus arthritic ankles. Therefore, a corrective translation should be added (lateral transfer in valgus ankles and medial transfer in varus ankles) in the correction of large deformities. Alternatively, a dome-shaped osteotomy may allow correcting the deformity even if the apex does not lie in the preferred metaphyseal area of the tibia (Figure 1).

Assessment of an inframalleolar deformity usually is even more of a challenge and can make the preoperative planning very difficult. The reason lies in the limited imaging modalities of the subtalar joint. The newer generation of weight-bearing computed tomographic scans may serve as a valuable tool to define the location and nature of the deformity.

[*]References 1, 4-6, 31, 40, 48, 56, 64.

[1]Department of Orthopaedic Surgery, Kantonsspital Baselland, Switzerland

Corresponding Author:
Markus Knupp, MD, Department of Orthopaedic Surgery, Kantonsspital Baselland, CH-4103 Bruderholz, Switzerland.
Email: knupp_m@hotmail.com

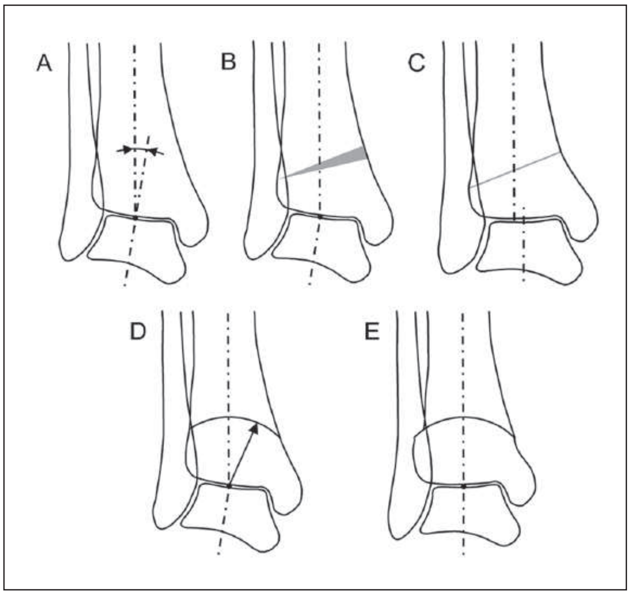

Figure 1. (A) Supramalleolar deformity with the apex within the joint line. (B) Medial closing wedge osteotomy with the level of correction proximal to the joint line. (C) Postoperative situation with corrected alignment but the center of the talus medialized. (D) Dome-shaped osteotomy of the same deformity with the center of the correction at the apex of the deformity. (E) Postoperative situation with corrected alignment and the talus centered under the mechanical axis of the tibia.

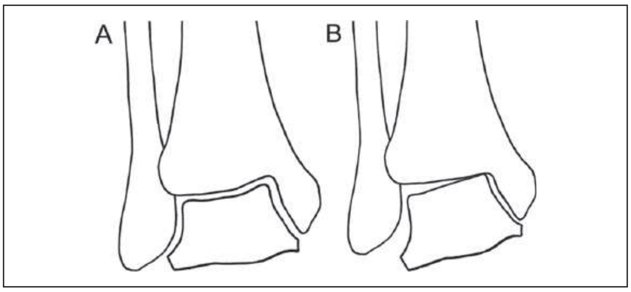

Figure 2. Illustration of the 2 types of supramalleolar deformities in asymmetric ankle arthritis: (A) congruent type with the talus lying parallel to the pilon, (B) incongruent type with the talus tilted in the ankle mortise.

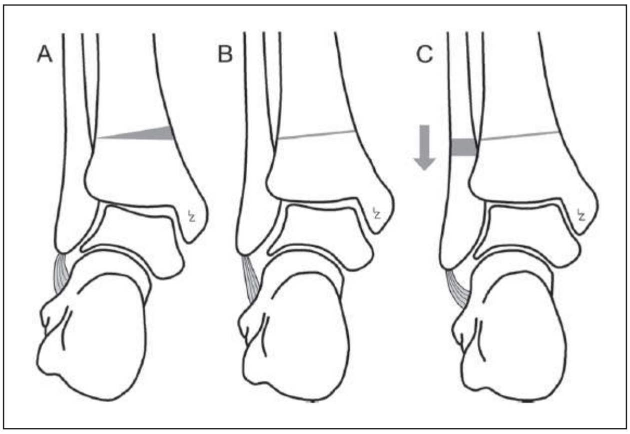

Figure 3. Illustration of the effect of ankle joint incongruity in supramalleolar osteotomies: (A) type II ankle prior to the osteotomy, (B) remaining tilt after correction of the distal tibial alignment with the talus still in the original positon, and (C) situation after correction of the fibula.

Supramalleolar osteotomy

Type of joint presentation. For prognostic reasons and for the planning of the type of osteotomy, 2 different types of malaligned ankles need to be distinguished. In the first group, the talus is not tilted within the mortise (congruent type; Figure 2A) whereas in the second group a tilt of the talus is present (incongruent type; Figure 2B).[33] This distinction may help to determine the type of supramalleolar osteotomy (dome-shaped vs wedge). Dome-shaped osteotomies are technically more demanding (surgical technique and planning of the correction) but may preserve joint congruity better than wedge osteotomies. Therefore, congruent types may be easier to correct with a dome-shaped osteotomy, whereas an incongruent ankle may be more easily addressed by a wedge osteotomy.

Role of the fibula. Biomechanical testing has shown that maintaining or restoring ankle joint congruity in supramalleolar osteotomies is very important to achieve reliable changes of the intra-articular forces with corrective osteotomies.[34,61,66] These findings are in accordance with earlier discussions in ankle fractures: if the fibula is shortened, the talus tends to lateralize.[14] Placing the talus adequately under the pilon therefore requires adjusting the length and position of the fibula in addition to the potential of osteotomy of the tibia or hindfoot.[34,71] In supramalleolar osteotomies, this is particularly true in congruent ankles (Figure 2A). Solely correcting the angle of the distal tibia on its own may not redistribute the intra-articular forces enough, an additional correction of the position and length of the fibula should be considered in every single case (Figure 3). [61,66]

Sagittal plane deformity. In the sagittal plane, procurvatum and recurvatum deformities are additional anatomic features of the tibia to consider in the treatment of OA of the ankle via osteotomy. Procurvatum of the distal tibia is better tolerated than recurvatum. Recurvatum is more joint destructive because the articular surface is not as covered leading to higher peak pressures in the ankle joint because of the anterior displacement of the center of rotation of the ankle joint. Procurvatum may be more painful for the patients as a result of anterior impingement, but usually the joint is spared from deterioration as the talar dome is well covered in the mortise.[41,50,58]

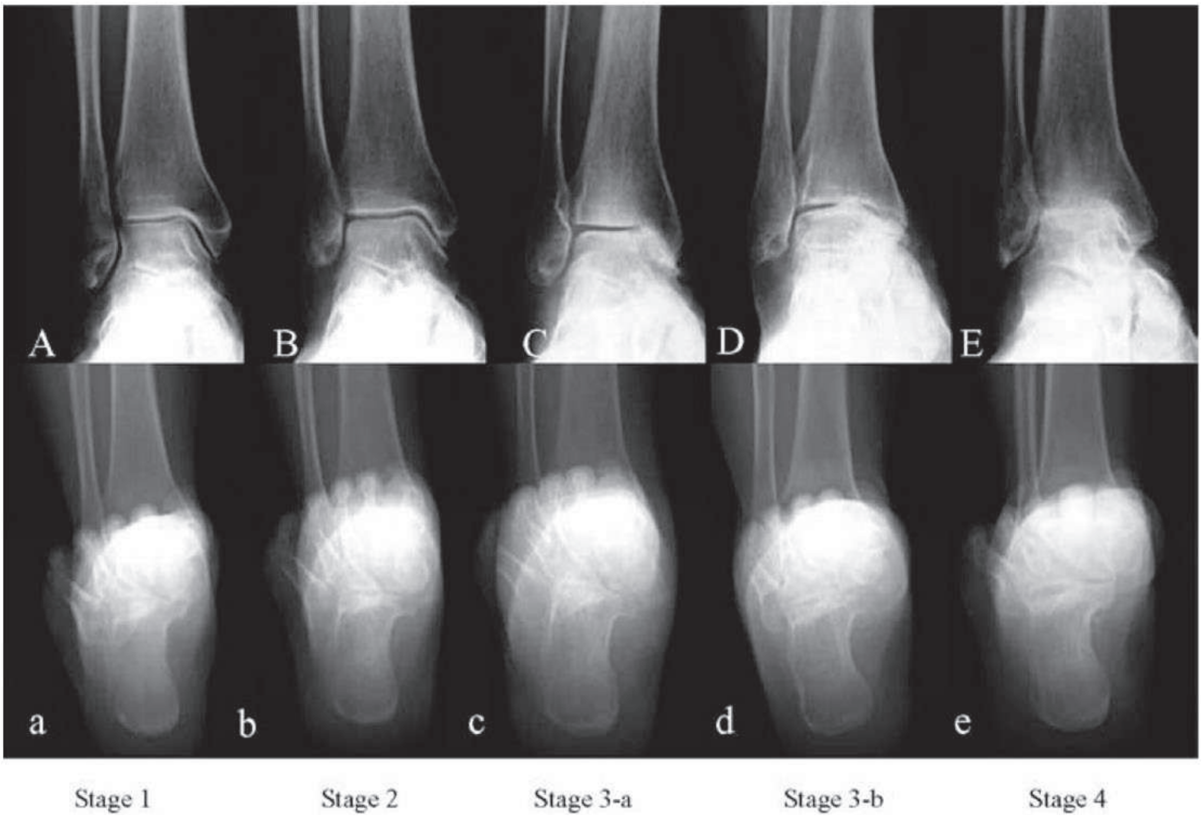

Figure 4. Illustration of the "tip over" effect on plain radiographs. The varus of the ankle joint is compensated by the subtalar joint in early stages (A-C). In advanced stages the subtalar joint tips over and increases the overall varus deformity of the hindfoot (D, E). Reprinted with permission from the American Orthopaedic Foot & Ankle Society.[22]

Inframalleolar Corrections

Several underlying causes may lead to an asymmetric wear pattern in the ankle joint. Traditionally, deformities of the lower leg and knee joint, ligamentous laxity, tendon dysfunction, and neurologic disorders have been noted to lead to an altered intra-articular load distribution.[8,27,30,45,51,57,66] Lately, it has been proposed that the ST joint may have a major influence on this process.[11,22,24,35]

Malalignment of the hindfoot distal to the ankle joint (inframalleolar deformities) results from anatomic variations of the calcaneal shape and the orientation and position of the subtalar joint or the result of forefoot deformity. As for the anatomic variations of the shape of the calcaneal body, there are only limited studies—mainly on posttraumatic deformities and patients with clubfeet.[15,35,53] When it comes to the influence of the ST joint, this has been investigated intensively in the last decade. The ST joint allows for movement in the frontal plane (inversion and eversion) and may therefore compensate for varus and valgus deformities of the lower extremity. Takakura et al speculated that the subtalar joint has a compensatory function in that it prevents the progression of osteoarthritis: the varus deformity of the ankle is thought to be compensated by the valgus inclination of the subtalar joint, and osteoarthritis begins to progress when the compensatory function is inoperative.[63] This has been confirmed in subsequent clinical studies.[70] Hayashi et al[22] described with plain radiographic images a more pronounced valgus inclination of the ST joint in the coronal plane at the intermediate stage of primary varus osteoarthritis, whereas in advanced stages the ST joint seemed to "tip over" and increase the overall hindfoot deformity (Figure 4). On the basis of on his observations, he suggested that the mechanism of primary varus-type OA is as follows: the varus inclinations of the tibial plafond and the talar dome trigger the disorder (stage 1); the varus inclination of the ankle progresses and the compensatory function (valgus inclination) of the subtalar joint increases so as not to concentrate the weight-bearing stress too medially in the ankle (stages 2 and 3a); the breakdown of the compensatory function leads to the varus inclination of the subtalar joint, the medial stress concentration in the ankle increases, and the disorder progresses to the terminal stage (stages 3b and 4; Table 1).

Table 1. Takakura Classification of Varus Ankles on Plain Radiographs.

Stage	Radiographic Finding
1	No narrowing of the joint space, but early sclerosis and formation of osteophytes
2	Narrowing of the medial joint space
3a	Obliteration of this space with subchondral bone contact (medial gutter only)
3b	Extension of the obliteration to the roof of the dome of the talus
4	Obliteration of the whole joint space with complete bone contact

Limitations for this theory include the highly variable anatomic presentation of the subtalar joint and the lack of intrinsic stability of this joint in the frontal plane. The ST joint varies significantly in shape and frontal plane orientation.[2,11,35,52] The posterior facet is concave in 88% of the healthy population and flat in 12%.[11] The latter group probably does not allow for much motion in the frontal plane, and these patients therefore may not be able to compensate varus and valgus deformities through their subtalar joint. This is also the case in patients with an arthritic ST joint and patients with coalitions.

The effect of the ST joint orientation has been investigated for both the ankle joint and the foot distal to the ST joint. Patients with varus-type ankle joint arthritis have varus inclination of the posterior facet, and those with valgus-type arthritis have valgus inclination of the posterior facet.[35] Furthermore, valgus tilt of the ST joint has been described to be a risk factor for the development of tibialis posterior tendon dysfunction and subsequent flatfoot deformity.[2,52]

Finally, the ability to compensate deformities in the frontal plane implies that the ST joint provides limited intrinsic stability in the frontal plane,[3] and therefore a normal hindfoot alignment view[55] does not automatically guarantee normal load distribution as a zig-zag deformity may be present (Figure 5).

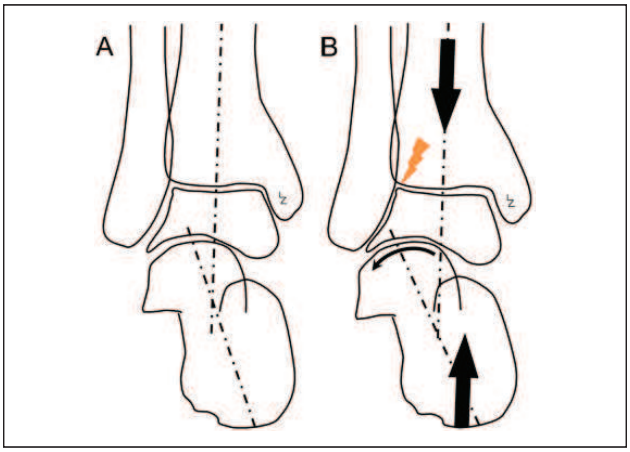

Figure 5. Sketch of a cross section through the hindfoot. The ankle joint provides high frontal plane stability whereas the ST joint, in a majority of cases, provides limited intrinsic stability. (A) The unloaded hindfoot after a medial displacement osteotomy of the calcaneus. (B) The possible paradox shift after a calcaneal osteotomy due to the tilting movement of the ST joint. The calcaneal tuberosity lies medial to the tibia, suggesting a medial shift of the load in the ankle. However, because of the inversion moment, the talus may tilt into valgus, leading to higher peak pressures in the lateral aspect of the ankle joint.

Suggested Algorithm

The following algorithm is a modification of an earlier suggestion and does not include soft tissue balancing, which may be an important part of the reconstructive procedures.[49]

1. Arthroscopy

Ankle joint arthroscopy can be used to complete the preoperative diagnostics and to exclude intra-articular risk factors for progression of ankle joint arthritis (loose bodies, instability).[44,49,64] Although there is controversy on the benefit for the arthritic joint, it allows for intraoperative functional testing of the stability, debridement, and removal of loose bodies. In case of anterior ankle impingement, scar tissue is debrided and if required, a talar neck plasty added. Caution should be taken in removing distal tibia osteophytes anteriorly, as they may function as a strut to prevent collapse of the tibiotalar joint, and removing them may allow accelerated cartilage wear and subsequent increasingly painful arthritis.

2. Deformity Above the Ankle Joint: Supramalleolar Correction

2.1. Frontal plane correction. The first step is a supramalleolar osteotomy (SMOT). The angle to be corrected in the frontal plane is the distal tibial joint surface (TAS; normal value for the Caucasian population 91 to 93 degrees, eg, slight valgus).[26] The type of osteotomy is determined by the level of the deformity, the type of fixation (eg, the hardware used to secure the correction), the condition of the soft tissues and the type of the joint presentation (congruent vs incongruent joints). Ideally, the correction is carried out at the apex of the deformity (see also section "Location of the Deformity" and Figure 1). Congruent joints (type I) are preferably corrected with dome-shaped osteotomies in order to preserve joint congruity (Figure 6).[58] Tilted ankles (type II) are corrected with wedge osteotomies unless the CORA lies within the joint or very close to it (Figure 7).[58] The latter are preferably corrected with dome-shaped osteotomies to avoid medial or lateral translation of the ankle joint (Figure1).[58]

Varus ankles. Varus ankles that qualify for a wedge osteotomy are addressed with a medial opening wedge osteotomy or a lateral closing wedge osteotomy. Dome-shaped

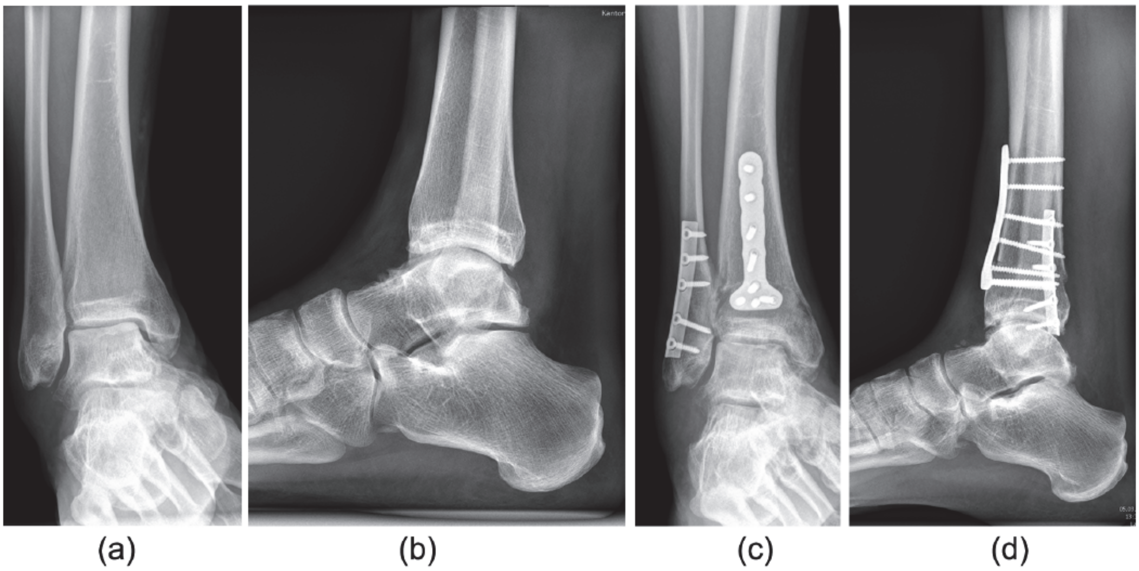

Figure 6. Case of a dome-shaped osteotomy in a congruent ankle. (A, B) Preoperative weight-bearing radiographs; (C, D) 9-month postoperative images of the same patient.

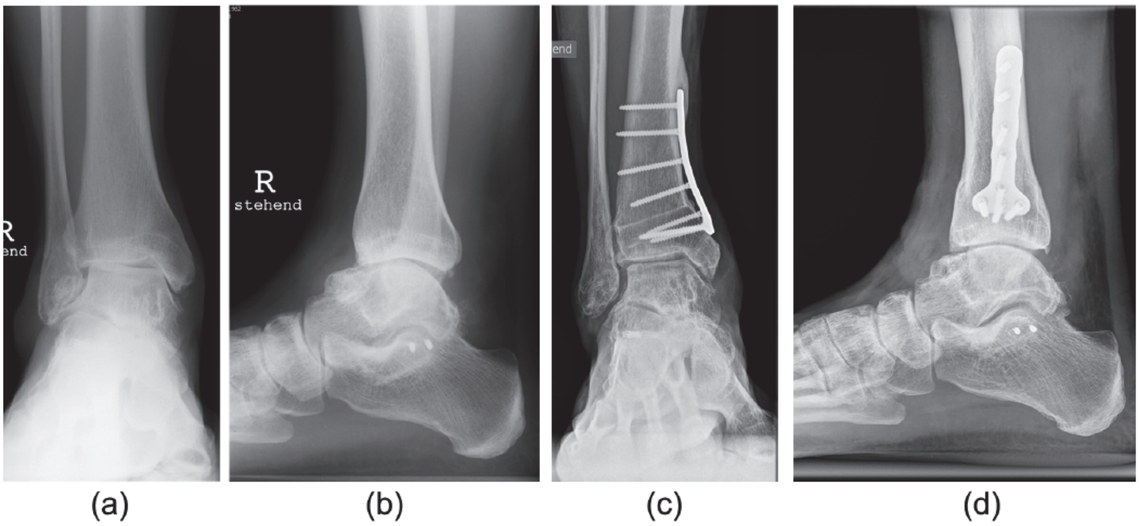

Figure 7. Case of an incongruent ankle with anterior extrusion out of the mortise (A, B). This has been corrected by a medial and posterior closing wedge osteotomy. As the joint appeared congruent intraoperatively, the fibula was left untouched. (C, D) Two-year postoperative weight bearing radiographs of the same patient. Note that the biplanar osteotomy not only centered the talus in the frontal but also in the sagital plane.

osteotomies are used in congruent types, large deformities, and deformities that cannot be addressed by a wedge-shaped osteotomy at the level of the deformity (Figure 6).

Valgus ankles. The type of osteotomy is chosen similar to that for the varus ankles. In case of a wedge osteotomy, a medial closing wedge (large majority) or a lateral opening osteotomy (rare) is used (Figure 7).[32,33]

Fibula osteotomy. After all supramalleolar corrections of the tibia, the length and position of the fibula must be reassessed and if required adjusted (see below).

Amount of correction. Overcorrection has been reported to lead to better results than undercorrection, particularly in advanced stages of OA.[19] The ideal amount of overcorrection is still a matter of debate. Although some authors recommend

3 to 5 degrees overcorrection,[33,65] others reported that overcorrection only had a limited effect on a large varus tilt and recommend not to overcorrect too excessively in the supramalleolar area and to add a calcaneal osteotomy instead.[44]

2.2. Sagittal plane correction. In the sagittal plane, the tibial lateral surface angle should be corrected to its normal range of 81 to 82 degrees.[65] This is particularly true in ankles with an anteriorly extruded talus (Figure 7). In these cases, a biplanar osteotomy is recommended, for example, frontal plane correction with additional anterior opening or posterior closing wedge osteotomies, to improve talar coverage in the anteroposterior direction.[7] The surgeon needs to be aware that improving the coverage of the talar dome by bringing the ankle into more recurvatum alignment can cause anterior impingement. This can be addressed by a talar neck plasty.[69]

3. Fibula Osteotomy

All dome-shaped osteotomies require a length correction of the fibula in order to maintain joint congruity. With wedge osteotomies, the ankle joint is checked under image intensification after correction of the distal tibial articular surface angle, and if the joint does appear incongruent the length and position of the fibula is corrected. Intraoperatively, the appropriate length and rotation are defined by (1) appropriate closure of the medial clear space with restoration of the relationship of the medial malleolus and the medial surface of the talus, (2) an anatomic position of the talus within the mortise with parallel articular surfaces of the tibiotalar joint, and (3) restoration of the normal length relationship of the medial and lateral malleoli.[14] Additional indicators for correct length are an unbroken "Shenton's line of the ankle" and an unbroken curve between the lateral part of the talar articular surface and the fibular recess.

In case of a normal TAS angle, where the alignment is addressed by a calcaneal osteotomy, the fibula may need correction of length and position to correct the tilting of the talus (Figure 8).

4. Deformity Below the Ankle Joint

If the deformity lies below the ankle joint line and in cases with remaining varus or valgus deformity after a supramalleolar correction, a correcting calcaneal osteotomy is performed. This normalizes the static overload by aligning the calcaneal tuberosity underneath the weight-bearing axis. Furthermore, shifting the force vector of the Achilles tendon eliminates the inversion in varus hind feet and the eversion in valgus feet, respectively.

However, the effect may be unpredictable or even lead to a paradoxical load shift (Figure 4) in patients with unstable ST joints. Preoperative imaging may be helpful to predict the outcome: patients with nonarthritic, convex-shaped[11] or subluxated ST joints[2,52] are at risk to not benefit from a calcaneal osteotomy for the treatment of ankle joint arthritis. In contrast, patients with coalitions, arthritic ST joints, or previous ST fusion joints are likely to respond in a desired manner to a calcaneus osteotomy. Finally, in tilted ankles with a normal TAS, the length of the fibula may require correction to reduce the tilted talus (Figure 8).

5. Osteotomies of the Medial Column

The medial column has a great influence on the load distribution in the ankle joint. In case of a flattened longitudinal arch, corrective fusions (naviculo-cuneiform joints, [closing wedge] tarsometatarsal joint arthrodesis) or plantar flexion osteotomies (medial cuneiform or first metatarsal) are performed (valgus feet). Restoration of the medial arch dorsiflexes the talus and thereby stabilizes the ankle joint as well as reduces the load on the lateral side of the joint.[46] In patients with a plantarflexed medial column (forefoot-induced hindfoot varus), a dorsiflexing osteotomy of the medial cuneiform or the first metatarsal is added. This reduces the load in the anteromedial aspect of the ankle joint.[37,38]

6. Soft Tissue Procedures

After the bony correction, soft tissue balancing is assessed. Tendon transfers (tibialis posterior or tibialis anterior in varus and flexor digitorum longus in valgus ankles) and ligament reconstructions (lateral ankle, deltoid, spring ligament) are added, if needed. However, the need for these procedures is controversial. A recent publication even questioned the need for ligament reconstructions after alignment corrections. The authors treated patients with cavovarus feet and lateral ankle joint instability with corrective osteotomies and tendon transfers only (without ligament reconstruction) and did not observe postoperative hindfoot instability.[38]

Results

Supramalleolar Osteotomy

Several authors have reported good clinical and radiographic results after supramalleolar correction for both varus[20,43,44,62,63] and valgus[23,33] ankles. Significant improvements of the clinical (AOFAS score) and radiographic parameters (alignment, mean Takakura stage; Table 1) were found in several studies.[14,20,33,44,59,65] Complications included nonunions, malunion (over- or undercorrection), progression to end-stage OA, and soft tissue problems (neuroma, wound healing problems, bulky hardware).

In our own series, Krahenbuehl et al assessed the complications and risk factors for failure in 294 supramalleolar osteotomies. Thirty-eight patients progressed to end-stage

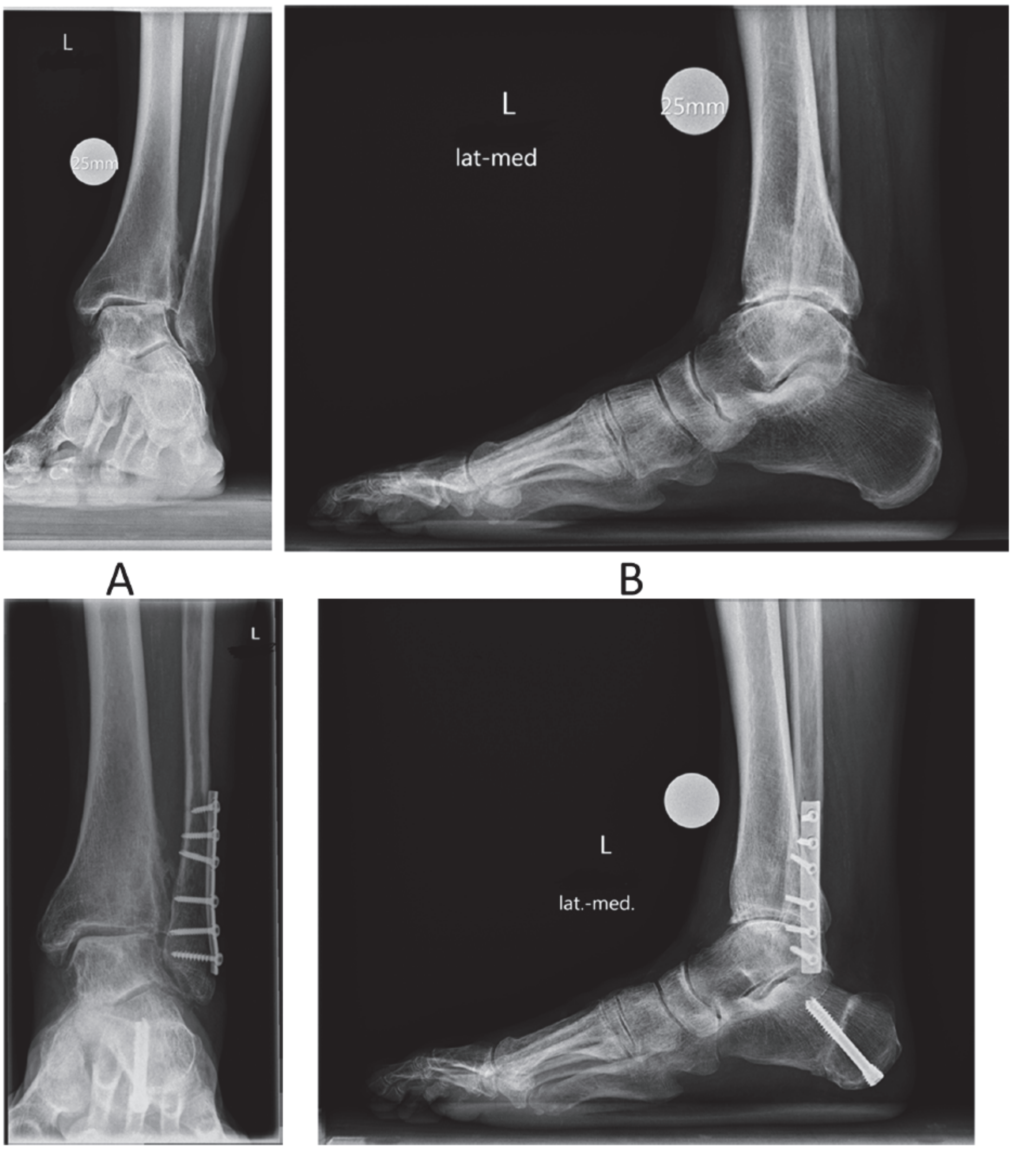

Figure 8. Preoperative (A, B) and 9-month postoperative (C, D) weight-bearing radiographs of a 52-year-old male patient with valgus-type arthritis. The apex of the deformity lies below the ankle joint (A, B), and therefore a medial displacement calcaneal osteotomy was done. Joint congruity was restored by lengthening of the fibula.

OA and were converted to a total ankle replacement (30 cases) or fusion (8 cases) after 5 years (2-16 years).[36] The 5-year survivorship in this series was 88%. Patients younger than 60 years with early- to mid-stage ankle OA (Takakura stages 1 to 3a) showed the best outcome. This is in accordance with earlier findings of Tanaka et al, who subsequently suggested that a stage 3b may not qualify for a supramalleolar osteotomy.[65] However, Lee et al found improvement of all their patients with a preoperative Takakura stage 3b to a Takakura stage 2.

Krahenbuehl et al found that patients older than 60 years and those with a large preoperative tilt in the ankle mortise had a higher risk for early failure.[36] We also were able to confirm that the cut-off for a worse outcome is around 7 degrees of talar tilt in the mortise.[5,44,64] Other risk factors include postoperative joint incongruity (eg, inadequate length or position of the fibula) and ankle joint instability.

Corrections distal to the ankle show less direct effect on the coronal plane alignment of the ankle. Only the calcaneal osteotomies directly influence the overall axis of the hindfoot. In arthritic ankles, calcaneal osteotomies have mainly been used in varus feet where the effect on the ankle has been assessed in several studies.[16,17,38,42,60] In valgus feet, calcaneal osteotomies are mainly used to address sequelae of posterior tibial tendon dysfunction and collapse of the medial arch because of a destructive arthritic process. However, they have been shown to have a beneficial effect on the tibiotalar load distribution.[16,21,47,54,60]

Osteotomies of the medial arch have no direct influence on the hindfoot alignment but indirectly affect the axes of the hindfoot.[10] Knowledge of the effect of these procedures on the ankle joint is sparse. Krause et al found good outcomes in cavovarus feet treated with osteotomies and tendon transfers. Combining the treatment included osteotomies of the medial column, the calcaneus, tendon transfers, and cheilectomy of the ankle joint and lead to reduction of symptoms and down-staging of arthritis on the ankle joint radiographs (less signs of ankle OA).[38]

Summary

A majority of patients with arthritis of the ankle joint present with a malaligned hindfoot. Corrective osteotomies aim to reduce peak pressures in the ankle joint to slow down the progression of ankle joint arthritis. Depending on the underlying pathology, they may be combined with procedures that balance the soft tissues (ligament reconstruction, tendon repairs and transfers). Supramalleolar deformities are corrected with supramalleolar osteotomies, paying great attention to preserve or restore joint congruity. The type of supramalleolar osteotomy (opening and closing wedge osteotomy, dome-shaped osteotomy) is determined by the level of deformity, the type of fixation, the soft tissue mantle, and the type of joint presentation (congruent vs incongruent joints). Best results were reported on patients with Takakura stages 1-3a with 10-year survivorships of 82%. Main risk factors for early tilt are advanced stages of OA, a tilt >7 degrees, age >60 years, postoperative joint incongruity.

Inframalleolar deformities result from variations of the calcaneal shape, the shape and orientation of the subtalar joint, and forefoot deformities. They can be addressed with calcaneal osteotomies; however, the effect on the ankle joint may not be predictable in patients with preserved inversion or eversion at the ST joint. The medial column is included in the preoperative planning. A plantarflexed talus (supinated forefoot) increases the risk for valgus tilting in the ankle joint and thereby increases the load transfer laterally in the ankle joint. A plantarflexed medial column increases the pressure on the anteromedial aspect of the ankle joint.

Acknowledgments

The author wishes to thank Tamara Horn Lang and Lukas Zwicky for the assistance in preparing the manuscript.

Declaration of Conflicting Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author received no financial support for the research, authorship, and/or publication of this article.

References

1. Ahmad J, Raikin SM. Ankle arthrodesis: the simple and the complex. *Foot Ankle Clin*. 2008;13(3):381-400, viii.
2. Apostle KL, Coleman NW, Sangeorzan BJ. Subtalar joint axis in patients with symptomatic peritalar subluxation compared to normal controls. *Foot Ankle Int*. 2014;35(11):1153-1158.
3. Aynardi M, Pedowitz DI, Raikin SM. Subtalar instability. *Foot Ankle Clin*. 2015;20(2):243-252.
4. Barg A, Knupp M, Henninger HB, Zwicky L, Hintermann B. Total ankle replacement using HINTEGRA, an unconstrained, three-component system: surgical technique and pitfalls. *Foot Ankle Clin*. 2012;17(4):607-635.
5. Barg A, Pagenstert GI, Horisberger M, et al. Supramalleolar osteotomies for degenerative joint disease of the ankle joint: indication, technique and results. *Int Orthop*. 2013;37(9):1683-1695.
6. Barg A, Zwicky L, Knupp M, Henninger HB, Hintermann B. HINTEGRA total ankle replacement: survivorship analysis in 684 patients. *J Bone Joint Surg Am*. 2013;95(13):1175-1183.
7. Cheng YM, Huang PJ, Hong SH, et al. Low tibial osteotomy for moderate ankle arthritis. *Arch Orthop Trauma Surg*. 2001;121(6):355-358.
8. Choisne J, Ringleb SI, Samaan MA, et al. Influence of kinematic analysis methods on detecting ankle and subtalar joint instability. *J Biomech*. 2012;45(1):46-52.
9. Coester LM, Saltzman CL, Leupold J, Pontarelli W. Long-term results following ankle arthrodesis for post-traumatic arthritis. *J Bone Joint Surg Am*. 2001;83-A(2):219-228.
10. Coleman SS, Chesnut WJ. A simple test for hindfoot flexibility in the cavovarus foot. *Clin Orthop Relat Res*. 1977;123:60-62.
11. Colin F, Horn Lang T, Zwicky L, Hintermann B, Knupp M. Subtalar joint configuration on weightbearing CT scan. *Foot Ankle Int*. 2014;35(10):1057-1062.
12. Daniels T, Thomas R. Etiology and biomechanics of ankle arthritis. *Foot Ankle Clin*. 2008;13(3):341-352, vii.
13. Daniels TR, Mayich DJ, Penner MJ. Intermediate to long-term outcomes of total ankle replacement with the Scandinavian Total Ankle Replacement (STAR). *J Bone Joint Surg Am*. 2015;97(11):895-903.
14. El-Rosasy M, Ali T. Realignment-lengthening osteotomy for malunited distal fibular fracture. *Int Orthop*. 2013;37(7):1285-1290.
15. Epeldegui T. Deformity of talus and calcaneous in congenital clubfoot: an anatomical study. *J Pediatr Orthop B*. 2012;21(1):10-15.
16. Fairbank A, Myerson M, Fortin PT, Yo-Yahiro J. The effect of calcaneal osteotomy on contact characteristics of the tibiotalar joint. *Foot*. 1995;5:137-142.

17. Fortin PT, Guettler J, Manoli A 2nd. Idiopathic cavovarus and lateral ankle instability: recognition and treatment implications relating to ankle arthritis. *Foot Ankle Int*. 2002;23(11): 1031-1037.
18. Haddad SL, Coetzee JC, Estok R, et al. Intermediate and long-term outcomes of total ankle arthroplasty and ankle arthrodesis. A systematic review of the literature. *J Bone Joint Surg Am*. 2007;89(9):1899-1905.
19. Haraguchi N, Ota K, Tsunoda N, et al. Weight-bearing-line analysis in supramalleolar osteotomy for varus-type osteoarthritis of the ankle. *J Bone Joint Surg Am*. 2015;97(4): 333-339.
20. Harstall R, Lehmann O, Krause F, Weber M. Supramalleolar lateral closing wedge osteotomy for the treatment of varus ankle arthrosis. *Foot Ankle Int*. 2007;28(5):542-548.
21. Havenhill TG, Toolan BC, Draganich LF. Effects of a UCBL orthosis and a calcaneal osteotomy on tibiotalar contact characteristics in a cadaver flatfoot model. *Foot Ankle Int*. 2005;26(8):607-613.
22. Hayashi K, Tanaka Y, Kumai T, Sugimoto K, Takakura Y. Correlation of compensatory alignment of the subtalar joint to the progression of primary osteoarthritis of the ankle. *Foot Ankle Int*. 2008;29(4):400-406.
23. Hintermann B, Barg A, Knupp M. Corrective supramalleolar osteotomy for malunited pronation-external rotation fractures of the ankle. *J Bone Joint Surg Br*. 2011;93(10): 1367-1372.
24. Hintermann B, Knupp M, Barg A. Joint-preserving surgery of asymmetric ankle osteoarthritis with peritalar instability. *Foot Ankle Clin*. 2013;18(3):503-516.
25. Horisberger M, Valderrabano V, Hintermann B. Posttraumatic ankle osteoarthritis after ankle-related fractures. *J Orthop Trauma*. 2009;23(1):60-67.
26. Inman VT, Stiehl JB. *Inman's Joints of the Ankle*. Baltimore, MD: Williams and Wilkins; 1991.
27. Jotoku T, Kinoshita M, Okuda R, Abe M. Anatomy of ligamentous structures in the tarsal sinus and canal. *Foot Ankle int*. 2006;27(7):533-538.
28. Kamrad I, Henricsson A, Karlsson MK, et al. Poor prosthesis survival and function after component exchange of total ankle prostheses. *Acta Orthop*. 2015;86(4):407-411.
29. Kerkhoff YR, Kosse NM, Metsaars WP, Louwerens JW. Long-term functional and radiographic outcome of a mobile bearing ankle prosthesis. *Foot Ankle Int*. 2016;37(12):1292-1302.
30. Kjaersgaard-Andersen P, Wethelund JO, Nielsen S. Lateral talocalcaneal instability following section of the calcaneofibular ligament: a kinesiologic study. *Foot Ankle*. 1987;7(6): 355-361.
31. Knupp M, Bolliger L, Hintermann B. Treatment of posttraumatic varus ankle deformity with supramalleolar osteotomy. *Foot Ankle Clin*. 2012;17(1):95-102.
32. Knupp M, Pagenstert G, Valderrabano V, Hintermann B. Osteotomies in varus malalignment of the ankle. *Oper Orthop Traumatol*. 2008;20(3):262-273.
33. Knupp M, Stufkens S, Bolliger L, Barg A, Hintermann B. Classification and treatment of supramalleolar deformities. *Foot Ankle Int*. 2011;32(11):1023-1031.
34. Knupp M, Stufkens SA, van Bergen CJ, et al. Effect of supramalleolar varus and valgus deformities on the tibiotalar joint: a cadaveric study. *Foot Ankle Int*. 2011;32(6):609-615.
35. Krahenbuhl N, Tschuck M, Bolliger L, Hintermann B, Knupp M. Measurement and reliability using weightbearing CT scans of the orientation of the subtalar joint. *Foot Ankle Int*. 2015;37(1):109-114.
36. Krähenbühl N, Zwicky L, Bolliger L, Schädelin S, Hinterman B, Knupp M. Mid- to Long-term Results of Supramalleolar Osteotomy. *Foot Ankle Int*. 2016 October 10. doi: 10.1177/1071100716673416 [Epub ahead of print]
37. Krause F, Windolf M, Schwieger K, Weber M. Ankle joint pressure in pes cavovarus. *J Bone Joint Surg Br*. 2007;89(12):1660-1665.
38. Krause FG, Henning J, Pfander G, Weber M. Cavovarus foot realignment to treat anteromedial ankle arthrosis. *Foot Ankle Int*. 2013;34(1):54-64.
39. Labek G, Janda W, Agreiter M, Schuh R, Bohler N. Organisation, data evaluation, interpretation and effect of arthroplasty register data on the outcome in terms of revision rate in total hip arthroplasty. *Int Orthop*. 2011;35(2):157-163.
40. Labib SA, Raikin SM, Lau JT, et al. Joint preservation procedures for ankle arthritis. *Foot Ankle int*. 2013;34(7):1040-1047.
41. Lamm BM, Paley D. Deformity correction planning for hindfoot, ankle, and lower limb. *Clin Podiatr Med Surg*. 2004;21(3):305-326, v.
42. Lee HS, Wapner KL, Park SS, et al. Ligament reconstruction and calcaneal osteotomy for osteoarthritis of the ankle. *Foot Ankle Int*. 2009;30(6):475-480.
43. Lee KB, Cho YJ. Oblique supramalleolar opening wedge osteotomy without fibular osteotomy for varus deformity of the ankle. *Foot Ankle Int*. 2009;30(6):565-567.
44. Lee WC, Moon JS, Lee K, Byun WJ, Lee SH. Indications for supramalleolar osteotomy in patients with ankle osteoarthritis and varus deformity. *J Bone Joint Surg Am*. 2011;93(13):1243-1248.
45. Lindsjo U. Operative treatment of ankle fracture-dislocations. A follow-up study of 306/321 consecutive cases. *Clin Orthop Relat Res*. 1985;199:28-38.
46. Lutz M, Myerson M. Radiographic analysis of an opening wedge osteotomy of the medial cuneiform. *Foot Ankle Int*. 2011;32(3):278-287.
47. Michelson JD, Mizel M, Jay P, Schmidt G. Effect of medial displacement calcaneal osteotomy on ankle kinematics in a cadaver model. *Foot Ankle Int*. 1998;19(3):132-136.
48. Ogilvie-Harris DJ, Sekyi-Otu A. Arthroscopic debridement for the osteoarthritic ankle. *Arthroscopy*. 1995;11(4): 433-436.
49. Pagenstert GI, Hintermann B, Barg A, Leumann A, Valderrabano V. Realignment surgery as alternative treatment of varus and valgus ankle osteoarthritis. *Clin Orthop Relat Res*. 2007;462:156-168.
50. Paley D, Herzenberg JE. *Ankle and Foot Considerations. Principles of Deformity Correction*. Berlin: Springer-Verlag; 2002:571-645.
51. Piazza SJ, Adamson RL, Sanders JO, Sharkey NA. Changes in muscle moment arms following split tendon transfer of tibialis anterior and tibialis posterior. *Gait Posture*. 2001; 14(3):271-278.

52. Probasco W, Haleem AM, Yu J, et al. Assessment of coronal plane subtalar joint alignment in peritalar subluxation via weight-bearing multiplanar imaging. *Foot Ankle Int*. 2015;36(3):302-309.
53. Rammelt S, Grass R, Zwipp H. Joint-preserving osteotomy for malunited intra-articular calcaneal fractures. *J Orthop Trauma*. 2013;27(10):e234-e238.
54. Resnick RB, Jahss MH, Choueka J, et al. Deltoid ligament forces after tibialis posterior tendon rupture: effects of triple arthrodesis and calcaneal displacement osteotomies. *Foot Ankle Int*. 1995;16(1):14-20.
55. Saltzman CL, el-Khoury GY. The hindfoot alignment view. *Foot Ankle Int*. 1995;16(9):572-576.
56. Saltzman CL, Hillis SL, Stolley MP, Anderson DD, Amendola A. Motion versus fixed distraction of the joint in the treatment of ankle osteoarthritis: a prospective randomized controlled trial. *J Bone Joint Surg Am*. 2012;94(11):961-970.
57. Sarrafian SK. Biomechanics of the subtalar joint complex. *Clin Orthop Relat Res*. 1993;290:17-26.
58. Siddiqui NA, Herzenberg JE, Lamm BM. Supramalleolar osteotomy for realignment of the ankle joint. *Clin Podiatr Med Surg*. 2012;29(4):465-482.
59. Stamatis ED, Cooper PS, Myerson MS. Supramalleolar osteotomy for the treatment of distal tibial angular deformities and arthritis of the ankle joint. *Foot Ankle Int*. 2003;24(10):754-764.
60. Steffensmeier SJ, Saltzman CL, Berbaum KS, Brown TD. Effects of medial and lateral displacement calcaneal osteotomies on tibiotalar joint contact stresses. *J Orthop Res*. 1996;14(6):980-985.
61. Stufkens SA, van Bergen CJ, Blankevoort L, et al. The role of the fibula in varus and valgus deformity of the tibia: a biomechanical study. *J Bone Joint Surg Br*. 2011;93(9):1232-1239.
62. Takakura Y, Takaoka T, Tanaka Y, Yajima H, Tamai S. Results of opening-wedge osteotomy for the treatment of a post-traumatic varus deformity of the ankle. *J Bone Joint Surg Am*. 1998;80(2):213-218.
63. Takakura Y, Tanaka Y, Kumai T, Tamai S. Low tibial osteotomy for osteoarthritis of the ankle. Results of a new operation in 18 patients. *J Bone Joint Surg Br*. 1995;77(1):50-54.
64. Tanaka Y. The concept of ankle joint preserving surgery: why does supramalleolar osteotomy work and how to decide when to do an osteotomy or joint replacement. *Foot Ankle Clin*. 2012;17(4):545-553.
65. Tanaka Y, Takakura Y, Hayashi K, et al. Low tibial osteotomy for varus-type osteoarthritis of the ankle. *J Bone Joint Surg Br*. 2006;88(7):909-913.
66. Thordarson DB, Motamed S, Hedman T, Ebramzadeh E, Bakshian S. The effect of fibular malreduction on contact pressures in an ankle fracture malunion model. *J Bone Joint Surg Am*. 1997;79(12):1809-1815.
67. Valderrabano V, Hintermann B, Horisberger M, Fung TS. Ligamentous posttraumatic ankle osteoarthritis. *Am J Sports Med*. 2006;34(4):612-620.
68. Valderrabano V, Horisberger M, Russell I, Dougall H, Hintermann B. Etiology of ankle osteoarthritis. *Clin Orthop Relat Res*. 2009;467(7):1800-1806.
69. Vaseenon T, Amendola A. Update on anterior ankle impingement. *Curr Rev Musculoskelet Med*. 2012;5(2):145-150.
70. Wang B, Saltzman CL, Chalayon O, Barg A. Does the subtalar joint compensate for ankle malalignment in end-stage ankle arthritis? *Clin Orthop Relat Res*. 2015;473(1):318-325.
71. Weber BG, Simpson LA. Corrective lengthening osteotomy of the fibula. *Clin Orthop Relat Res*. 1985;199:61-67.