International Orthopaedics (SICOT) (2015) 39:2275–2280
DOI 10.1007/s00264-015-2944-y

ORIGINAL PAPER

Subtalar arthrodesis stabilisation with screws in an angulated configuration is superior to the parallel disposition: a biomechanical study

Martin Eichinger[1] **· Werner Schmölz**[1] **· Alexander Brunner**[1] **· Raul Mayr**[1] **· Andreas Bölderl**[1]

Received: 29 May 2015 / Accepted: 16 July 2015 / Published online: 8 August 2015

Abstract
Purpose The purpose of this study was to compare the stability of two established screw configurations (SC) for subtalar arthrodesis using a cyclic loading model.
Methods Eight paired human cadaver hindfoot specimens underwent subtalar arthrodesis with either parallel or angulated SC. The instrumented specimens were subjected to a cyclic loading protocol (1000 cycles: ±5 Nm rotation moment, 50 N axial force). The joint range of motion (ROM) was quantified before and after cyclic loading, in the three principal motion planes of the subtalar joint using pure bending moments of ±3 Nm.
Results After instrumentation, the angulated SC showed significantly less mean ROM compared to the parallel SC in internal/external rotation (1.4°±2.2° vs. 3.3°±2.8°, P= 0.006) and in inversion/eversion (0.9°±1.4° vs. 1.5°±1.1°, P=0.049). After cyclic loading, the angulated SC resulted in significantly less mean ROM compared to the parallel SC in internal/external rotation (3.3°±4.6° vs. 8.8°±8.0°, P=0.006) and in inversion/eversion (1.9°±2.3° vs. 3.9°±3.9°, P= 0.017). No significant differences in the mean ROM were found between the angulated and parallel SC in dorsal extension/plantar flexion.
Conclusion The angulated SC resulted in decreased ROM in the subtalar arthrodesis construct after instrumentation and after cyclic loading compared to the parallel SC. The data from our study suggest that the clinical use of the angulated SC for subtalar arthrodesis might be superior to the parallel SC.

Keywords Subtalar · Arthrodesis · Screw fixation · Hindfoot · Biomechanics

✉ Andreas Bölderl
andreas.boelderl@i-med.ac.at

[1] Department of Trauma Surgery, Medical University of Innsbruck, Anichstrasse 35, 6020 Innsbruck, Austria

Introduction

Subtalar arthrodesis is considered a salvage procedure for patients with isolated subtalar osteoarthritis when conservative treatment has failed. The principle is to prevent painful motion in the affected joint. Achieving stable bony fusion of the subtalar joint in a physiologically favourable position is crucial for a good functional outcome. Reported post-operative non-union rates following arthrodesis vary between 2 and 30 % [1–5]. This is influenced by patient-related factors, including diabetes, smoking and bone health [2, 5]. Achieving a secure bony fusion is also crucially dependant on mechanical factors, particularly compression and stability between the articular surfaces [6, 7]. Therefore, the primary surgical goal is to secure early stability of the arthrodesis in order to encourage bony fusion in the desired anatomical position [6–9].

During the last few decades internal fixation with screws has become established as the standard procedure for isolated subtalar arthrodesis [2, 3, 10]. In a biomechanical study, Chuckpaiwong et al. [9] showed that a screw configuration (SC) using two arthrodesis screws instead of one could triple the initial compressive forces and also significantly increase rotatory stability of the arthrodesis construct [9]. In clinical practice, two screws are often placed either parallel to each other or else angulated [8, 11]. Angular placement of screws is reported to result in greater resistance to torsional loading [9, 12]. However, only the initial stability of different SCs using static test protocols has been assessed. During post-operative patient mobilisation, cyclic loading is inevitable and may cause the screws to loosen leading to early loss of compression. To our knowledge the effect of different SCs on the stability of subtalar arthrodesis under cyclic loading conditions has not been reported.

Here we describe a biomechanical study comparing two established techniques for subtalar arthrodesis, both using two-screw SCs in a cyclic loading model with parallel versus angulated positioning. We hypothesized that the angulated configuration would be associated with less joint motion both initially after instrumentation and following cyclic loading.

Materials and methods

Specimens

Eight fresh frozen human hindfoot pairs were used in our studies. Four were from females. The mean age (±SD) at salvage was 69.9±10.8 years (range, 52–85 years). Bone mineral density (BMD) was assessed by quantitative computed tomography (CT; LightSpeed VCT, GE Healthcare, Milwaukee, USA) using a calibration phantom. The mean BMDs for the calcaneus and talus bones were 177.1±59.2 mg/cm³ and 282.7±67.0 mg/cm³, respectively. Specimens were stored at −20°C and thawed overnight at 4°C before testing. Skin and muscle were removed by dissection, leaving the isolated talocalcaneal unit, with most of the subtalar joint capsule intact [7, 9, 12]. Left and right talocalcaneal units were randomly allocated to either the parallel or angulated SC groups, in order to allow a pairwise comparison of the groups.

Surgical technique

All surgical procedures were performed by the same senior foot surgeon (AB). A drilling frame was used to ensure accurate screw positioning. The talocalcaneal units were temporarily fixed using 1.2-mm K-wires.

Drill holes for the arthrodesis screws were prepared using a cannulated 3.2-mm drill and tapped to a diameter of 6.5 mm. The length of screws to be used was determined using a depth gauge. Two 6.5-mm cannulated screws (Synthes, Oberdorf, Switzerland) with 17-mm thread lengths were inserted either parallel or angulated to each other, depending on which group the unit had been allocated to. The screws were tightened manually using the standard AO technique until a firm three-finger grip was felt [5, 9]. This ensured that the screws were not over-tightened.

For the parallel screw configuration, the first screw was inserted at the posterolateral calcaneal tuberosity, just posterior to the weight-bearing surface. It was oriented across the posterior facet of the subtalar joint at a 90° angle, with its tip located in the lateral talar dome. The second screw was inserted 15 mm medial to the entry point of the first screw, at the posteromedial calcaneal tuberosity, just posterior to the weight-bearing surface. It was oriented parallel to the first screw, with its tip located in the medial talar dome [9, 13] (Fig. 1).

For the angulated screw configuration, the first screw was also inserted at the posterolateral calcaneal tuberosity in an identical manner to that described above. The insertion point of the second screw was the lateral plantar aspect of the anterior calcaneus, 10 mm proximal to the calcaneocuboid joint. It was directed at an approximate angle of 45° running dorsally and medially (parallel to the Chopart's joint line), into the head or neck of the talus [8, 11] (Fig. 2).

Biomechanical testing

After screw insertion, the posterior third of the calcaneus and the talar dome were embedded in polymethylmethacrylate (PMMA, Technovit 3040, Heraeus Kulzer, Wehrheim, Germany). Woodscrews were inserted into the medial and lateral shoulders of the trochlea tali to prevent talar movement within the PMMA fixation. The talocalcaneal unit was oriented with an inclination of 40° and a deviation of 20° medial to the long axis of the foot in the transverse plane. This is considered to be the physiological axis of subtalar motion [9, 14–16].

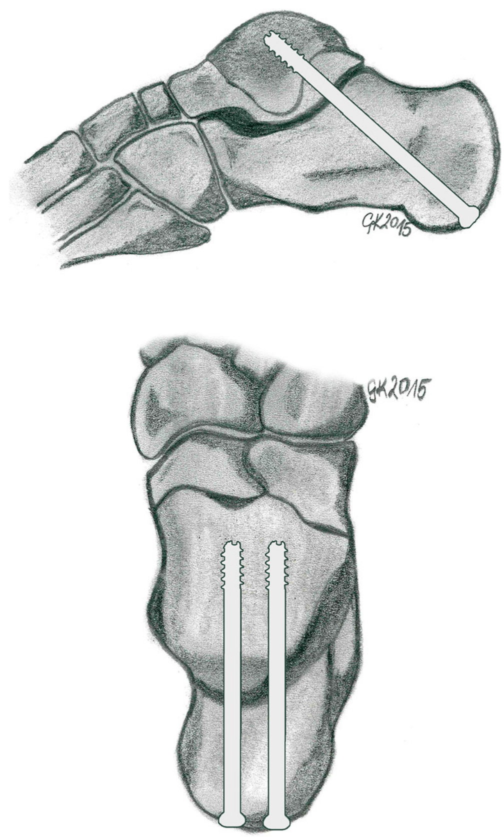

Fig. 1 Parallel screw configuration. **a** Sagittal. **b** Transverse

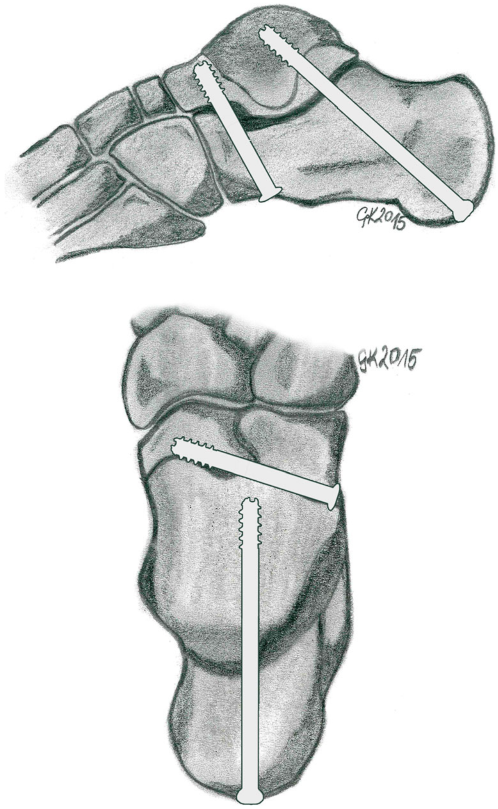

Fig. 2 Delta screw configuration. **a** Sagittal. **b** Transverse

Flexibility testing

All flexibility tests were carried out in a test setup, using pure bending moments of ±3 Nm in the three main motion planes of the subtalar joint, (i.e., internal/external rotation [IER], inversion/eversion [IE] and dorsal extension/plantar flexion [DEPF], applied by a force couple). Loading was induced by rotation around one axis; the other five degrees of freedom were unconstrained. A six component force/torque load cell was used to control the loading of the specimens. An ultrasound based 3-D motion analysing system (Winbiomechanics, Zebris, Isny, Germany) was fixed to the front of the PMMA embedding to record the relative motion of the talus and calcaneus with a sampling rate of 60 Hz. The ROM in the three principal motion planes was determined (Fig. 3a).

Cyclic loading

The talar side of the embedded specimens were attached to the actuator of a servohydraulic material testing machine (MTS Mini-Bionix 858; MTS, Eden Prairie, Minnesota). On the calcaneal side the specimens were mounted on an x-y bearing table with two translational degrees of freedom during testing. On the talar side a universal joint was used to allow two rotational degrees of freedom (Fig. 3b). Specimens were loaded statically in the axial direction with 50 N and cyclically with an internal-external rotation moment of ±5 Nm with an angular rate of 4°/s for 1000 cycles. The initial three cycles and every hundredth of the following cycles were recorded.

Specimens were tested as follows: (i) first flexibility testing, after instrumentation—three motion planes (±3 Nm); (ii) cyclic loading (axial load: 50 N, rotation moment: ±5 Nm, 4°/s, 1000 cycles); and (iii) second flexibility testing, after 1000 cycles—three motion planes (±3 Nm)

Statistical analysis

Data are presented as means±SD. Normal distribution was tested and confirmed with the Kolmogorov–Smirnov test. Differences between the two groups were compared using a paired t-test. The significance level was set at $P<0.05$.

Results

Immediately after instrumentation the mean ROM was significantly less for both IER and IE for specimens instrumented with the angulated SC compared to the parallel SC (1.4°±2.2° vs. 3.3°±2.0°, $P=0.007$; and 0.9°±1.4° vs. 1.5°±1.1°, $P=0.049$, respectively; Fig. 4a, b). There was no significant difference in the mean ROM for DEPF between the specimens instrumented with the angulated SC compared to the parallel SC (2.1°±1.9° vs. 2.2°±2.3°, $P=0.816$; Fig. 4c).

After 1,000 cycles of loading, the mean ROM was significantly less for both IER and IE for specimens instrumented with the angulated SC compared to the parallel SC (3.3°±4.6° vs. 8.8°±8.0°, $P=0.006$; and 1.9°±2.3° vs. 3.9°±3.9°, $P=0.017$ respectively; Fig. 4a, b). There was no significant difference in the mean ROM for DEPF between the specimens instrumented with the angulated SC compared to the parallel SC (3.2°±2.8° vs. 6.8°±7.7°, $P=0.086$; Fig. 4c).

Discussion

The results of this study confirm the hypothesis that the angulated SC in subtalar arthrodesis is more resistant to cyclic loading than the parallel SC. It leads to less joint motion during flexibility testing immediately after instrumentation and in response to cyclic torsional loading.

The higher mean ROM for the parallel SC immediately after instrumentation confirms the findings of previously published non-cyclic biomechanical investigations [9, 12].

Hungerer et al. reported higher mean ROMs immediately after instrumentation with the parallel SC compared to the

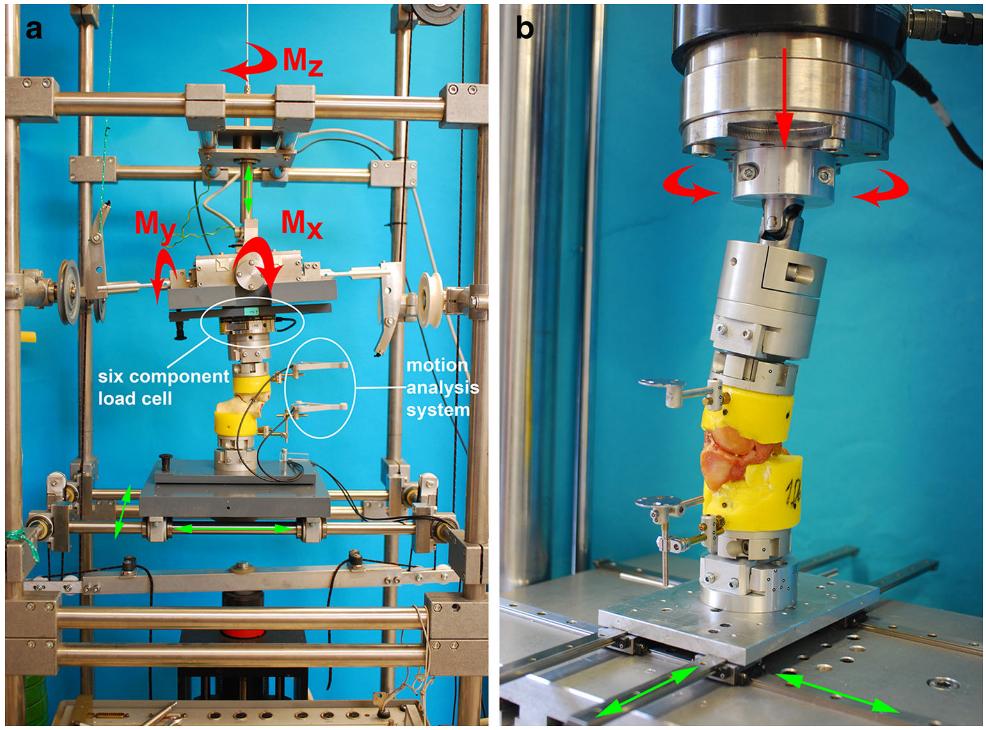

Fig. 3 **a** Test setup for flexibility testing. Tester with six degrees of freedom, six component load cell and 3D motion analysis system. The curved *arrows* indicate the applied pure bending moments (±3 Nm, Mx, My, Mz) and rotational axes. The double-headed arrows indicate the three translations permitted by the setup. **b** Test setup for cyclic loading. Specimens were connected to the material testing machine (MTS) using an xy-table (*double-headed arrows*) and a universal joint. The three single arrows indicate the applied forces for axial loading (50 N) and internal-external rotation (±5 Nm)

angulated SC (IER 3.7° and IE 10.5° vs. 2.3° and 1.7° respectively) [12]. Chuckpaiwong et al. reported higher mean ROMs when the parallel SC was compared to a diverging SC (IER 14.0° vs. 10.0°) [9].

After subtalar arthrodesis early weight-bearing is desirable [8]. Therefore, static testing does not fully reproduce the loading conditions which are likely to occur during postoperative mobilisation. By using a cyclic loading protocol, we simulated forces and movements likely to occur during postoperative mobilisation. To our knowledge, this is the first such study. After 1,000 cycles of rotational loading the angulated SC showed significantly less ROM in the IER and IE motion planes in comparison to the parallel SC. Indeed the results for the angulated SC after cyclic loading were comparable to the results of the parallel SC immediately after instrumentation. The superiority of the angulated SC may be a result of the bigger distance between the screws that is created by the angulation. This will lead to increased resistance to rotational forces [8, 9, 12]. The complex geometry of the articular surfaces of the subtalar joint is important in limiting the rotation of the subtalar arthrodesis [9, 12]. The angulated SC may achieve superior distribution of compression [9, 12]. We observed a similar trend for DEPF as we did for IER and IE. That it did not reach statistical significance may have been a consequence of the fact that this is generally the most constrained plane of motion of the subtalar joint [16, 17].

The two screw configurations investigated by us were chosen because they represent two of the most widely used techniques in clinical practice [2, 8, 9, 11, 12, 18]. The angulated position has become the standard procedure for isolated subtalar arthrodesis at our institution. In comparison with two diverging screws inserted from behind, it allows more relative angulation of the screws to each other and a longer distance between the screws. This is likely to increase the positive effects on rotatory, and consequently, overall stability [8, 11, 12]. Other clinical advantages include the increased raw bone contact area with only one screw penetrating the posterior joint facet. Additionally this avoids a second screw head on the plantar calcaneus which can become prominent with weight-bearing. Boffeli and Reinking [11] reported high fusion rates and favourable clinical results using the angulated SC. Bürgi and Hintermann [8] reported that it achieved better initial stability, thereby allowing earlier mobilisation with weight-bearing.

We chose to study an inferior to superior screw trajectory with the thread positioned in the talar bone because most recent clinical reports have adopted this approach. Advantages of it are said to be an easier initial approach, availability of the denser talar bone and a reduced risk of damage to the neurovascular bundle [2, 6, 10].

We consider the particular cyclic testing model we used, with rotational/torsional loading, to have been particularly well-suited to test our hypothesis, since published data indicates that all combined motions of the subtalar joint involve IE rotational motion [3, 9, 12, 16, 17]. We approximated the ideal axis of the rotational force to the normal axis of subtalar motion and use of the x-y table and a universal joint enabled us to reproduce physiologic subtalar joint rotation [9, 14–16]. Our

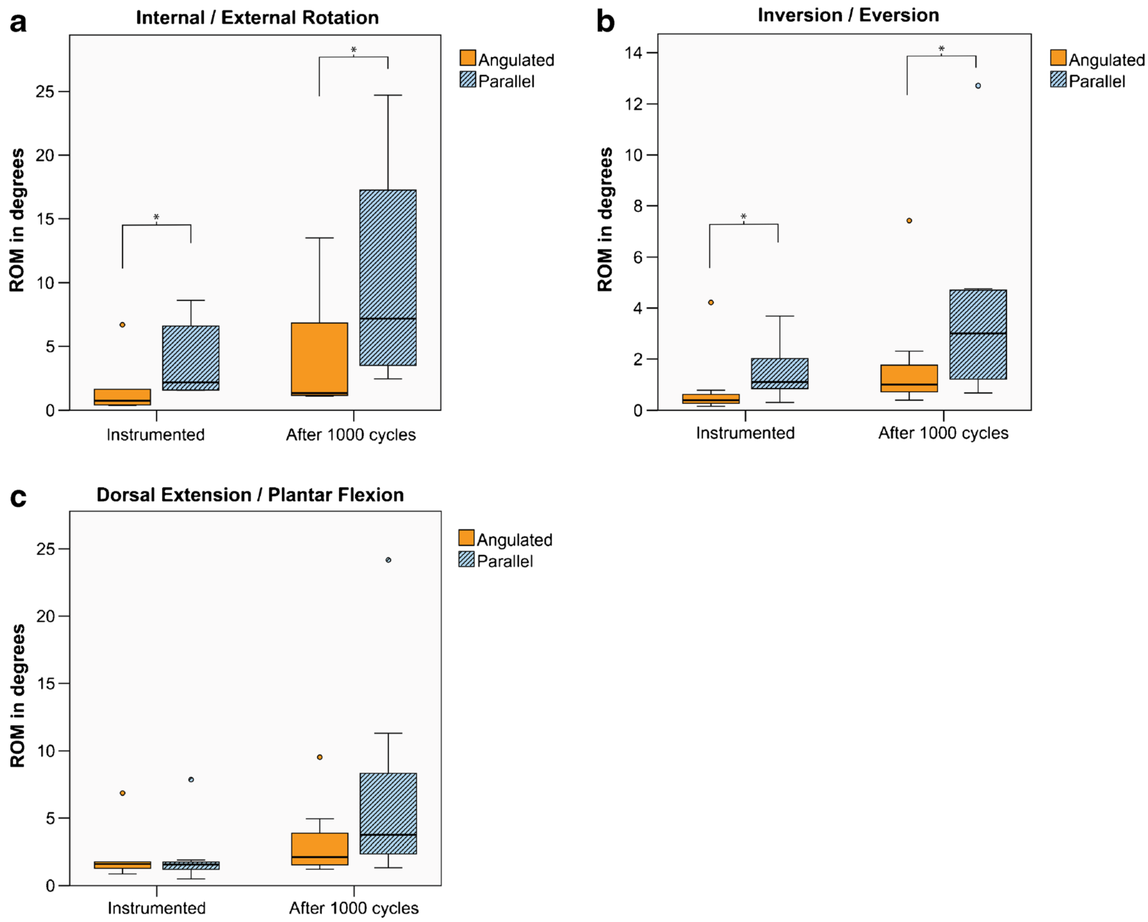

Fig. 4 Range of motion (degrees) in the subtalar joint measured in the flexibility test of the instrumented specimens and after 1,000 load cycles, presented as box plots with medians and interquartile ranges (25–75%). The *circles* indicate outliers. *Statistically significant difference between the groups ($P<0.05$). **a** Internal/external rotation. **b** Inversion/eversion. **c** Dorsal extension/plantar flexion

flexibility testing system allowed assessment of six degrees of freedom. This meant that the impact of cyclic loading on the subtalar arthrodesis construct could be assessed in all three of the principal planes of motion of the subtalar joint.

Notwithstanding the above, it is important to recognise that the complexity of the motions at the subtalar joint are difficult to reproduce and our model can only be an approximation. Studies on cadaveric specimens can never entirely reproduce *in vivo* conditions. Randomized controlled trials will be necessary to evaluate if the angulated SC improves union rates after subtalar arthrodesis in clinical practice. Until these are available, our study suggests the angulated SC may help to optimize early stability of subtalar arthrodeses, allowing for earlier post-operative mobilisation [8].

In conclusion, the angulated screw configuration resulted in decreased joint motion in the subtalar arthrodesis construct immediately after instrumentation and following cyclic loading when compared to the parallel screw configuration. This suggests that for isolated subtalar arthrodesis, two screws in an angulated configuration should be preferred over a parallel configuration.

Acknowledgments Special thanks to Kathrin Gehmacher for kindly providing the illustrations and Benjamin Placzek for his assistance in the mechanical testing.

Conflicts of interest The authors declare that they have no conflict of interests.

References

1. Donley BG, Ward DM (2002) Implantable electrical stimulation in high-risk hindfoot fusions. Foot Ankle Int 23(1):13–18
2. Easley ME, Trnka HJ, Schon LC, Myerson MS (2000) Isolated subtalar arthrodesis. J Bone Joint Surg Am 82(5):613–624
3. Mann RA, Beaman DN, Horton GA (1998) Isolated subtalar arthrodesis. Foot Ankle Int 19(8):511–519
4. Sammarco GJ, Tablante EB (1998) Subtalar arthrodesis. Clin Orthop Relat Res 349:73–80
5. Hungerer S, Trapp O, Augat P, Buhren V (2011) Posttraumatic arthrodesis of the subtalar joint - outcome in workers compensation and rates of non-union. Foot Ankle Surg 17(4):277–283
6. Dahm DL, Kitaoka HB (1998) Subtalar arthrodesis with internal compression for post-traumatic arthritis. J Bone Joint Surg Am 80(1):134–138

7. Hintermann B, Valderrabano V, Nigg B (2002) Influence of screw type on obtained contact area and contact force in a cadaveric subtalar arthrodesis model. Foot Ankle Int 23(11):986–991
8. Bürgi M, Hintermann B (2003) Subtalar arthrodesis with ideal compression screws® allowing early weight bearing. Oper Orthop Traumatol 4:402–414
9. Chuckpaiwong B, Easley ME, Glisson RR (2009) Screw placement in subtalar arthrodesis: a biomechanical study. Foot Ankle Int 30(2): 133–141
10. Davies MB, Rosenfeld PF, Stavrou P, Saxby TS (2007) A comprehensive review of subtalar arthrodesis. Foot Ankle Int 28(3): 295–297
11. Boffeli TJ, Reinking RR (2012) A 2-screw fixation technique for subtalar joint fusion: a retrospective case series introducing a novel 2-screw fixation construct with operative pearls. J Foot Ankle Surg 51(6):734–738
12. Hungerer S, Eberle S, Lochner S, Maier M, Hogel F, Penzkofer R, Augat P (2013) Biomechanical evaluation of subtalar fusion: the influence of screw configuration and placement. J Foot Ankle Surg 52(2):177–183
13. Greisberg J, Sangeorzan B (2007) Hindfoot arthrodesis. J Am Acad Orthop Surg 15(1):65–71
14. Leardini A, Stagni R, O'Connor JJ (2001) Mobility of the subtalar joint in the intact ankle complex. J Biomech 34(6):805–809
15. Lewis GS, Kirby KA, Piazza SJ (2007) Determination of subtalar joint axis location by restriction of talocrural joint motion. Gait Posture 25(1):63–69
16. Sarrafian SK (1993) Biomechanics of the subtalar joint complex. Clin Orthop Relat Res 290:17–26
17. de Asla RJ, Wan L, Rubash HE, Li G (2006) Six DOF in vivo kinematics of the ankle joint complex: application of a combined dual-orthogonal fluoroscopic and magnetic resonance imaging technique. J Orthop Res 24(5):1019–1027
18. Rammelt S, Zwipp H (2013) Corrective arthrodeses and osteotomies for post-traumatic hindfoot malalignment: indications, techniques, results. Int Orthop 37(9):1707–1717