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Computer-assisted surgery (CAS) based correction of posttraumatic ankle and hindfoot deformities—Preliminary results

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Abstract

The first clinical experiences with a computer assisted surgery based (CAS) guided correction arthrodeses at ankle, hindfoot and midfoot were evaluated.

Methods: Time spent, accuracy, surgeons' rating (Visual Analogue Scale [VAS], 0–10 points) were analyzed. The accuracy was assessed by ISO-C 3D (Siremobile™, Siemens, Germany).

Results: 10 patients were included (ankle, $n = 3$; subtalar joint, $n = 6$; ankle and subtalar joint, $n = 2$; Lisfranc joint, $n = 1$). Time needed for preparation was 500 s (400–900). The correction process took 45 s (30–60). All angles/translations were achieved as planned before surgery ($\leq \pm 1^\circ/\pm 1$ mm). The ratings of the three involved surgeons were: feasibility, 9.5 (9–10); accuracy 9.8 (9.5–10); clinical benefit 9 (8–10).

Conclusions: CAS guided correction of posttraumatic deformities of the ankle and hindfoot region provides very high accuracy and a fast correction process. The significance of the introduced method may be high in those cases, because the improved accuracy may lead to an improved clinical outcome.

Keywords: Computer assisted surgery (CAS); Hindfoot; Midfoot; Correction

1. Introduction

Posttraumatic ankle and hindfoot deformities are not uncommon after complex trauma of the ankle and hindfoot [1–11]. The biomechanical consequences of these deformities frequently lead to clinical symptoms like pain and gait disturbances [7,10,12–20]. The correction of the deformities is challenging since nonunion and remaining deformity with symptoms is frequent [7,10,11,20–22]. The pre-operative diagnostic with radiographs and CT allows accurate planning of the correction and the level of accuracy is improved by the use of computerized planning systems [23]. However, during the operative procedure the realization of the planned correction is difficult, because the correction process is performed by the surgeon without guidance beyond a conventional C-arm [7,10,11,21,22,24]. In other fields of orthopaedic surgery like spine, hip and knee surgery, computer assisted surgery (CAS) was found to be helpful and more accurate than the conventional methods without navigation [25–35]. For the foot region, a system for C-arm based CAS guided correction was developed since CT-based CAS did not work successfully in vitro [36]. In this study, the first clinical experiences with C-arm based CAS guided correction arthrodesis at foot and ankle were analyzed.

2. Methods

2.1. Devices

A navigation system with wireless Dynamic Reference Bases (DRB) was used (VectorVision™, BrainLAB Inc.,

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Kirchheim-Heimstetten, Germany). The system was connected with a modified C-arm (Exposcope™, Instrumentarium Imaging Ziehm Inc., Nuernberg, Germany, Fig. 2). The accuracy of the correction was checked with C-arm and intraoperative three-dimensional imaging with ISO-C-3D™ (Siemens Inc., Germany) (Fig. 6). ISO-C-3™ is a motorized mobile C-arm that provides fluoroscopic images during a 190° orbital rotation, resulting in a 119 mm data cube [37]. Multiplanar and two-dimensional reconstructions can be obtained from these 3D data sets [37].

2.2. Setting

This clinical study was performed in a university hospital level I trauma center. The surgical staff involved in the study consisted of qualified and experienced orthopaedic trauma surgeons as well as interns, residents and fellows in training. The surgical procedures were exclusively performed by the head of the trauma department or attending surgeons.

2.3. CAS-procedure

One DRB was fixed to each of the two bones or fragments that had been planned for correction in relation to each other (Fig. 1). With the C-arm, anteroposterior and lateral digital radiographic images were obtained, and the data were transferred to the navigation device (Figs. 2 and 4). A verification process with a DRB-equipped pointer follows (Fig. 2). Then the correction was performed. During the correction, the angle motion and translational motion between the bones or fragments in all degrees of freedom were displayed on the screen of the navigation system (Fig. 3 and 5a,b). Furthermore, virtual radiographs with the moving bones or fragments were displayed on the screen (Fig. 3). C-arm use was not used during the correction process. After correction, retention was performed with 3.0 mm K-wires. Then the accuracy of the correction was checked with C-arm and intraoperative three-dimensional imaging with ISO-C-3D (Fig. 6). Finally screw fixation

Fig. 2. Same patient as Fig. 1. Image aquisition with a modified C-arm (device on the left side, Exposcope™, Instrumentarium Imaging Ziehm Inc., Nuernberg, Germany) and transfer of the data to the navigation device (device on the right side, VectorVision™, BrainLAB Inc., Kirchheim-Heimstetten, Germany). Verification with a DRB-equipped pointer (in the hand of the surgeon on the left side), i.e. approval of the accuracy of the data for navigation. The pointer touches defined landmarks of the situs which is shown in real-time on the screen of the navigation device and must be displayed exactly at the landmark to approve adequate accuracy for the further navigation process.

Fig. 1. C-arm based CAS guided correction of an ankle deformity after in a malunited pilon fracture with posttraumatic ankle osteoarthritis. The talus was in a fixed varus position of 10° and a fixed euqinus position of 12°. A correction arthrodesis of the ankle was indicated. Wireless Dynamic Reference Bases (DRBs) were fixed to the distal tibia and the posterior process of the calcaneus. The subtalar joint was transfixed with K-wires before to ''fuse'' the calcaneus and talus temporarily for the correction process and to maintain enough space at the talus for later screw fixation to the tibia.

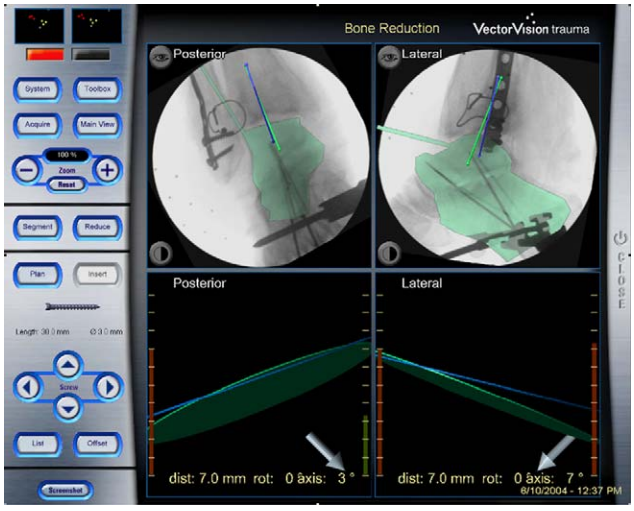

Fig. 3. Same patient as Figs. 1 and 2. Image on the screen of the navigation device (VectorVision™, BrainLAB Inc., Kirchheim-Heimstetten, Germany). During the correction, the angle motion and translational motion between the bones or fragments (here: ''fragment'' 1, tibia; ''fragment'' 2, talus/calcaneus) in all degrees of freedom were displayed on the screen of the navigation system. Furthermore, virtual radiographs with the moving bones or fragments were displayed on the screen. The C-arm is not used during the correction process.

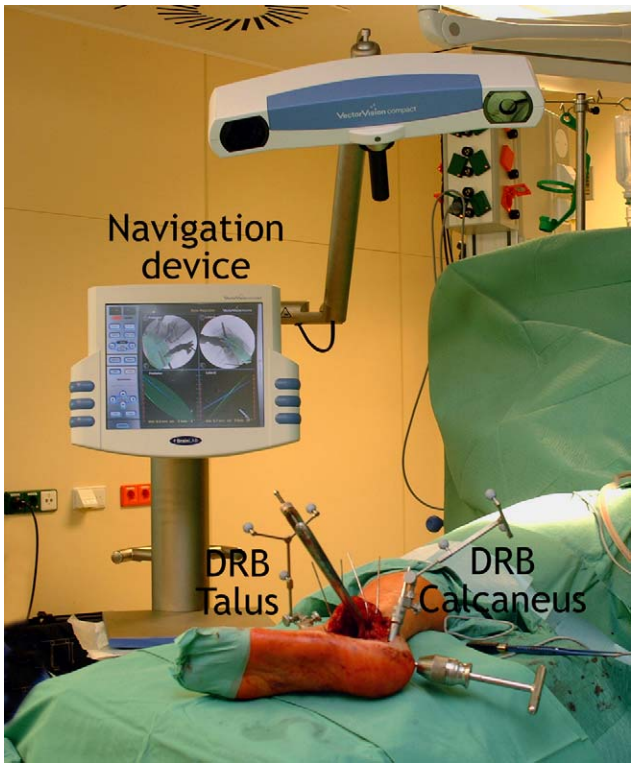

Fig. 4. C-arm based CAS guided correction of hindfoot deformity after malunited calcaneus fracture with flattening of the longitudinal arch and the Boehler's angle (0°), and hindfoot varus (10°). A correction arthrodesis of the subtalar joint with elevation of the longitudinal arch (planned Boehler's angle 30°) and correction of the varus was indicated. The DRBs were fixed to the talar neck and to the posterior process of the calcaneus. Image acquisition and verification had been performed (process describe in figure legend 2).

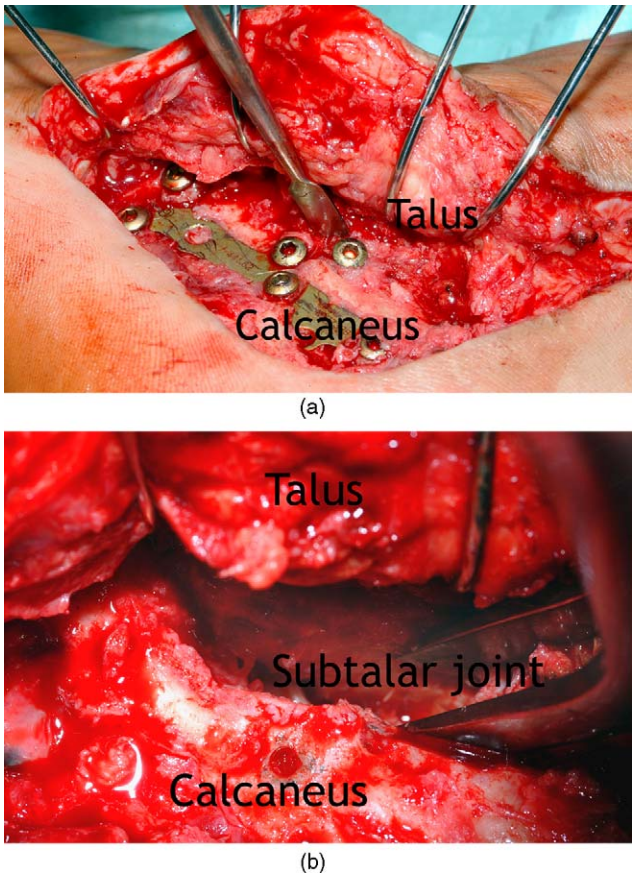

Fig. 5. (a) and (b) Same patient as Fig. 1. Situs before implant removal (a) and after the CAS guided correction (b). After the correction, the gap in the subtalar joint was filled with two tricortical bone blocks from the ipsilateral anterior pelvic rim.

followed. The insertion of the screws was also C-arm based CAS guided (data not shown).

Figs. 4–6 show a clinical example (case history in figure legends).

2.4. Inclusion criteria

The following inclusion criteria were defined: all patients who were treated at the institution between January 1st, 2003 and July 31st, 2005 were considered for inclusion in the study. Patients with posttraumatic deformities of the ankle, subtalar or Lisfranc joint were designated for inclusion. The devices were not always available for the study since it was also being used for procedures other than in foot and ankle surgery. No exclusion criteria were defined. The posttraumatic deformities of the subtaler joint after calcaneus malunion were classified due to Stephens/Sanders [20].

2.5. Evaluation

C-arm based CAS guided arthrodeses with correction of the deformity were performed. Time spent, accuracy, surgeons' rating (Visual Analogue Scale [VAS], 0–10 points) were recorded and analysed. Time spent included

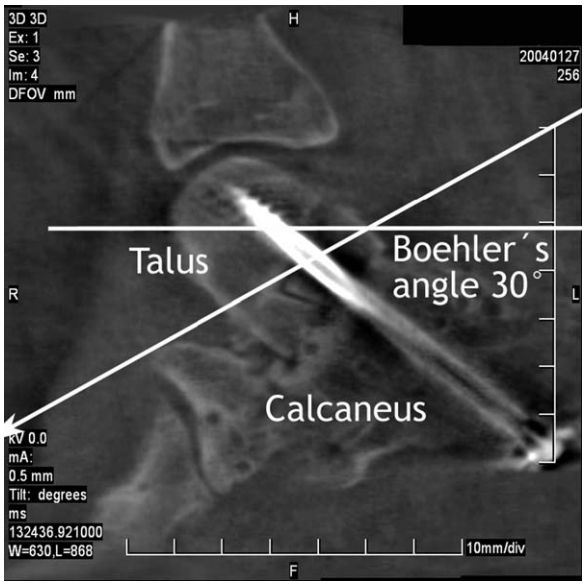

Fig. 6. Same patient as Figs. 1 and 5. Intraoperative imaging with ISO-C-3D (Siemens, Germany) after correction and screw fixation with bone blocks in the subtalar joint. The achieved Boehler's angle was 30°. For the measurement of the Boehler's angle, the formerly posterior edge of the posterior facet was defined as the point located at the middle, i.e. the half height of the posterior rim of the posterior bone block.

the preparation (connecting and turning on of the devices, placement of the DRB, image acquisition, verification) and the correction process. The translations and angles of the preoperative planning were measured by one of the surgeons involved in the study (MR) together with a radiologist on preoperative CT scan images with the software that was installed on the computer used in the radiology department for CT scan evaluation. The accuracy of the corrections was assessed after the correction and the internal fixation by intraoperative C-arm and a new C-arm based three-dimensional imaging device use (ISO-C-3D, Siremobile™, Siemens Inc., Germany). The ISO-C-3D-images were assessed and measured by one of the co-investigators (SZ) who was not involved in the planning or the surgical procedures. These measurements were performed with the software that was installed on the ISO-C-3D. The accuracy was analyzed by a comparison of the achieved angles and translations with the pre-operative planning (Table 1). A

Table 1
Case description and accuracy analysis

No.	Type of correction arthrodesis	Deformity	Planned correction	Achieved correction	Difference planned/achieved correction $^{\circ}$ mm^{-1} (%)
1	Ankle	Fixed talus equinus 10° Fixed talus varus 4° Talus lateral shift 6 mm	Talus dorsal extension 10° Talus valgisation 4° Talus medial shift 6 mm	Talus equinus 1° Talus varus −1° Talus lateral shift −1 mm	1° (10%) 1° (25%) 1 mm (17%)
2	Ankle	Fixed talus equinus 16° Fixed talus valgus 8° Talus ventral shift 10 mm	Talus dorsal extension 16° Talus varisation 8° Talus dorsal shift 10 mm	Talus equinus −1° Talus valgus 0° Talus ventral shift 1 mm	1° (6%) 0° (0%) 1 mm (10%)
3	Ankle	Fixed talus equinus 12° Talus dorsal shift 10 mm	Talus dorsal extension 12° Talus ventral shift 10 mm	Talus equinus 0° Talus dorsal shift 1 mm	0° (0%) 1 mm (10%)
4	Subtalar joint (Figs. 4–6)	Talo-calcaneal angle 5° Boehler's angle 0° Calcaneus varus 10°	Increase of talo-calcaneal angle 30° Increase of Boehler's angle 30° Calcaneus valgisation 10°	Talo-calcaneal angle 34° Boehler's angle 30° Calcaneus varus 0°	1° 0° (0%) 0° (0%)
5	Subtalar joint	Talo-calcaneal angle −5° Boehler's angle −12° Calcaneus varus 8°	Increase of talo-calcaneal angle 35° Increase of Boehler's angle 32° Calcaneus valgisation 8°	Talo-calcaneal angle 30° Boehler's angle 21° Calcaneus varus −1°	0° (0%) 1° (5%) 1° (13%)
6	Subtalar joint	Talo-calcaneal angle 12° Boehler's angle 2° Calcaneus valgus 10°	Increase of talo-calcaneal angle 28° Increase of Boehler's angle 28° Calcaneus varisation 10°	Talo-calcaneal angle 40° Boehler's angle 30° Calcaneus valgus 0°	0° (0%) 0° (0%) 0° (0%)
7	Subtalar joint	Talo-calcaneal angle 20° Boehler's angle 12° Calcaneus varus 22°	Increase of talo-calcaneal angle 20° Increase of Boehler's angle 18° Calcaneus valgisation 22°	Talo-calcaneal angle 40° Boehler's angle 31° Calcaneus varus 21°	0° (0%) 1° (3%) 1° (5%)
8	Subtalar joint	Talo-calcaneal angle 10° Boehler's angle 3° Calcaneus valgus 12°	Increase of talo-calcaneal angle 30° Increase of Boehler's angle 27° Calcaneus varisation 12°	Talo-calcaneal angle 39° Boehler's angle 30° Calcaneus valgus 0°	1° 0° (0%) 0° (0%)
9	Subtalar joint	Talo-calcaneal angle 15° Boehler's angle 10° Calcaneus varus 15°	Increase of talo-calcaneal angle 20° Increase of Boehler's angle 20° Calcaneus valgisation 15°	Talo-calcaneal angle 35° Boehler's angle 30° Calcaneus varus 0°	0° (0%) 0° (0%) 0° (0%)
10	Ankle and subtalar joint	Fixed talus equinus 10° Fixed talus varus 4° Talus dorsal shift 12 mm Talo-calcaneal angle 15° Boehler's angle 10° Calcaneus varus 12°	Talus dorsal extension 10° Talus valgisation 4° Talus ventral shift 12 mm Increase of talo-calcaneal angle 25° Increase of Boehler's angle 20° Calcaneus valgisation 12°	Talus equinus 0° Talus varus −1° Talus dorsal shift 1 mm Talo-calcaneal angle 39° Boehler's angle 30° Calcaneus varus 0°	0° (0%) 1° (25%) 1 mm (8%) 1° 0° (0%) 0° (0%)
11	Ankle and subtalar joint	Fixed talus equinus 5° Fixed talus varus 4° Talus dorsal shift 10 mm Talo-calcaneal angle 5° Boehler's angle 0° Calcaneus varus 10°	Talus dorsal extension 5° Talus valgisation 4° Talus ventral shift 10 mm Increase of talo-calcaneal angle 30° Increase of Boehler's angle 30° Calcaneus valgisation 10°	Talus equinus 0° Talus varus −1° Talus dorsal shift 1 mm Talo-calcaneal angle 35° Boehler's angle 30° Calcaneus varus 0°	0° (0%) 1° (25%) 1 mm (90%) 0° (0%) 0° (0%) 0° (0%)
12	Lisfranc joint 15°	Forefoot abduction 20° Forefoot dorsal ext. 18° (Talo-metatarsal axis 18°) Forefoot lateral shift 8 mm	Forefoot adduction 20° Forefoot plantar flex. 18° (Talo-metatarsal axis 18°) Forefoot medial shift 8 mm	Foerefoot abduction 1° Forefoot dorsal ext. 1° (Talo-metatarsal axis 1°) Forefoot lateral shift 1 mm	1° (5%) 1° (6%) 1 mm (13%)

Only the most significant measurements are shown.

maximum deviation of 1 mm for translations or 1° for angles was considered to be an excellent accuracy. The surgeons' rating was recorded by interview directly after the operative procedure. Three assessments were requested (feasibility, accuracy, clinical benefit). The used VAS scale itself is valid and reliable, and the used questions were used before [37–39].

3. Results

3.1. Patients and deformities

Twelve patients were included (ankle correction arthrodesis, $n = 3$; subtalar joint correction arthrodesis, $n = 6$; ankle and subtalar joint correction arthrodesis, $n = 2$; Lisfranc joint correction arthrodesis, $n = 1$) (Table 1). All isolated subtalar joint deformities were caused by calcaneus malunion. Four of these deformities were classified type III (Cases no. 4, 5, 7 and 9), and two type II (Cases no. 6 and 8) (Table 1) [20].

The ankle arthodeses included fixation with four screws and cancellous bone autograft from the ipsilateral proximal tibia. The isolated subtalar joint arthrodeses were fixed with two screws and tricortical bone block autografts from the ipsilateral anterior pelvic rim were used (e.g. Fig. 6). For the combined ankle and subtalar joint arthrodeses, cancellous bone autograft from the ipsilateral pelvic rim was used for the ankle, tricortical bone block autografts from the ipsilateral anterior pelvic rim were used for the subtalar joint, and the stabilization was performed with a retrograde calcaneal-talar-tibial locking nail. The Lisfranc arthrodesis was stabilized with two plates for the first and second ray, screws for the third to fifth ray and and cancellous bone autograft from the ipsilateral proximal tibia.

3.2. Time spent for CAS

The average time needed for preparation, including the placement of the two DRBs, scanning time and preparation on the screen for the correction was 500 s (400–900). The correction process took 45 s (30–60).

3.3. Accuracy

All planned angles and translations were exactly achieved as planned before surgery (deviation from planned correction less than $\pm 1°/\pm 1$ mm for angles/translations) (Table 1). The average planned correction was 16.7°/mm (range, 4–35°/mm; standard deviation, 9.3), and the average achieved correction was 16.6°/mm (range, 5–35°/mm; standard deviation, 9.3). The average difference between the achieved and the planned correction was 0.46°/mm (range, −1 to 1°/mm; standard deviation, 0.5), or 5.0% (range, 0–25%; standard deviation, 7.3). The planned correction was achieved on average 95.0% (range, 75–100%; standard deviation, 7.3). For the correction of the subtalar joint alone (cases 4–11), the planned correction was achieved on average 98.6% (range, 87.5–100%; standard deviation, 3.0).

3.4. Surgeons' rating

The ratings of the three surgeons were feasibility, VAS 9.5 (9–10); accuracy 9.8 (9.5–10); clinical benefit 9 (8–10).

4. Discussion

Foot and ankle surgery at the end of the 20th century was characterized by the use of sophisticated computerized preoperative and postoperative diagnostic and planning procedures [23,24]. However, intraoperative computerized tools that assist the surgeon during his or her struggle for the planned optimal operative result are missing. This results in an intraoperative "black box" without optimal visualization, guidance and biomechanical assessment [24]. The future will be characterized by breaking up this intraoperative "black box". We will have more intraoperative tools to achieve the planned result [24].

Intraoperative three-dimensional imaging (ISO-C-3D), computer assisted surgery (CAS) and intraoperative pedography (IP) are three possible innovations to realize the planned procedure intraoperatively [24]. These novel methods are in clinical use at our institution for further development.

In this study, the first clinical experiences with a computer assisted surgery based (CAS) guided correction at ankle, hindfoot and midfoot were evaluated.

4.1. Time spent

The time spent was less than 10 minutes for preparation. The correction process itself was very fast, especially regarding the problems with the conventional C-arm based correction [10]. In our experience, the correction without CAS guidance needs more time because of the necessary frequent C-arm controlling [40]. However, we found no exact data from other groups in the literature about the time spent on the correction process in comparable cases.

4.2. Accuracy

We were surprised by the high accuracy of the CAS guided correction. Despite pre-operative planning correction is sometimes limited by soft tissues and other restraints [7,10,11,20–22]. Still, the surgeons involved in this study were always able to achieve the pre-operative planning goals intraoperatively. The complex deformities involved in this study had bony abnormalites which were not correctable with the CAS system and not exactly measureable with the ISO-C-3D system (e.g. widening of the lateral wall of the

calcaneus). These components of the deformities were *assessed* but not *measured* with a pre-operative CT and, after the correction, with an intraoperative ISO-C-3D scan (data not shown). A *measurement* of these components of for example the widening of the lateral wall of the calcaneus has not been performed in any other study as far as we know. Since we were able to *measure* the main components of the deformities and the correction, we renounced to report weak *assessment* data. We are aware of the problems in measuring angles on images as other authors [10,11,16,21,41]. To avoid these problems in our study, the angles and translations were measured digitally on the computer that was involved in obtaining the images, either preoperative CT or intraoperative ISO-C-3D. The correction–accuracy was measured by a co-investigator who was not involved in the planning and the surgical procedures images which were made *intraoperatively*. A re-evaluation of the ''remaining'' accuracy at a later stage is missing so far. The same is true for a clinical follow-up of the subjects involved in this study. This follow-up study is currently in progress to assess the potential benefit of the introduced method for the patient. We have planned a follow-up time of at least 2 years. Therefore, we would like to report the preliminary results without follow-up now.

We could not isolate data from the literature regarding measurements of the difference of the pre-operatively planned versus the achieved corrected angles and translations with conventional correction without [10,11,16,21,41]. Even in own previous data from conventional arthrodesis of the subtalar joint, we could not work out such because the planned correction was not recorded [40]. Rammelt et al. indirectly reported a difference between the planned and the achieved correction in correction arthrodeses of the subtalar joint [11]. They described that the measurements of the unaffected side were used as a template for the planning of the correction [11]. These measurements, i.e. the planned corrections, were achieved 38.5–61.8% for the different measurements [11]. In our study the planned correction was achieved 75–100% (mean, 95.0%) for all types of correction arthrodesis, and 87.5–100% (mean, 98.6%) for correction arthrodeses of the subtalar joint. Regarding the higher percentages in our study, a sufficient comparison of the conventional correction without CAS and CAS guided correction in one single randomized controlled study is missing so far.

4.3. Surgeons' rating

The rating of the surgeons with the VAS scale shows only the surgeon's impression of feasibility, accuracy and clinical benefit after the operation. We have no data to compare time spent and accuracy.

Based on the results of this study, we state that CAS is helpful in complex three-dimensional corrections or reduction, and in closed placement of drillings and/or screw positioning [24,36]. The significance of the introduced CAS-methods might be high in those cases, because the improved accuracy may lead to an improved clinical outcome like complex corrections in the hind- and midfoot deformities [7,10,12–19,42]. CAS is too complex and time consuming for all those cases that are accurately and easily performed by the experienced surgeon.

For the future, the integration of the different computerized systems will improve the handling and clinical feasibility. An integration of pre-operative pedography, planning software, CAS, ISO-C-3D and intraoperative pedography (IP) in one integrated computer system for operative procedures (ICOP) will be favorable. Within this kind of ICOP, the pre-operative computerized planning will be able to include pre-operative radiographic, CT, MRI and pedography data. The pre-operative computerized planning result will be transferred to the CAS device. The CAS-system will be guided by biomechanical assessment with IP that allows not only morphological but also biomechanical based CAS. The intraoperative three-dimensional imaging (ISO-C-3D) data and the IP-data will be matched with the data from the planning software to allow immediate improvements of reduction, correction and or drilling/implant position in the same procedure [24].

In conclusion C-arm based CAS guided correction of posttraumatic deformities of the ankle and hindfoot region is feasible and provides very high accuracy and a fast correction process [24]. The significance of the introduced method is high in those cases, because the improved accuracy may lead to an improved clinical outcome [7,10,12–19,42]. Further studies including clinical outcome assessment will show if the patient will profit from this novel method.

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