Computer based systems in foot and ankle surgery at the beginning of the 21st century

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Der Einsatz von Computersystemen in der Fuß- und Sprunggelenkschirurgie zu Beginn des 21. Jahrhunderts


Schlussfolgerungen ISO-C-3D kann im Fußbereich wertvolle Informationen bieten, die mit einem herkömmlichen C-Arm allein nicht erbracht werden können. Der Nutzen der vorgestellten CAS-Methoden ist dann besonders hoch, wenn eine höhere Genauigkeit ein besseres Ausheilungsergebnis erwarten lassen. IP kann sinnvoll sein, wenn eine intraoperative biomechanische Evaluation zu einer Verbesserung des chirurgischen Ergebnisses führen kann.


Schlüsselwörter Computer Assistierte Chirurgie (CAS) – Intraoperative Pedographie – Fußchirurgie – Computer system für Operative Prozeduren (ICOP)
Summary  Purpose At the beginning of the 21st century the computer has supplemented the possibilities of orthopedic surgery. This article analyzes the current feasibility and potential clinical benefit of computer use for foot and ankle surgery.

Methods The experimental evaluation and clinical use of the following different options of computer use for foot and ankle in a level one trauma center were analyzed: intraoperative three-dimensional imaging with a mobile motorized C-arm (ISO-C-3D), CT-based Computer Assisted Surgery (CAS), ISO-C-3D-based CAS, C-arm-based CAS, and Intraoperative Pedography (IP).

Results ISO-C-3D: Intraoperative three-dimensional imaging with an ISO-C-3D was used in 101 cases. In 39% of the cases, reduction and/or implant position was corrected after ISO-C-3D-scan during the same procedure. The operation was interrupted for ISO-C-3D use for 430 seconds on average.

CAS: CAS was used for retrograde drillings in osteochondral defects of the talus and for correction of ankle and hindfoot deformities. CAS-guided retrograde drilling in osteochondral defects worked without problems and accurate in all ten cases that were included. The CAS-guided correction of posttraumatic deformities of the ankle and hindfoot region was feasible and provided very high accuracy and a fast correction process in the ten cases so far.

IP: For an intraoperative introduction of standardized forces to the footsole, a device named “Kraftsimulator Intraoperative Pedographie” (KIOP, manufactured in the Workshop of the Hannover Medical School, Hannover, Germany; Registered Design No. 20 007 755.8 by the German Patent Office, Munich, Germany) was developed. During a validation process, no statistically significant differences were found between the measurements of the introduced method for IP in anesthesized individuals and the standard dynamic and static pedography. The introduced method is valid for IP.

Conclusion The ISO-C-3D provides important information which could not be obtained from plain films or C-arm alone. The benefit of the introduced CAS methods is high when improved accuracy can lead to an improved clinical outcome. IP will be useful for all those cases in which intraoperative biomechanical assessment may lead to an immediate improvement of the achieved surgical result. In the future, computerized methods for improved intraoperative imaging, guidance and biomechanical assessment will help to realize the planned operative result. The integration of the different computerized systems into one Integrated Computer System for Operative Procedures (ICOP) will improve the handling and clinical feasibility.

Key words Computer assisted surgery (CAS) – intraoperative pedography – foot and ankle trauma – foot and ankle reconstruction – integrated computer system for operative procedures (ICOP)

Introduction

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 [13, 46]. However, intraoperative computerized tools that assist the surgeon during his or her struggle in achieving the planned optimal operative result did not exist. An intraoperative “black box” without optimal visualization, guidance and biomechanical assessment remains [46]. The future will be characterized by opening up this intraoperative “black box”. We will have more intraoperative tools to better achieve the planned result [46].

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. These novel methods are in clinical use at our institution for further development. This article analyzes the feasibility and potential clinical benefit of this kind of computer use for foot and ankle surgery.

Intraoperative three-dimensional imaging (ISO-C-3D)

In foot and ankle trauma care, malposition of extraosseous or intra-articular screws, and gaps or steps in joint lines frequently remain undiscovered when using intraoperative fluoroscopy, and are only recognized on postoperative computed tomography (CT) scans [18]. Earlier preclinical studies showed that evaluation of reduction and implant position with a new C-arm-based three-dimensional imaging device (ISO-C-3D) is better than with plain films or C-arm alone and comparable to CT scans [18, 34–36, 49, 50].

A prospective consecutive clinical study was performed at a level one trauma center. The aim of the study was to evaluate the feasibility and benefit of the intraoperative use of the ISO-C-3D for foot and
ankle trauma care in this special environment. The hypothesis was that the ISO-C-3D could detect failures of reduction or implant position that had not been detected with a conventional C-arm in a considerable percentage.

ISO-C-3D (Siemens Inc., Germany) is a motorized C-arm that provides fluoroscopic images during a 190 degree orbital rotation computing a 119 mm data cube (Fig. 1a). From these 3D data sets two-dimensional and multiplanar reconstructions can be obtained on the screen of the device without delay (Fig. 1b). Patients with foot and ankle trauma or reconstruction surgery that were treated at our institution between January 1, 2003 and December 31, 2004 were considered for inclusion in the study. Before the use of the device, the reduction and implant position had to be judged to be correct by the surgeon using a conventional C-arm. The patients were either placed on a special metal-free carbon table or on a standard table. Time spent, changes after use of the ISO-C-3D and surgeons’ ratings (visual analogue scale, VAS, 0–10 points) were recorded. The surgeons’ ratings for image quality for the carbon table and the standard table were compared (t-test, significance level 0.05). The surgeons’ ratings for image quality for the carbon table and the standard table were compared (t-test, significance level 0.05).

> Patients A total of 101 patients/cases (no bilateral ISO-C-3D use) were included (fractures: pilon, n=15; Weber-C ankles, n=12; isolated dorsal Volkmann, n=3; talus, n=7; calcaneus, n=32; navicular, n=2; cuboid, n=2; Lisfranc fracture dislocation, n=8; ankle/hindfoot arthrodesis with or without correction, n=4/16).

> Table use Carbon table, n=80 (79%); a standard table, n=21 (21%).

> Time spent The operation was interrupted for 430 seconds on average (range, 300–700 s); 100 seconds on average for preparation, 120 seconds on average for the ISO-C-3D-scan and 210 seconds on average for evaluation of the images by the surgeon.

> Changes after ISO-C-3D use In 39% (39 of 101) of the cases, the reduction (n=16, 16%) and/or implant position (n=30, 30%) was corrected after the ISO-C-3D scan during the same procedure.

> Surgeons’ rating The ratings of the eight surgeons involved were 9.2 (5.2–10) for feasibility, 9.5 (6.1–10) for accuracy and 8.2 (4.5–10) for clinical benefit. The image quality was rated 9.1 (8.0–10) for the carbon tables, and 8.7 (7.0–10) for the standard tables (difference rating carbon table versus standard table, t-test, p>0.05). Figure 2 shows a clinical example. In almost 40% of cases in this study, reduction and/or implant position was corrected after the ISO-C-3D scan during the same procedure. The radiation exposure is comparable to a standard CT scan and corresponds to 39 seconds fluoroscopy time with a modern digital C-arm. The image quality with a carbon table was not judged to be better than with a standard table. Consequently, the use of a carbon table is not necessary for the ISO-C-3D scan of the foot region.

In conclusion, the intraoperative three-dimensional visualization with the ISO-C-3D can provide important information in foot and ankle trauma care that cannot be obtained from plain films or a C-arm.
alone [47]. The use is not considerably time consuming. The ISO-C-3D is extremely useful in evaluating reduction and/or implant position intraoperatively and can replace a postoperative CT scan.

**Computer assisted surgery (CAS)**

- **CT-based CAS**

The accuracy of the reduction in hind- and midfoot fractures and fracture-dislocations correlates with the clinical result [1, 4, 10, 23, 25, 48, 59, 71, 72]. The same is true for the correction of hind- and midfoot [2, 12, 33, 39, 42, 53, 58, 65, 68, 71]. However, an accurate correction or reduction with the conventional C-arm based procedure is challenging [5, 67, 71]. CT based computer assisted surgery (CAS) has become a valuable tool for the correction and reduction in other body regions [6, 11, 14–16, 20–22, 24, 26–28, 30–32, 37, 38, 40, 41, 43, 44, 55, 63, 64, 69]. Especially a more exact reduction could be achieved [6, 9, 14, 26–28, 32, 37, 38, 41, 44, 54, 56, 61, 64]. CT based CAS may also be useful for the correction of hind- and midfoot deformities and for the reduction in hind- or midfoot fractures and fracture-dislocations, although it has not been used in the foot region so far [7]. The purpose of an experimental study at our institution was to compare CT based CAS assisted correction of hind- and midfoot deformities with C-arm based correction [45].

Sawbone™ (Pacific Research Laboratories, Vashon, WA, USA) specimen models “Large Left Foot/Ankle”, “Large Left Foot/Ankle With Equinus Deformity”, “Large Left Foot/Ankle With Calcaneus Malunion”, “Large Left Foot/Ankle With Equinovarus Deformity” were used. A CT scan of each deformity specimen model (n=3) was performed. The goal of the correction was to transform the shape of the pathology specimen models into the shape of the normal specimen model. Two methods were used for the correction, a) a conventional C-arm-based correction and b) a CAS (CT based, Surgigate™, Medivision, Oberdorf, Switzerland & Northern Digital Inc., Waterloo, Ontario, Canada) based correction. Five specimens of each deformity model were corrected with each method. Standardized osteotomies were performed before the correction when necessary (in models with calcaneus malunion and equinovarus). The surgeon's direct view to the specimens was avoided by drapes. During the correction procedure, the visualization of the specimen was exclusively provided by the image of the C-arm or the CAS device. Retention was performed with 1.8 mm titanium K-wires. The following parameters were registered: time needed for the entire procedure and the different steps of procedure, time of fluoroscopy, foot length, length and height of longitudinal arch, calcaneus inclination, hindfoot angle for all models (n=30) and additionally Boehler’s angle, calcaneus length for the “Calcaneus Malunion” specimen models (n=10). The shape of the corrected specimen was graded as normal, nearly normal, abnormal, or severely abnormal. The parameters of the two correction method groups (CAS vs. C-arm) were statistically compared (t- and Chi²-tests). According to the specimen measurements, the differences between the corrected specimen models and the normal specimen models were also compared.

The shape was graded normal in all specimens (n=15) in the CAS group, and in eight of the specimens in the C-arm group (other grades in C-arm group: nearly normal, n=6, abnormal, n=1, Chi²-test, p=0.05). The time needed for the procedure was longer in the CAS group, and the fluoroscopy time was shorter in the CAS group than in the C-arm group (mean values and range shown, t-test util-
lized): time entire procedure, CAS, 782 (450–1,020) s, C-arm, 410 (210–600) s, p < 0.001; fluoroscopy time, CAS, 0 s, C-arm, 11 (8–19) s, p < 0.001. In three cases in the CAS group, the system crashed and was restarted (times for entire procedure in these cases 1,000, 1,010 and 1,020 s).

The measurement differences between the corrected specimens and the normal specimen model were as follows (mean values and standard deviation shown, t-test utilized): foot length, CAS, −1.7 ± 1.9 mm, C-arm, −4.1 ± 3.8 mm, p = 0.03; length of longitudinal arch, CAS, −0.9 ± 0.9 mm, C-arm, −5.6 ± 4.9 mm, p = 0.001; height of longitudinal arch, CAS, −0.1 ± 0.5 mm, C-arm, −0.1 ± 0.5 mm, p = 0.14 calcaneus inclination, CAS, 0.1 ± 1.4°, C-arm, 2.7 ± 4.8°, p = 0.03; calcaneus length, CAS, −0.5 ± 0.4 mm, C-arm, −2.8 ± 1.3 mm, p = 0.005; Boehler’s angle, CAS, 0.4 ± 1.1°, C-arm, 4.1 ± 8.6°, p = 0.37. When further analyzing the correction in the different pathology specimen models, the highest differences (lowest t values) between the CAS group and the C-arm group were observed in “Calcaneus Malunion” specimen model, followed by the “Equinus Deformity” and the “Equinovarus Deformity” specimen models.

In conclusion, in an experimental setting, CT based CAS provided higher accuracy for the correction of hind- and midfoot deformities than the C-arm based correction [45].

The reasons for the double time needed with CT based CAS in comparison with the C-arm based method are the requirements of the data transfer of the DICOM data of the preoperative CT scan to the CAS device and especially the very time consuming matching process during the registration procedure. The main problems with the matching are based on the difficult bony architecture of the foot with 28 bones and more than 30 joints. Due to these anatomic conditions, the foot does not regularly maintain its complete integrity and position during the preoperative CT and the registration. This makes the registration in the foot much more difficult than in other body regions like the spine or the pelvis with fewer and larger bones and joints [7, 16, 20, 26, 38, 41]. In the clinical application of CT-based CAS of the foot, the problems with the registration will still increase, although the soft tissue coverage is favorably thin. When the registration was finally finished, the CT-based CAS as used in our study was more accurate and even easier and faster than the conventional C-arm, but the problems with the registration will prevent broad clinical use. Fortunately, while this experimental study was planned and being performed, two CAS methods without registration were intended: the C-arm-based CAS and the ISO-3D based CAS. These CAS methods without registration are especially interesting for the foot region. Clinical studies must show if these registration-free methods can achieve the high accuracy of the CT based CAS in real operations, and if this leads to better clinical results.

**ISO-C-3D-based CAS**

ISO-3D was used for the treatment of osteochondrale defects of the talus. The goal in osteochondral defects of the talus in stages I and II according to Berndt and Harty is revascularization of the lesion [8]. A debridement of the chondral part is required if symptomatic [3, 62]. This debridement is limited to loose cartilage or cartilage with poor quality [3, 60, 62].

Subchondral drilling of the lesion allows revascularization. Retrograde drillings leave the chondral surface intact and is therefore advantageous com-
pared with antegrade drillings [19]. Arthroscopically
guided drillings are limited to those lesions that
could be arthroscopically identified [60]. In the re-
mainin cases, open procedures are justified [57].
Based on these principles, CT-based computer as-
isted surgery (CAS) guided retrograde drilling of
osteochondral lesions has been described with
promising results as a new technique [19, 52]. Com-
puted tomography (CT)- and fluoroscopy-based nav-
igation systems in current use are limited in their
flexibility [45]. The drawback of fluoroscopy is the
lack of intraoperative three-dimensional imaging.
CT-based navigation still requires cumbersome in-
traoperative registration, extra preoperative plan-
ing, and imaging with further technical resources.

In addition to the current method of arthroscopic
evaluation and treatment, we also introduce an alter-
native technique of using an ISO-C-3D-based CAS
guided retrograde drilling of the lesion.

All retrograde drillings in osteochondral defects
of the talus in stadium II according to Berndt and
Harty of the talus between June 1, 2003 and Decem-
ber 31, 2004 in a level 1 trauma center were per-
formed with the described method (see below). Time
spent, accuracy, problems, surgeons’ rating (Visual
Analogue Scale [VAS], 0–10 points) were recorded
and analyzed. The accuracy of the drillings were as-
essed by ISO-C-3D.

**Technical background** An ISO-C-3D (description
above, Fig. 1) was connected to a navigation system
(Surgigate™, Medivision, Oberdorf, Switzerland &
Northern Digital Inc., Waterloo, Ontario, Canada).
After fixation of a Dynamic Reference Basis (DRB)
to the bone (Fig. 4a), an ISO-C-3D scan follows
(Fig. 3b). The data are transferred to the navigation
system. The starting and end point, direction and
length of the drilling is planned on the screen of the
navigation system using the standard software. A
trajectory for the following drilling is placed in the
virtual bone on the screen. The drilling is performed
with a modified navigated electrical power drilling
machine (Powerdrive, Synthes Inc., Bochum, Ger-
many, Fig. 4a, b). The direction and length of the
drilling is shown on the monitor of the navigation
device. Standard fluoroscopy is not needed during
the entire procedure.

**Patients** Ten patients (n=6 at lateral talar
shoulder; n=4 at medial talar shoulder) were treated
with ISO-C-3D-based CAS guided retrograde dril-
ling.

**Time spent** Time needed for preparation, includ-
ing the placement of the DRB, scanning time and
preparation of the trajectories was 580 s (500–750 s).

**Accuracy** All drillings were in the correct position.

**Problems** In 1 (20%) case an error during the
data-transfer occurred and the scan had to be per-
formed twice.

**Surgeons’ rating** Feasibility, VAS 9.2 (7.3–10); Ac-
curacy 9.8 (8.1–10); Clinical Benefit 9.2 (7.4–10).

The ISO-C-3D-based CAS worked without problems
in the described cases. However, the handling of the
system is very complex. During the development pro-
cess, the systems were very trouble-prone due to com-
puter control failures. To date, the introduced system is reliable and in frequent use at our department for surgical procedures in different body regions.

Another important issue are the device costs, which are much higher for the ISO-C-3D-based CAS (approximately 500,000 Euro) than for arthroscopy systems. These tremendous device costs for the ISO-C-3D-based CAS will prevent standard use for retrograde drilling in osteochondral lesions of the talus alone despite the advantages. However, the ISO-C-3D-based CAS is also useful for other body regions like the spine and pelvis. Furthermore, the ISO-C-3D alone is a valuable tool for intraoperative three-dimensional visualization.

Radiation protection for the patient and personnel is another essential topic. The radiation of an ISO-C-3D-based CAS guided drilling procedure is of course higher compared with arthroscopically based drilling. However, the ISO-C-3D-based CAS procedures produce less radiation than all conventional C-arm-based procedures and CT-based CAS.

The advantages of the introduced technique are an actual and almost real-time intraoperative three-dimensional imaging for the use of navigation without the need for anatomical registration and an immediate intraoperative control of surgical treatment [46]. Our results reveal that ISO-C-3D-based computer assisted surgery (CAS) guided retrograde drilling is an alternative to arthroscopically guided or open drilling for osteochondral lesions of the talus.

C-arm-based CAS

Posttraumatic ankle and hindfoot deformities are not uncommon after complex trauma of the ankle and hindfoot [1, 4, 10, 23, 25, 48, 59, 71, 72]. The biomechanical consequences of these deformities frequently lead to clinical symptoms like pain and gait disturbances [2, 12, 33, 39, 42, 53, 58, 65, 68, 71]. The correction of the deformities is challenging [5, 67, 71]. The preoperative diagnostic with radiographs and CT allows accurate planning of the correction even with computerized planning systems [13]. However, during the operative procedure the realization of the planned correction is difficult, because the correction process is performed by the surgeon without guidance. Thus, a C-arm-based CAS guided correction was developed. In this feasibility study, the first clinical experiences were analyzed.

Patients with posttraumatic deformities of the ankle or subtalar joint with deformity (malalignment) that were treated at our institution between June 1, 2003 and December 31, 2004 were considered for inclusion. C-arm-based CAS guided arthrodeses with correction of the deformity were performed. Time spent, accuracy, problems, surgeons’ rating (Visual Analogue Scale [VAS], 0–10 points) were recorded and analyzed. The accuracy of the corrections was assessed by a new C-arm-based three-dimensional imaging device (ISO-C-3D).

Technical background

A navigation system with wireless Dynamic Reference Bases (DRB) was used (VectorVision™, BrainLAB Inc., Kirchheim-Heimstetten, Germany). The system was connected with a

Fig. 5 C-arm-based computer assisted surgery (CAS). C-arm-based CAS guided correction of hindfoot deformity after malunited calcaneus fracture. Fixation of a wireless Dynamic Reference Base (DRB) to the talar neck and the tuber calcanei. Image acquisition with a modified digital C-arm (a). Anteroposterior and lateral digital radiographic images were obtained, and the data were transferred to the navigation device. 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 (b). Furthermore, virtual radiographs with the moving bones or fragments were displayed on the screen.
modified C-arm (Exposcope™, Instrumentarium Imaging Ziehm Inc., Nürnberg, Germany, Fig. 5a). One DRB was fixed to each of the two bones or fragments that had been planned for correction in relation to each other. With the C-arm, anteroposterior and lateral digital radiographic images were obtained, and the data were transferred to the navigation device. 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. 5b). Furthermore, virtual radiographs with the moving bones or fragments were displayed on the screen. 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 (Siemens Inc., Germany). Finally screw fixation followed. The insertion of the screws was also C-arm-based CAS guided (data not shown, extra abstract).

► Patients Ten patients were included (ankle correction arthrodesis, n=3; subtalar correction arthrodesis, n=6; Lisfranc correction arthrodesis, n=1).

► Time spent 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 s). The correction process took 45 s (30–60 s).

► Accuracy All planned angles and translations were exactly achieved as planned (deviation from planned correction less than ±1° for angles or ±1 mm for translations).

► Surgeons’ rating Three surgeons were involved. Feasibility, VAS 9.5 (9–10); Accuracy 9.8 (9.5–10); Clinical Benefit 9 (8–10).

The feasibility of the introduced method is favorable. The time spent is less than 10 minutes for preparation. The correction process is very fast and extremely accurate, especially regarding the problems with the conventional C-arm-based correction. In our experience, the correction without CAS guidance needs more time because frequent controlling with a C-arm is necessary.

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 [46]. The significance of the introduced method is high in those cases, because the improved accuracy may lead to an improved clinical outcome [2, 7, 12, 33, 39, 42, 53, 58, 65, 68, 71]. Further studies will show if the patient will benefit from this novel method.

### Intraoperative pedography (IP)

For any kind of reduction or correction at the foot and ankle an immediate biomechanical assessment of the reduction result would be desirable [2, 12, 33, 39, 42, 53, 58, 65, 68, 71]. This is especially true for a CAS guided reduction or correction, which is supposed to be more accurate than a conventional reduction [46]. The reduction or correction control is normally performed with a C-arm or an ISO-C-3D if available [45, 46]. Analyzing the position of the bones radiographically allows conclusions to be made about the biomechanics of the foot [70, 71]. However, pedography is considered to be more effective for the analysis of the biomechanics of the foot [51]. So far, pedography for biomechanical assessment was only available during clinical follow-up [46]. An intraoperative pedography (IP) would be useful for immediate intraoperative biomechanical assessment [46]; thus a new device was developed. First, a feasibility study was performed and then the newly introduced method was compared with standard dynamic pedography.

For an intraoperative introduction of standardized forces to the foot sole, a device named the Kraftsimulator Intraoperative Pedographie (KIOP, manufactured at the Workshop of the Hannover Medical School, Hannover, Germany; Registered Design No. 20 2004 007 755.8 by the German Patent Office, Munich, Germany) was developed. The pedographic measurement is performed with a customized mat with capacitive sensors (PLIANCETM, Novel Inc., Munich, Germany). The system allows real-time pedography and comparison to the contralateral side. The measurements were performed in neutral ankle position. In this neutral ankle position, the influence of the missing muscle action in the anesthesized patient is considered to be minimal since the EMG in awake standing individuals with comparable ankle position is silent [17, 29, 66].

► Feasibility study During the first case the forces were applied in the neutral ankle position before and after a correction arthrodesis of the talonavicular joint after a malunited Chopart fracture-dislocation. For the first attempt only the forefoot region was measured. For the second case (correction arthrodesis of the calcaneocuboid joint), the entire foot region was measured with a customized mat (Figs. 6 and 7). When the introduced force increased
from 300 N to 400 N before the correction in case 1, the resulting force beneath the first and second metatarsal head also increased critically. After the correction arthrodesis, the critically increased force beneath the first and second metatarsal head was not present any more. In case 2, after the first attempt of the correction arthrodesis, a significant difference of the force distribution between the contralateral foot and the corrected foot occurred. The force under the 5th metatarsal head was significantly higher than at the contralateral side, resulting in an insufficient biomechanical result of the correction. In the same procedure, the correction arthrodesis was modified with a flattening of the longitudinal arch at the lateral column to decrease the overload under the 5th metatarsal head. The result was again analyzed with IP and a comparable force distribution with the contralateral side confirmed the improved biomechanical result.

**Validation** The validation was performed in two steps:

**Step 1.** Comparison of standard dynamic pedography (walking, third step, three trials, mid stance force pattern), static in standing position (three trials) and pedography with KIOP in healthy volunteers (three trials, total force 400 N). For dynamic pedography and pedography in the standing position, a standard platform (EMED™, Novel Inc., Munich, Germany) was used.

**Step 2.** Comparison of pedography in the standing position, pedography with KIOP in non-anaesthesized and anesthesized patients (three trials, total force 400 N). Patients with operative procedures performed at the knee or distal to the knee were excluded. Only patients with general or spinal anaesthesia were included.

In addition, a qualitative analysis was performed for both steps (Fig. 8). The analysis was focused on the force distribution and not on the force values. The relation of the forces of different regions as hindfoot, midfoot, forefoot (1st metatarsal, 2nd–4th metatarsal, 5th metatarsal), and medial versus lateral were compared. The different measurement and qualitative analyses were compared (t-test, One-way ANOVA).

The results of the validation process were as follows. **Step 1:** 30 individuals were included (age, 26.1±8.6 years; gender, male:female = 24:6). **Step 2:** 30 individuals were included (age, 55.3±30.3 years; gender, male:female = 24:6). No statistical significant differences were found for both steps between the methods, nor between the methods of step 1 and 2 (t-test & ANOVA, p > 0.05).

In conclusion, IP is feasible and valid since no statistical significant differences were found between
the measurements of the introduced method for IP in anesthesized individuals and the standard dynamic and static pedography. In the future, dynamic IP with registration of the entire foot sole is planned for an even more sophisticated biomechanical assessment [46]. In any case, IP is able to detect insufficient biomechanical behavior of the foot and may lead to modifications in the same procedure, and not after pedography in the office weeks or months later [46]. Further clinical studies are in progress to evaluate the clinical benefit of IP.
What do we need when?

A perfect surgeon who does not make any mistakes without any guidance does not need any of the introduced systems. However, the surgical staff involved in foot and ankle surgery consists of experienced surgeons as well as interns, residents and fellows in training. In times of increasing legal pressure regarding working hours, the acquisition of surgical experience is becoming more difficult. Tools for improved intraoperative imaging (ISO-C-3D), guidance (CAS) or biomechanical assessment (IP) may help the less experienced surgeon to achieve the planned result with less experience [46].

ISO-C-3D

The ISO-C-3D is most helpful in closed procedures and/or when axial reformations provide information that is not possible to obtain with a C-arm or with direct visualization. Weber-C fractures and calcaneus fractures are examples for these special situations. The ISO-C-3D is less helpful when easy visualization with a C-arm or under direct vision is possible as for example in Weber-B fractures during open reduction and internal fixation.

Computer assisted surgery (CAS)

CAS is helpful in complex three-dimensional corrections or reductions, and in closed placement of drillings and/or screw positioning [45, 46]. The significance of the introduced CAS methods is high in those cases, because the improved accuracy may lead to an improved clinical outcome like complex corrections in the hind- and midfoot deformities [2, 7, 12, 33, 39, 42, 53, 58, 65, 68, 71]. CAS is too complex and time consuming for all those cases that are accurately and easily performed by the experienced surgeon.

Intraoperative pedography (IP)

IP will be useful for all those cases in which biomechanical assessment may lead to an immediate improvement of the achieved surgical result [46]. The same cases that are currently analyzed with clinical pre- or postoperative pedography, will potentially profit from IP. The surgeons’ experience is also crucial for the use of IP, since experienced surgeons who do not use pedography in their office, may also not use it intraoperatively. IP as introduced was made possible by the newly developed device for intraoperative force introduction (Kraftsimulator Intraoperative Pedographie (KIOP), registered design no. 202004007755.8, German Patent Institute, Munich, Germany).

The future: Integrated computer system for operative procedures (ICOP)

For the future, the integration of the different computerized systems will improve the handling and clinical feasibility. An integration of preoperative pedography, planning software, CAS, ISO-C-3D and IP into one Integrated Computer System for Operative Procedures (ICOP) will be favorable. Within this kind of ICOP, the preoperative computerized planning will be able to include preoperative radiographic, CT, MRI and pedography data. The preoperative computerized planning result will be transferred to the CAS device. An intraoperative two-dimensional (C-arm) or three-dimensional (ISO-C-3D) imaging will allow registration-free CAS and will be matched with preoperative CT and or MRI images. 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 [46].

In conclusion, in the future computerized methods for improved intraoperative imaging, guidance and biomechanical assessment will help to realize the planned operative result [46]. The development will be similar to navigation systems in the car. A decade ago, many people doubted that we need these systems. Today almost everybody has a system, but of course no one uses them for short and easy routes but they are used for long and difficult journeys. Similarly, we will have these systems (ISO-C-3D, CAS, IP) available in a few years, but they will not be used in the easy standard case but for difficult and complex procedures. The costs of these systems are high, but the improved outcome will even decrease the overall costs for the medical system [46].

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