Computer aided surgery in foot and ankle: applications and perspectives

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Abstract

Purpose At the beginning of the twenty-first century, the computer has supplemented the possibilities of orthopaedic surgery. This article analyses the feasibility and potential clinical benefit of intraoperative three-dimensional imaging (3D), computer assisted surgery (CAS) and intraoperative pedography (IP) in foot and ankle surgery.

Methods The feasibility, accuracy and clinical benefit of 3D, CAS and IP were analysed in ongoing experimental and prospective studies at the institution in which the inventor of IP and principal user of 3D and CAS in foot and ankle surgery operates.

Results Three dimensional imaging: In approximately one third of the cases, reduction/correction and/or implant position was corrected after intraoperative 3D scan during the same procedure in different prospective, consecutive, non-controlled studies (Level III). CAS: CAS guidance for the correction of deformities of the ankle, hindfoot and midfoot/tarsometatarsal (TMT) joint provided higher accuracy, a faster correction process and better scores at a minimum follow-up of two years in comparison without CAS guidance in a single-centre matched-pair follow-up study (Level II). IP: Additional use of IP as the only difference between two groups with correction and/or arthrodesis at foot and/or ankle led to improved clinical outcome scores at a mean of two years follow-up in a prospective randomised controlled study (Level I).

Conclusions Three dimensional imaging provides important information which could not be obtained from two-dimensional C-arm alone. The benefit of CAS is high when improved accuracy may lead to an improved clinical outcome. Intraoperative pedography is useful when intraoperative

biomechanical assessment may lead to an immediate improvement of the achieved surgical result.

Introduction

Foot and ankle surgery at the end of the twentieth century was characterised by the use of sophisticated computerised preoperative and post-operative diagnostic and planning procedures [1, 2]. However, intraoperative computerised tools that assist the surgeon during his or her struggle for the planned optimal operative result are not available [1, 2]. This results in an intraoperative “black hole” without optimal visualisation, guidance and biomechanical assessment [1, 2]. The future will be characterised by breaking up this intraoperative black hole. We will have more intraoperative tools to achieve the planned result [1, 2].

Intraoperative three-dimensional imaging (3D), computer assisted surgery (CAS) and intraoperative pedography (IP) are three possible innovations to realise the planned procedure intraoperatively [1, 2]. These methods have been in clinical use at our institution for the last decade [1, 2]. This article analyses the feasibility and clinical benefit of this kind of computer use for foot and ankle surgery.

Intraoperative three-dimensional imaging

Background

When using intraoperative fluoroscopy in foot and ankle surgery, incorrect position of bones, bone fragments and/or implants frequently remains undiscovered and is only recognised on post-operative computed tomography (CT) scans [3–5]. A mobile C-arm with 3D imaging (ISO-C-3D, Siemens, Erlangen, Germany) has been developed to enhance the intraoperative recognition of problems with fracture reduction and fixation [4]. The conclusions of the first

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clinical experience using this device was that the intraoperative 3D visualisation with the ISO-C-3D could provide useful information in foot and ankle trauma care that cannot be obtained from plain films or conventional C-arms alone [4]. The ISO-C-3D appeared to be most helpful in procedures with closed reduction and internal fixation, and/or when axial reformations provide information that is not possible with a conventional C-arm and/or direct visualisation during open reduction and internal fixation (ORIF). The ISO-C-3D introduces the possibility of replacing a post-operative CT scan as two-dimensional images for documentation can also be performed [4]. The radiation contamination that corresponded to 39 seconds of fluoroscopy time with a conventional digital C-arm and the time spent with 440 seconds interruption of the surgical procedure have been criticised [4]. The second-generation device has been developed to minimise these problems and to improve handling. The aim of a second study was to assess the clinical use of the new device (ARCADIS-3D, Siemens) in comparison with earlier experience with the first-generation device (ISO-C-3D, Siemens). In this study, reconstructive procedures were also included in addition to trauma cases [3]. This clinical study was performed in a Level I trauma centre, which is also a university hospital (ISO-C-3D group, institution A), and a Level II trauma centre, which is also a university teaching hospital (ARCADIS-3D group, institution B). The surgical staff involved in the study consisted of experienced orthopaedic surgeons as well as interns, residents and fellows in training. The devices were always used after reduction/correction and positioning of implants had been judged to be correct by the surgeon using a conventional C-arm. When incorrect reduction and/or implant positions were detected with the conventional C-arm, a correction of the reduction/correction and/or implant was performed.

Technical equipment

ISO-C-3D/ARCADIS-3D (Siemens) are motorised mobile C-arms that provide fluoroscopic images during a 190° orbital rotation, resulting in a 119-mm data cube (Fig. 1). Multiplanar and two-dimensional reconstructions can be obtained from these 3D data sets.

Study results

On average, the operation was interrupted for 440 seconds in the ISO-C-3D group (120 seconds, on average, for the scan and 210 seconds, on average, for evaluation of the images by the surgeon). In the ARCADIS-3D group, the operation was interrupted for 320 seconds on average (60 seconds, on average, for the scan and 180 seconds, on average, for evaluation). The net radiation time during a 100-image scan was 39.3 seconds for the ISO-C-3D and 19.6 seconds for ARCADIS-3D. Using the ISO-C-3D scan,

Fig. 1 ARCADIS-3D scan after pan-correction arthrodesis of the foot. The lower leg, ankle and foot is placed on a splint which is covered by a sterile plastic bag to maintain a neutral foot and ankle position during the scan. Then, the entire table with lower legs, ankles and feet is covered with a second plastic bag to maintain sterility. During the scan, the entire staff leaves the area of radiation contamination

the position of the implant alone was corrected in 26 % of cases (16 of 62), the reduction alone was corrected in 19 % of cases (12 of 62), and both implant position and reduction were corrected in seven percent of cases (four of 62). A second ISO-C-3D scan was performed in 12 cases after the corrections (50 % of cases in which corrections were performed). In none of those 12 cases were further corrections made after the second scan. Using the ARCADIS-3D scan, the position of the implant alone was corrected in 26 % of cases (16 of 62), the reduction alone was corrected in 15 % of cases (ten of 62), and both implant position and reduction were corrected in 8 % of cases (five of 62). A second ARCADIS-3D scan was performed in 14 cases after the corrections (66 % of cases in which corrections were performed). In none of those 14 cases were further corrections made after the second scan. The level of the surgeon's experience did not differ between the ISO-C-3D and ARCADIS-3D groups (χ^2 test, $p>0.05$). The percentage of correction did not significantly differ between groups with different experience (head of department, attending surgeon, senior resident and junior resident, and ISO-C-3D versus ARCADIS-3D, χ^2 test, $p>0.05$).

Discussion

In this landmark study, the intraoperative use of the ISO-C-3D in foot and ankle fracture care and in corrections of post-traumatic deformities in the hindfoot region led to changes of reduction/correction and/or implant position in more than one third of the cases [3]. Other studies have shown the same effect [6, 7]. In those institutions where an ISO-C-3D/ARCADIS-3D is available it will be used intraoperatively as described despite the questionable impact on the outcome [3]. The goal of the surgical procedure is to achieve anatomical reduction and optimal implant position [3]. The aim is to avoid insufficient reduction/correction and intra-articular implant position and the ISO-C-3D/ARCADIS-3D is helpful for this purpose [3]. In particular the possibility of

obtaining axial reformations was found to be extremely helpful, for example in Weber C fractures. We recognised rotational malpositions of the distal fibula when using the ISO-C-3D/ARCADIS-3D intraoperatively and were able to correct the reduction in the same procedure [3]. Another important finding in this study was the high percentage of screws penetrating joints when ORIF of calcaneus fractures was performed (Fig. 2a–d) [3]. Although the posterior facet and the calcaneocuboid joint were visible from the lateral side, we frequently found screws penetrating these joints medially when we performed an intraoperative ISO-C-3D/ARCADIS-3D scan [3]. Both joints are oblique and the posterior facet is especially difficult to visualise with a C-arm (Broden's view) [8, 9]. Significant steps in the joint line of the posterior facet were also recognised with the ISO-C-3D/ARCADIS-3D only, and correction during the same operative procedure was possible [3]. A major concern for new technical devices is always the time factor. In our study, the use of the ISO-C-3D/ARCADIS-3D was not especially time consuming [3]. The operation was interrupted for 7.20 minutes on average for the ISO-C-3D/ARCADIS-3D use.

In summary, the ISO-C-3D/ARCADIS-3D is most helpful in closed procedures and/or when axial reformations provide information which are impossible to obtain with a C-arm or by direct visualisation [3].

Fig. 2 a–d Intraoperative 3D imaging with ARCADIS-3D of a Weber C ankle. **a** C-arm image after ORIF including syndesmosis screw. The ARCADIS-3D scan shows a massive internal rotation of the distal fibula leading to incongruity of the ankle joint (**b**). This was not recognised with the C-arm (**a**). After correction of the ORIF, the C-arm showed no significant difference (**c**). The ARCADIS-3D shows a correct rotation of the distal fibula and anatomical congruity of the ankle joint (**d**). **b** and **d**: green lines, medial and lateral talar wall; **b**: red lines, medial and lateral malleolus with different angle than medial and lateral talar wall; **d**: yellow lines, medial and lateral malleolus with similar angle to medial and lateral talar wall

Computer assisted surgery

ISO-C-3D/ARCADIS-3D-based CAS for retrograde drilling in osteochondrosis dissecans (OCD) of the talus [10, 11]

Background The goal in osteochondral defects of the talus in stages I and II according to Berndt and Harty is revascularisation of the lesion [12]. A debridement of the chondral part is required if symptomatic [13, 14]. This debridement is limited to loose cartilage or cartilage with poor quality [13–15]. Subchondral drilling of the lesion allows revascularisation. Retrograde drillings leave the chondral surface intact and are therefore advantageous compared with antegrade drillings [16]. Arthroscopically guided drillings are limited to those lesions that can be arthroscopically identified [15]. In the remaining cases open procedures are justified [17]. Based on these principles CT-based CAS-guided retrograde drilling of osteochondral lesions has been described with promising results as a new technique [18]. CT- and fluoroscopy-based navigation systems in current use are limited in their flexibility [17]. The drawback of fluoroscopy is lack of 3D imaging intraoperatively. CT-based navigation still requires intraoperative cumbersome registration, extra preoperative planning and imaging with further technical resources [19].

Technical equipment In addition to the current method of arthroscopic evaluation and treatment, we earlier introduced an alternative technique of using 3D imaging with ISO-C-3D (Siemens)-based CAS-guided retrograde drilling of the lesion [19]. This method was feasible, accurate and showed good clinical outcome [1, 19]. However, the technical equipment of the earlier 3D imaging devices (model ISO-C-3D, Siemens) and CAS devices (model Surgigate, Medivision, Oberndorf, Switzerland) was somewhat cumbersome in handling and error-prone [1, 19]. These devices were further developed for easier and faster handling and less prone to error. The follow-up of the patients treated with ISO-C-3D navigated CAS has been analysed.

Study results Time of follow-up was 18 (12–28) months. Nine patients could be included in the follow-up study. One patient required an Osteochondral Autograft Transfer System (OATS) procedure after initial clinical improvement. This patient had to be excluded. The Visual Analogue Scale Foot and Ankle (VAS FA) score was 92 (86–98) [20]. We later introduced a 3D imaging-based CAS-guided retrograde drilling with a combination of these actual devices (model ARCADIS-3D, Siemens, and model NaviVision, Brainlab) [10, 11].

Conclusions In conclusion, the advantages of this technique are an actual intraoperative 3D imaging for navigation without the need for anatomical registration (matching) and an

immediate intraoperative control of surgical treatment. The results of this case demonstrate accurately navigated drilling with the described system. The accuracy was confirmed with immediate intraoperative 3D imaging. Our results indicate that ARCADIS-3D-based CAS-guided retrograde drilling is a good alternative to arthroscopically guided or two-dimensional imaging-based CAS-guided drilling of OCD lesions of the talus.

C-arm-based computer assisted surgery

Background Ankle, hindfoot and midfoot deformities are not uncommon [21–24]. The biomechanical consequences of these deformities frequently lead to clinical symptoms such as pain and gait disturbances [21–24]. The correction of the deformities is challenging since nonunion and remaining deformity with symptoms are frequent [21, 23–27]. The preoperative diagnostic assessment with radiographs and CT allows accurate planning of the correction and the level of accuracy is not diminished by the use of computerised planning systems [28–33]. However, during the operative procedure the realisation of the planned correction is difficult, because the correction process is performed by the surgeon without guidance beyond a conventional C-arm [1, 21, 23–26]. In other fields of orthopaedic surgery including spine, hip and knee surgery, CAS was found to be helpful and more accurate than the conventional methods without navigation [34–38].

Technical equipment 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 [17]. This system then showed adequate feasibility and accuracy in the first clinical cases [1, 39]. To date, the method is in routine use in the author's institution.

Study results In a matched-pair study, the correction of deformities of the ankle, hindfoot and midfoot/tarsometatarsal (TMT) joint with and without CAS were compared. All patients who were treated with correction arthrodesis between 1 January 2005 and 30 June 2008 ($n=503$) were considered for inclusion. The patients were not randomised. All patients were principally considered for CAS-guided correction due to availability of CAS systems, and 118 patients were included in the CAS group. Of the remaining 385 patients that were not treated with CAS, 118 were considered for the group without CAS. These 118 matched-pair patients were selected to match demographic data and correction location of the CAS group. The preoperative angles or translations, the planned correction and the amount of correction was then drawn with lines, angles and translations in the corresponding CT images using a software of the institutional Picture Archiving Communication System (PACS) (Fig. 3a–g). These images served as the baseline for

the planned correction. The deviation from the achieved correction in comparison to the planned correction was analysed with corresponding images from an intraoperative CT. A maximum deviation of two millimetres for translations or two degrees for angles was considered to be sufficient accuracy. The clinical

Fig. 3 a–g CAS-guided correction arthrodesis of the subtalar joint. The case is a malunited calcaneus fracture with post-traumatic osteoarthritis of the subtalar joint. The lateral talocalcaneal angle is 22.5° (a), i.e. 7.6° decreased in comparison with the healthy contralateral side (b). The hindfoot angle is not pathological (c). A correction arthrodesis with restoration of the contralateral side was planned (d). The talus and calcaneus were equipped with dynamic reference basis (DRB, i.e. passive markers), and lateral and Saltzman views were acquired for CAS-guided correction (e). CAS-guided correction and insertion of two autologous tricortical bone blocks from the ipsilateral dorsal pelvic rim. CAS-guided drilling for special screws (Midfoot Fusion Bolt, Synthes, West Chester, PA, USA). Intraoperative 3D imaging was performed to analyse the correction and implant position which showed an optimal talocalcaneal angle (f, white arrow). The post-operative radiograph validates an optimally corrected talocalcaneal angle (g)

examination included the American Orthopaedic Foot and Ankle Society (AOFAS) clinical rating system and VAS FA [20, 40].

The correction location for both groups was: correction arthrodeses at ankle, $n=24$; subtalar joint, $n=28$; ankle and subtalar joint, $n=19$; midfoot/TMT joint, $n=28$; others, $n=19$. Within the CAS group, the time needed for preparation of the CAS system was 345 seconds (5 min, 45 s) (4–30 min). The correction process took 27 seconds (12–240) with CAS and 312 seconds (62–660) without CAS. The CAS system encountered malfunctions in four procedures (3 %) in which the verification process was not successful. In the remaining 114 cases with CAS, and in 62 cases (53 %) of the group without CAS, all the achieved angles/translations were within a maximum deviation of $2^\circ/\text{mm}$ when compared to the planned correction. Consequently, 3 % of cases with CAS and 47 % of cases without CAS were considered to be not of sufficient accuracy as defined ($p=0.02$).

After more than 24 months (mean 40.2, range 24–70), 98/97 (82/82 %) CAS/without CAS completed follow-up. Fusion was registered in all cases. The scores were higher with CAS than without CAS (CAS/without CAS, AOFAS 83/71, VAS FA 81/69, $p<0.05$).

Conclusions CAS guidance for the correction of deformities of the ankle, hindfoot and midfoot/TMT joint provided higher accuracy, a faster correction process and better scores at a minimum follow-up of two years in comparison to CAS without guidance in a single-centre matched-pair follow-up study.

Intraoperative pedography

Background

Pedography is an effective method for the analysis of the improved biomechanical function at clinical follow-up [41]. In the year 2005, we completed the development and validation of a device and method for IP [42].

Technical equipment

A device named Kraftsimulator Intraoperative Pedographie® (KIOP®, R-Innovation) was developed for a standardised intraoperative introduction of forces to the foot sole (Fig. 4) [42]. The pedographic measurements are registered by a custom-made mat with capacitive sensors (model Pliance®, Novel) connected to an IBM compatible laptop computer with modified software (model Pliance Expert® spec. IP, Novel, Fig. 4). This method allows static pedography in anaesthetised subjects in the supine position without statistically significant force distribution differences in comparison to the standing

Fig. 4 System for IP

position [42]. IP was used to detect non-optimal biomechanical conditions of the foot allowing the surgeon to modify a reduction or correction during the same operative procedure (Fig. 5a–i) [42].

Study results

A prospective randomised controlled clinical follow-up study was started to evaluate the potential clinical benefit of the system during operative corrections and/or arthrodeses of foot pathologies [43]. The preliminary results showed that a modification of the surgical correction/arthrodesis was made after IP in the same surgical procedure in almost half of the cases [43]. However, it remained questionable whether these modifications led to changes in the clinical outcome. A Level I study (randomised, prospective, consecutive, blinded, clinical follow-up) comparing treatment with IP (study group) and without IP (control group) was started [44]. Patients (age 18 years and older) who underwent an arthrodesis and/or correction arthrodesis of the foot and ankle were included, starting 1 September 2006. All subjects receive preoperative clinical and radiographic assessment and standard dynamic pedography. The subjects are randomised into two groups: (1) use of IP versus (2) no use of IP. The IP of the foot that was operated upon was used after the surgeon considered the correction process and the internal fixation to be optimal based on the surgeon's experience including the evaluation of the clinical appearance of the foot and C-arm images. In the IP group, the contralateral foot and the involved foot before correction are measured in the preparation area after the beginning of the anaesthesia. The following scores are used: AOFAS clinical rating system, VAS FA and Short Form 36 (SF-36, standardised to 100-point maximum). Intraoperative consequences after the use of IP and any adverse effects were recorded. Follow-up including clinical examination, radiological studies, dynamic pedography, and foot and ankle focused assessment was performed. One hundred cases

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Fig. 5 a–h Bilateral forefoot deformity with hallux valgus. **a** Dorsoplantar bilateral radiograph with full weight-bearing with massive malposition of the 1st metatarsal heads in relation to the sesamoids and a relevant overlength of the 2nd metatarsals. **b** Bilateral metatarsal head skyline view with pronation and malposition of the 1st metatarsal heads in relation to the sesamoids and distinct deep position of the 2nd metatarsal heads right (in figure *left*) more than right (in figure *left*). **c** Maximum pressure image of the preoperative dynamic standard pedography with obvious decrease of the force under the 1st metatarsal head in comparison with the contralateral side (see *lower arrow*) and an explicit increase of the force under the 2nd metatarsal heads on both sides (see *upper arrow*). **d** Maximum pressures of the preoperative dynamic standard pedography with decrease of maximum pressure under the 1st metatarsal head in comparison with the contralateral side (see *lower arrow*) and an increase of maximum pressure under the 2nd metatarsal heads on both sides (see *upper arrow*). A correction with distal 1st metatarsal correction osteotomy and a soft tissue procedure were performed (**e**). Then, due to an unsatisfactory force distribution of the intraoperative pedography with decreased force under the 1st metatarsal head and increased force under the 2nd metatarsal head (see **h second image from left after correction and image left before correction**), a modified Weil osteotomy of the 2nd metatarsal followed. This osteotomy was then again modified with removal of an additional slice of bone at the osteotomy site due to a remaining unsatisfactory force distribution (**h second image from right**). Finally, optimal position (**f and g**) and force distribution (**h right**)

No complications related to the use of IP such as infection were observed. All patients completed follow-up after six to 24 months (12 months on average). The follow-up scores were AOFAS 92.5 ± 19.7 , VAS FA 90.2 ± 13.4 , SF-36 94.3 ± 18.8 . The scores at follow-up were significantly higher than the preoperative scores (t test, $p < 0.05$). The scores from the IP group were significantly higher than the scores from the group without IP (t test, $p < 0.05$).

Conclusions

In conclusion, at a mean of two years follow-up in a Level I but single-centre study, additional use of IP as the only difference between two groups with correction and/or arthrodesis at foot and/or ankle led to improved clinical outcome scores. Low scores (less than 69 points in all scores) were avoided with IP. This has to be critically re-analysed when longer follow-up, greater case numbers and data from other study centres are available.

What do we need when?

The perfect surgeon who does not make any mistakes without any guidance does not need any of the new 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 harder.

Tools for improved intraoperative imaging (ISO-C-3D), guidance (CAS) or biomechanical assessment (IP) may help the surgeon in training to achieve the planned result with less experience [1].

Intraoperative three-dimensional imaging

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 visualisation. [2].

Computer assisted surgery

CAS is helpful in complex 3D corrections or reduction and in closed placement of drillings and/or screw positioning [28–32]. The significance of the introduced CAS methods is high in those cases, because the improved accuracy may lead to an improved clinical outcome for complex corrections in hind- and midfoot deformities [21, 23, 45–50]. CAS is too complex and time consuming for all those cases that are accurately and easily performed by the experienced surgeon.

Intraoperative pedography

IP will be useful for all those cases in which biomechanical assessment may lead to an immediate improvement of the achieved surgical result [44]. The same cases that are currently analysed with clinical pre- or post-operative pedography will potentially profit from IP. The surgeon's 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 (KIOP, R-Innovation).

Fig. 6 Holographic virtual display of bone position and force distribution above the operative situs during a navigated correction arthrodesis of the midfoot/Lisfranc joint

Perspectives

Future developments will include larger areas for 3D scans, corrective navigation with more than two fragments or bones and with 3D images, additional force-based navigation and better visualisation such as with holographic displays (Fig. 6). Larger scan areas will be enabled by larger flat panel detectors which are already available. Navigation of more than two fragments/bones in the 3D environment is based on more powerful computers and smaller navigation markers and is under development. A force-based navigation means that the guidance of the navigation system is not only based on bone/fragment position but also on forces that are calculated with a finite element model based on the data of the IP. This will give the bone/fragment position and the virtual resulting force distribution of this bone/fragment position (Fig. 6). Finally, a holographic visualisation above the operative situs will be the most ergonomic possibility to display all kinds of information such as images from C-arm, ARCADIS-3D, CT, magnetic resonance imaging (MRI), ultrasound and pedography and data such as distances, angles, forces and pressures (Fig. 6).

References

- Richter M (2006) Computer based systems in foot and ankle surgery at the beginning of the 21st century. *Fuss Sprungg* 4:59–71
- Richter M (2012) *Computergestützte Fußchirurgie*. Springer, Berlin
- Richter M, Zech S (2009) Intraoperative 3-dimensional imaging in foot and ankle trauma—experience with a second-generation device (ARCADIS-3D). *J Orthop Trauma* 23:213–220
- Richter M, Geerling J, Zech S, Goesling T, Krettek C (2005) Intraoperative three-dimensional imaging with a motorized mobile C-arm (SIREMOBIL ISO-C-3D) in foot and ankle trauma care: a preliminary report. *J Orthop Trauma* 19:259–266
- Euler E, Wirth S, Linsenmaier U, Mutschler W, Pfeifer KJ, Hebecker A (2001) Vergleichende Untersuchung zur Qualität der C-Bogen-basierten 3D-Bildgebung am Talus. *Unfallchirurg* 104:839–846
- Geerling J, Kendoff D, Citak M, Zech S, Gardner MJ, Hüfner T, Krettek C, Richter M (2009) Intraoperative 3D imaging in calcaneal fracture care-clinical implications and decision making. *J Trauma* 66:768–773
- Kendoff D, Citak M, Gardner M, Kfuri M Jr, Thumes B, Krettek C, Hüfner T (2007) Three-dimensional fluoroscopy for evaluation of articular reduction and screw placement in calcaneal fractures. *Foot Ankle Int* 28:1165–1171
- Myerson MS, Fisher RT, Burgess AR, Kenzora JE (1986) Fracture dislocations of the tarsometatarsal joints: end results correlated with pathology and treatment. *Foot Ankle* 6:225–242
- Hansen STJ (2000) *Functional reconstruction of the foot and ankle*. Lippincott Williams & Wilkins, Philadelphia
- Richter M, Zech S (2008) 3D imaging (ARCADIS)-based computer assisted surgery (CAS) guided retrograde drilling in osteochondritis dissecans of the talus. *Foot Ankle Int* 29:1243–1248
- Richter M, Zech S (2011) Navigierte retrograde Anbohrung OCD Talus. *Oper Orthop Traumatol* 23:473–482
- Berndt AL, Harty M (1959) Transchondral fractures (osteochondritis dissecans) of the talus. *J Bone Joint Surg Am* 41-A:988–1020
- Alexander AH, Lichtman DM (1980) Surgical treatment of transchondral talar-dome fractures (osteochondritis dissecans). Long-term follow-up. *J Bone Joint Surg Am* 62:646–652
- Tol JL, Struijs PA, Bossuyt PM, Verhagen RA, van Dijk CN (2000) Treatment strategies in osteochondral defects of the talar dome: a systematic review. *Foot Ankle Int* 21:119–126
- Taranow WS, Bisignani GA, Towers JD, Conti SF (1999) Retrograde drilling of osteochondral lesions of the medial talar dome. *Foot Ankle Int* 20:474–480
- Fink C, Rosenberger RE, Bale RJ, Rieger M, Hackl W, Benedetto KP, Künzel KH, Hoser C (2001) Computer-assisted retrograde drilling of osteochondral lesions of the talus. *Orthopade* 30:59–65
- Richter M (2003) Experimental comparison between computer assisted surgery (CAS) based and C-arm based correction of hind- and midfoot deformities. *Osteo Trauma Care* 11:29–34
- Rosenberger RE, Bale RJ, Fink C, Rieger M, Reichkendler M, Hackl W, Benedetto KP, Künzel KH, Hoser C (2002) Computer-assisted drilling of the lower extremity. Technique and indications. *Unfallchirurg* 105:353–358
- Richter M, Geerling J, Zech S, Krettek C (2005) ISO-C-3D based computer assisted surgery (CAS) guided retrograde drilling in a osteochondrosis dissecans of the talus: a case report. *Foot* 15:107–113
- Richter M, Zech S, Geerling J, Frink M, Knobloch K, Krettek C (2006) A new foot and ankle outcome score: questionnaire based, subjective, visual-analogue-scale, validated and computerized. *Foot Ankle Surg* 12:191–199
- Zwipp H (1994) *Chirurgie des Fusses*. Springer, Vienna
- Richter M, Wippermann B, Krettek C, Schratz E, Hüfner T, Thermann H (2001) Fractures and fracture dislocations of the midfoot: occurrence, causes and long-term results. *Foot Ankle Int* 22:392–398
- Marti RK, de Heus JA, Roolker W, Poolman RW, Besselaar PP (1999) Subtalar arthrodesis with correction of deformity after fractures of the os calcis. *J Bone Joint Surg Br* 81:611–616
- Rammelt S, Grass R, Zawadski T, Biewener A, Zwipp H (2004) Foot function after subtalar distraction bone-block arthrodesis. A prospective study. *J Bone Joint Surg Br* 86:659–668
- Madezo P, de Cussac JB, Gouin F, Bainvel JV, Passuti N (1998) Combined tibio-talar and subtalar arthrodesis by retrograde nail in hindfoot rheumatoid arthritis. *Rev Chir Orthop Reparatrice Appar Mot* 84:646–652
- Trnka HJ, Easley ME, Lam PW, Anderson CD, Schon LC, Myerson MS (2001) Subtalar distraction bone block arthrodesis. *J Bone Joint Surg Br* 83:849–854
- Stephens HM, Sanders R (1996) Calcaneal malunions: results of a prognostic computed tomography classification system. *Foot Ankle Int* 17:395–401
- Richter M, Zech S (2008) Computer assisted surgery (CAS) guided arthrodesis of the foot and ankle: an analysis of accuracy in 100 cases. *Foot Ankle Int* 29:1235–1242
- Richter M (2010) Navigierte Korrekturarthrodese des Lisfrancgelenks und Mittelfusses. *Oper Orthop Traumatol*
- Richter M (2009) Navigierte Korrekturarthrodese des oberen Sprunggelenks. *Oper Orthop Traumatol* 21:313–322
- Richter M (2010) Navigierte Korrekturarthrodese des oberen und unteren Sprunggelenks mit retrograder Marknagelfixierung. *Oper Orthop Traumatol* 23:141–150
- Richter M (2010) Navigierte Korrekturarthrodese des unteren Sprunggelenks. *Oper Orthop Traumatol* 22:402–413
- Dahlen C, Zwipp H (2001) Computer-assistierte OP-Planung 3D-Software für den PC. *Unfallchirurg* 104:466–479
- Chauhan SK, Clark GW, Lloyd S, Scott RG, Bredahl W, Sikorski JM (2004) Computer-assisted total knee replacement. A controlled

- cadaver study using a multi-parameter quantitative CT assessment of alignment (the Perth CT Protocol). *J Bone Joint Surg Br* 86:818–823
35. Haaker RG, Stockheim M, Kamp M, Proff G, Breitenfelder J, Ottersbach A (2005) Computer-assisted navigation increases precision of component placement in total knee arthroplasty. *Clin Orthop Relat Res* 433:152–159
 36. Langdown AJ, Auld J, Bruce WJ (2005) Computer-assisted knee arthroplasty versus a conventional jig-based technique. *J Bone Joint Surg Br* 87:588–589
 37. Richter M, Mattes T, Cakir B (2004) Computer-assisted posterior instrumentation of the cervical and cervico-thoracic spine. *Eur Spine J* 13:50–59
 38. Richter M, Amiot LP, Neller S, Kluger P, Puhl W (2000) Computer-assisted surgery in posterior instrumentation of the cervical spine: an in-vitro feasibility study. *Eur Spine J* 9(Suppl 1):S65–S70
 39. Richter M, Geerling J, Frink M, Zech S, Knobloch K, Dammann F, Hankemeier S, Krettek C (2006) Computer assisted surgery (CAS) based correction of posttraumatic ankle and hindfoot deformities—preliminary results. *Foot Ankle Surg* 12:113–119
 40. Kitaoka HB, Alexander IJ, Adelaar RS, Nunley JA, Myerson MS, Sanders M (1994) Clinical rating systems for the ankle-hindfoot, midfoot, hallux, and lesser toes. *Foot Ankle Int* 15:349–353
 41. Schmiegel A, Vieth V, Gaubitz M, Rosenbaum D (2008) Pedography and radiographic imaging for the detection of foot deformities in rheumatoid arthritis. *Clin Biomech (Bristol, Avon)* 23:648–652
 42. Richter M, Frink M, Zech S, Vanin N, Geerling J, Droste P, Krettek C (2006) Intraoperative pedography: a validated method for static intraoperative biomechanical assessment. *Foot Ankle Int* 27:833–842
 43. Richter M, Zech S (2009) Is intraoperative pedography helpful in clinical use—preliminary results of 100 cases from a consecutive, prospective, randomized, controlled clinical study. *Foot Ankle Surg* 15:198–204
 44. Richter M, Zech S (2009) Leonard J. Goldner Award 2009. Intraoperative pedobarography leads to improved outcome scores: a Level I study. *Foot Ankle Int* 30:1029–1036
 45. Bechtold JE, Powless SH (1993) The application of computer graphics in foot and ankle surgical planning and reconstruction. *Clin Podiatr Med Surg* 10:551–562
 46. Adelaar RS, Kyles MK (1981) Surgical correction of resistant talipes equinovarus: observations and analysis - preliminary report. *Foot Ankle* 2:126–137
 47. Coetzee JC, Hansen ST (2001) Surgical management of severe deformity resulting from posterior tibial tendon dysfunction. *Foot Ankle Int* 22:944–949
 48. Mosier-LaClair S, Pomeroy G, Manoli A (2001) Operative treatment of the difficult stage 2 adult acquired flatfoot deformity. *Foot Ankle Clin* 6:95–119
 49. Sammarco GJ, Conti SF (1998) Surgical treatment of neuroarthropathic foot deformity. *Foot Ankle Int* 19:102–109
 50. Stephens HM, Walling AK, Solmen JD, Tankson CJ (1999) Subtalar repositional arthrodesis for adult acquired flatfoot. *Clin Orthop* 365:69–73