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Computer-assisted surgery and navigation in foot and ankle: state of the art and fields of application

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- Computer-assisted orthopaedic surgery (CAOS) is a real-time navigation guidance system that supports surgeons intraoperatively.
- Its use is reported to increase precision and facilitate less-invasive surgery.
- Advanced intraoperative imaging helps confirm that the initial aim of surgery has been achieved and allows for immediate adjustment when required.
- The complex anatomy of the foot and ankle, and the associated wide range of challenging procedures should benefit from the use of CAOS; however, reports on the topic are scarce.
- This article explores the fields of applications of real-time navigation and CAOS in foot and ankle surgery.

Keywords: CAOS; foot and ankle surgery; navigated surgery

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CAOS: where do we stand in the field of foot and ankle surgery?

Computer-assisted orthopaedic surgery (CAOS) provides a real-time navigation system with improved visualization capacity and increased accuracy.[1–3] Furthermore, the use of computer-assisted navigation allows improved control during surgery within deep areas that are difficult or impossible to visualize directly, helps to achieve surgical goals as planned,[4–6] and is especially useful for less-invasive surgery (LIS).[7,8] Additionally, this technique can be useful for younger surgeons as the results of the surgery are immediately visible and therefore shorten the learning curve.

Historically, CAOS was mainly used in spinal and cranial surgery, in which it optimized the clinical outcomes, especially for complicated surgeries, and reduced risks of neural damage.[1] However, the efficacy of CAOS in other fields of orthopaedics, in particular in hips and the lower limb, remains controversial.[3,9] In the field of foot and ankle surgery, there remains a lack of studies, case reports and other forms of publication exploring the possible application of such technology and their accompanying advantages and disadvantages. Nevertheless, there is increasing interest in using CAOS in this challenging field, particularly for complex or less-invasive surgery. CAOS has been previously adapted for use during syndesmotic reduction, as demonstrated in a cadaveric study[3,4] and a case report.[10] The accuracy of CAOS has also been demonstrated for foot and ankle joint fusion,[4,11,12] to treat osteochondritis dissecans (OCD),[11] as well as for a tarsal navicular stress fracture.[13] During these surgeries, accuracy was shown to be increased and radiation exposure was decreased compared to standard fluoroscopy.[10,12,13]

There are two main intraoperative 3D imaging technologies that can be used in the field of foot and ankle surgery. The C-Arm is a 2D fluoroscopy that can be upgraded to provide 3D imaging for more efficient and accurate surgery.[4,12,14] The O-Arm™ provides real-time visualization using low-dose cone beam computed tomography (CBCT) scanning, with probably lower radiation exposure than conventional fluoroscopy due to decreased numbers of recurrent shots.[2,8,15,16] Both technologies combine multiplanar imaging, 3D reconstruction and real-time instrumented navigation. This technology allows for less exposure than conventional fluoroscopy due to decreased numbers of recurrent shots, provided that the sequences are optimized with precise planning.

At our institution, the O-Arm™ has been routinely used for foot and ankle surgery since 2008. Technically, a single initial intraoperative scan of the target region is obtained with a reference frame fixed with two 1.6 mm K-wires to the bones of the area of interest (Fig. 1 a, b). The reference frame faces the camera, providing a clear field with the reflective

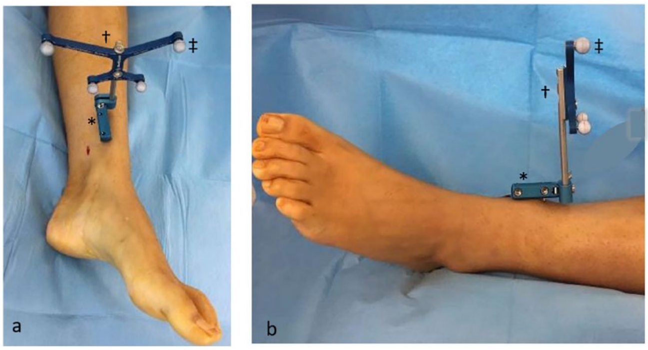

Fig. 1 Position of reference frame. (a, b) Patient reference frame fixation on the target zone. * Reference base fixed to the bone with two 1.6 mm K-wires, † reference frame, ‡ reflective spheres.

spheres out of the way of the operator's instruments. An intraoperative CBCT scan is then acquired after ensuring satisfactory position and fixation of the reference frame.

Automatic registration of the patient's anatomy using the reference frame and tracking of surgical instruments using infrared light emitted by LED sources and reflective spheres allows real-time 3D triangulation of their relative position in space.[17,18] A final intraoperative CBCT is acquired when the critical steps of the surgery are completed with the help of the navigation system to ensure that the goals of the preoperative plan have been achieved. This approach allows the surgeon to adjust, readapt or validate the obtained results intraoperatively, sparing the patient from potential reoperation in case of less than optimal results.

Over time, we have refined this technology for use in our particular field of application and adapted the setup of the operating room for each patient so as to optimize the overall time of surgery and the clinical outcome. This approach has allowed us to gradually increase the indications for CAOS in foot and ankle surgery. Here, we present possible fields of application for this technology based on our experience of over 1000 cases. The main indications include supramalleolar osteotomies, tibia plafond and talar dome osteochondral defects retrograde drilling and filling, pilon fractures open reduction and internal fixation (ORIF), calcaneum less-invasive ORIF, midfoot fusions, tibia derotations osteotomies, internal fixation of fifth metatarsal stress fractures, ankle and subtalar fusions and syndesmotic injuries.

Fields of application

Calcaneus fracture: less-invasive osteosynthesis

Calcaneal fractures remain a challenge in orthopaedic surgery and require a significant learning curve. Calcaneus tongue-type fractures (Fig. 2 a, b) can be approached by a less-invasive osteosynthesis, which minimizes surgery-related soft tissue secondary trauma. However, LIS is a challenging procedure in terms of fracture reduction, restoration of anatomy and screw fixation, which are optimized by CAOS.

Calibration of the power drill on the reference frame is followed by verification of navigation accuracy and identification of the different entry points. Navigation of the Schanz pin on the power drill allows for accurate entry

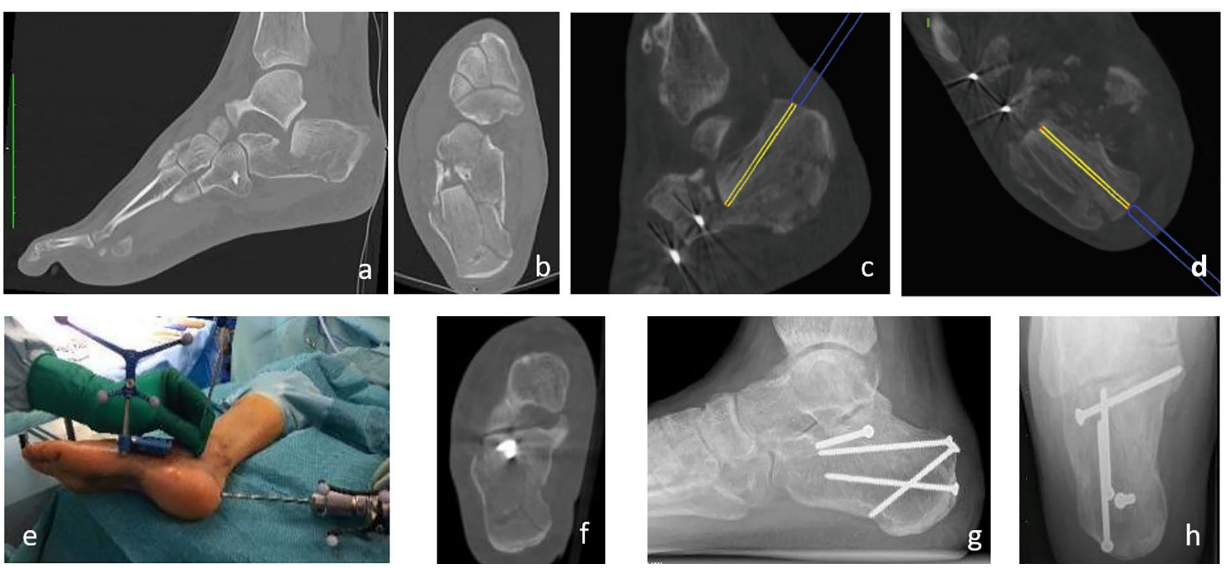

Fig. 2 Calcaneus fracture: less-invasive osteosynthesis. (a) Computerized tomography (CT) scan sagittal view. (b) CT scan axial view. (c, d, e) Accurate Schanz pin placement with navigation. (f) Intraoperative CT scan showing the reduction. (g, h) One-year postoperative standard radiographs.

point selection and optimal placement in the centre of the tongue fragment. This entry point is ideally located at the proximal tip of the calcaneal tuberosity just below the dorsal cortex (Fig. 2 c, d, e).

Reduction manoeuvre of the tongue fragment with the Schanz pin used as joystick is followed by a preliminarily fixation with 1.6 mm K-wires. The O-Arm is then used as a fluoroscope to assess fracture reduction. An intraoperative scan using a low-dose exposure technique can then be obtained to assess anatomic reduction and joint surface restoration (Fig. 2 f). Navigating the screws as they are placed allows for optimal results and an exact calculation of the length and trajectory for each screw, while avoiding any unintentional damage to adjacent joints or neighbouring structures on the medial side. Standard weight-bearing radiographs (Fig. 2 g, h) reveal the restoration of hindfoot height and of the calcaneal width.

Calcaneus malunion: osteotomy through the primary fracture line and subtalar fusion

In our practice, CAOS is used to treat calcaneal malunions either due to lack of indicated surgery or sub-optimal ORIF. We detail the steps of addressing calcaneal malunion in varus and loss of height of the hindfoot following non-operative treatment of a joint depression calcaneal fracture (Fig. 3 a, b). The challenge in such cases is to perform the osteotomy through the original fracture line (primary fracture line) in order to regain hindfoot height and alignment. The operative plan shall lay out the osteotomy site through the original fracture line followed by a subtalar joint fusion, if already arthritic.

The osteotome is calibrated using the adapter and then navigated to allow for accurate entry point selection and exact recreation of the primary fracture line (Fig. 3 c, d, e). Intraoperative CBCT shows the osteotomy line exactly through the primary fracture as planned (Fig. 3 f). Calibration of the power drill on the reference frame is followed by verification of navigation accuracy and identification of the entry points for the subtalar arthrodesis screws. The subtalar joint is then prepared and filled with cancellous bone graft taken from the ipsilateral distal tibia. Navigated placement of the screws allows for optimal results. It permits an exact calculation of the length and trajectory for each screw while avoiding any damage to the adjacent joints. A minimum of two screws is mandatory to secure osteotomy and fusion sites. Postoperative standard radiographs show the restoration of hindfoot height and of the calcaneus width (Fig. 3 g, h).

Calcaneonavicular coalition fusion

In our institution, COAS is used to treat multitude of congenital pathologies of the foot. The technique of using navigation and CAOS for coalitions of the calcaneonavicular (CN) joint (Fig. 4 a, b) is described here step by step. Indications for surgical intervention are a symptomatic foot with decreased quality of life and failure of

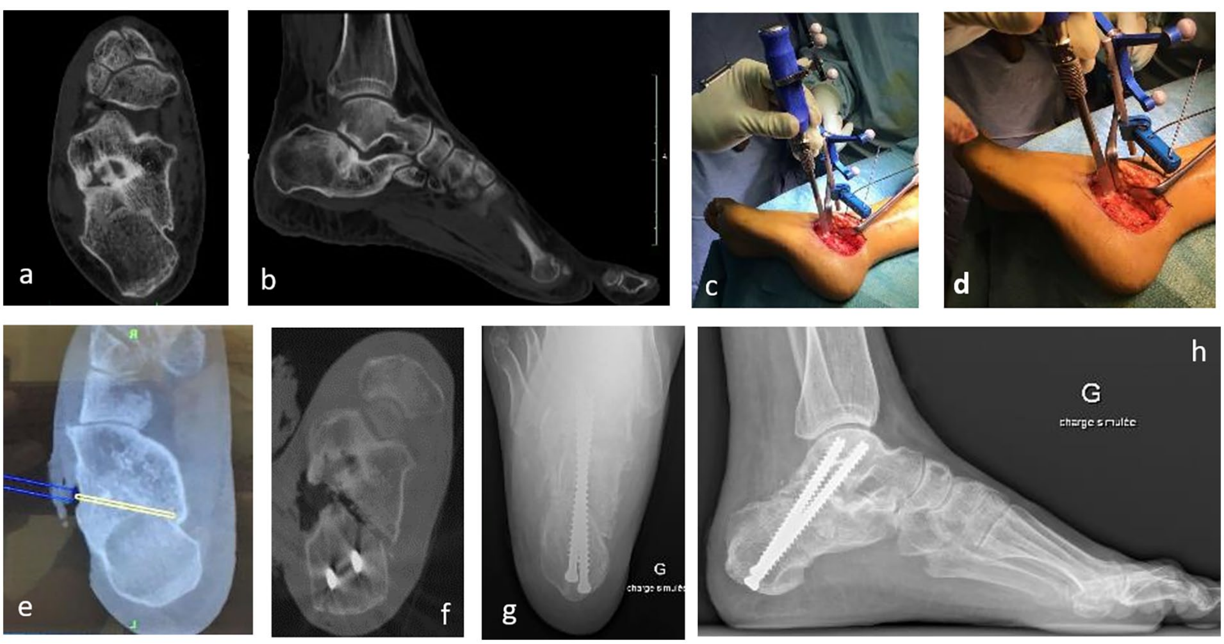

Fig. 3 Calcaneus malunion: osteotomy through the primary fracture line and subtalar fusion. (a) Computerized tomography (CT) scan axial view. (b) CT scan sagittal view. (c, d, e) Accurate entry point (blue line) and trajectory (yellow line) of the osteotome with navigation. (f) Intraoperative CT scan showing the osteotomy through the primary fracture line. (g, h) Postoperative standard radiographs with simulated weight-bearing.

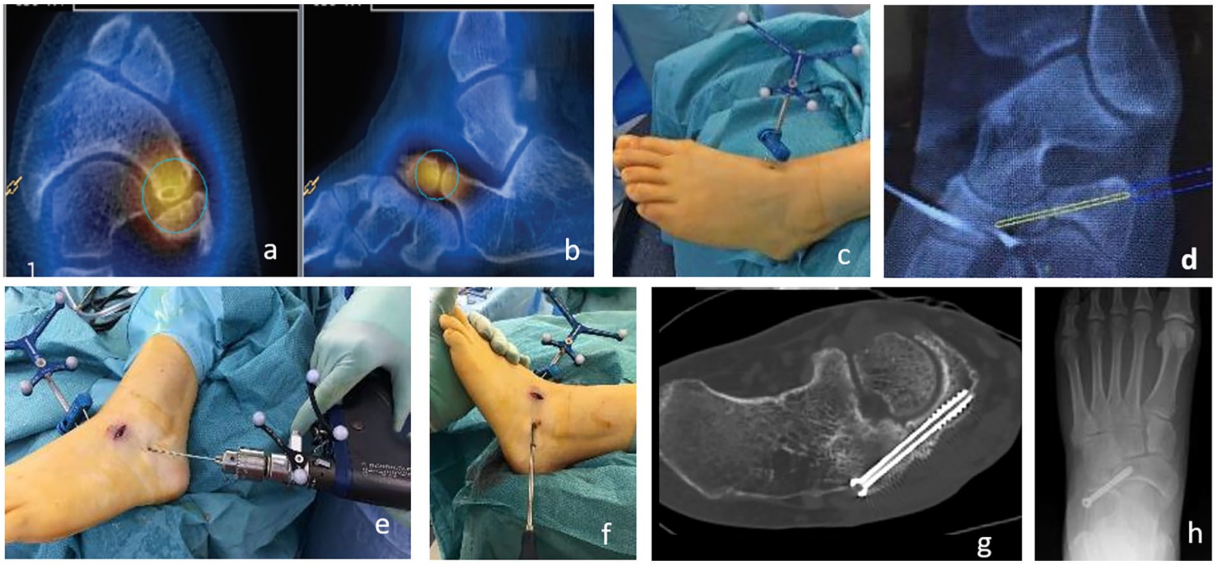

Fig. 4 Calcaneonavicular coalition fusion. (a, b) SPECT-CT scan views with hypercaptation at the coalition site, axial and sagittal views. (c) Reference frame fixation. (d) Navigation trajectory on the CT scan (blue line, entry point; yellow line, trajectory and length). (e, f) Less-invasive drilling and screw placement. (g) Intraoperative CBCT shows the optimal screw position. (h) Postoperative standard radiographs.

Note. SPECT, single photon emission computed tomography; CT, computerized tomography; CBCT, cone beam computed tomography.

non-operative treatment for over two years. Surgical challenges to be aware of and prepared for include fusion site debridement and grafting, optimal selection of the appropriate entry point, trajectory and length of the screw. A common complication to be avoided is to have the screw penetrate into an adjacent joint (e.g., talonavicular).

The universal pointer and the power drill are calibrated, and the reamer is used to break the coalition and prepare the CN fusion site. A cancellous bone graft can be obtained from the distal ipsilateral tibia. The guide wire is navigated, and a cannulated partially threaded screw is placed in a less-invasive manner under continuous visualization of the trajectory (Fig. 4 d, e, f). A final intraoperative CBCT is obtained to ensure the correct and optimal screw position (Fig. 4 g). Simulated weight-bearing standard radiographs demonstrate perfect screw positioning and length (Fig. 4, h).

Midfoot fusion with bolts for Charcot foot

The use of CAOS for multilevel foot arthrodesis revision surgery is illustrated for advanced neuroarthropathy of the midfoot (Charcot foot) with fragmentation of the navicular bone. Previous operations in another medical facility resulted in nonunion at the subtalar and the talonavicular joints (Fig. 5 a, b). Such a situation raises important surgical challenges ranging from poor-quality bone and multiple nonunion sites, to medial arch collapse (loss of plantigrade foot) and the placement of an intramedullary implant positioning with midfoot fusion bolt.

Intervention for a complex reconstruction of the foot must be carefully planned. Hardware removal and resection of the fragmented (necrotic) navicular bone is followed by an autograft of cortical strut and cancellous bone taken from the ipsilateral tibia. Then, the whole construct is fixed with a medial column retrograde intramedullary screw (midfoot fusion bolt), with plate and screws augmentations. With the patient in the supine position, the hardware is removed, and fragmentation of the navicular bone is addressed. The majority of the necrotic navicular bone must be removed, and the subtalar joint debrided (Fig. 5 c). The first cuneometatarsal joint is prepared for fusion. The foot shall be realigned in the three planes. Insertions of multiple temporary K-wires secures the plantigrade position.

An 8×1 cm cortical strut is harvested from the ipsilateral proximal tibia and placed in a carved split along the medial aspect of the foot medial column (Fig. 5 d). It is important to restore to a functional length that does not create too much tension on soft tissue. A cannulated bolt wire is calibrated using the adapter and the entry point at the level of the first metatarsal head is identified by the projected navigation line that passes through the first metatarsal shaft longitudinal axis, the centre of the talar head and the centre of the talar dome sagittal radius (a straight Meary line). The bolt is then inserted after drilling along the bolt wire (Fig. 5 e). A long and thick medial column plate can be used to augment the strength of the construct (Fig. 5 f). An additional K-wire is inserted through the first metatarsophalangeal joint (MTP1), in order to force the joint into

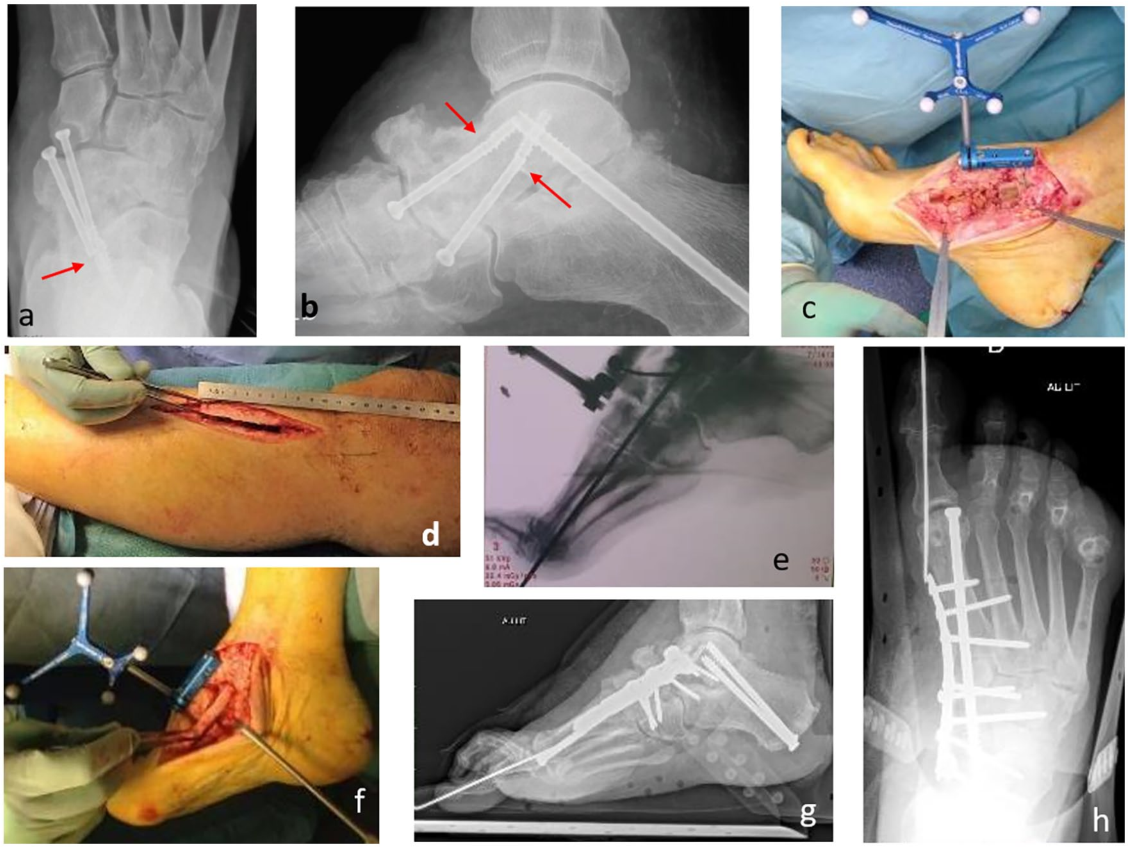

Fig. 5 (a, b) Standard weight-bearing radiographs showing hardware failure (red arrows). (c) Reference frame fixation and débridement of the zone. (d) Cortical bone harvest from the ipsilateral tibial. (e) Bolt guide wire placement with navigation (fluoroscopy post insertion). (f) Strut placement at the medial column. (g, h) Post-operative standard radiographs.

plantar flexion. This relieves the soft tissue tension at the level of the plantar entry point of the bolt. K-wires are then removed after two weeks. Standard radiographs show restoration of the foot medial arch (Fig. 5 g, h).

Pilon fracture: posterior plating

ORIF of pilon fractures are particularly challenging. Use of CAOS may simplify some steps of the overall procedure. Here we illustrate a case of a pilon type B fracture (Fig. 6 a, b). In this particular case, the surgical challenge is the combined posterior and medial column fractures. Reduction and fixation of a posterior column fracture can be difficult due to the limited field of vision. Accurate screw placement close to the tibiofibular joint and to the tibiotalar joint can be an issue. Anatomic reduction of the joint surface and rigid fixation of the fractures are essential. The screws of the posterior plate need to be as close as possible to the tibiotalar joint and to the fibular incisura (lateral screw) but not through it. The power drill is navigated to ensure satisfactory fixation of the posterior plate screws in terms of trajectory and length.

The patient is placed in the prone position and the modified posteromedial approach is used. The fracture site is prepared, and the impacted articular fragment is anatomically reduced. The fracture is temporarily fixed with 1.6 mm K-wires. Intraoperative CBCT is used to ensure anatomical reduction and joint surface restoration (Fig. 6 c, d) prior to definitive fixation.

The power drill is calibrated using the adapter. An anatomical posterior plate is used and placed as distally as possible. Compression screws through the plate are placed as close as possible to the tibiotalar joint and to the fibular incisura (lateral screw) avoiding any joint penetration. The power drill is navigated allowing for continuous visualization of the drilling trajectory and screw length calculation (Fig. 6 c–f). After adequate irrigation, the site is closed plane by plane. The patient is then turned to the supine position. The medial malleolus is then reduced through an anteromedial approach and fixed with an anti-glide plate and screws. Standard radiographs show complete consolidation and absence of arthrosis (Fig. 6 g, h).

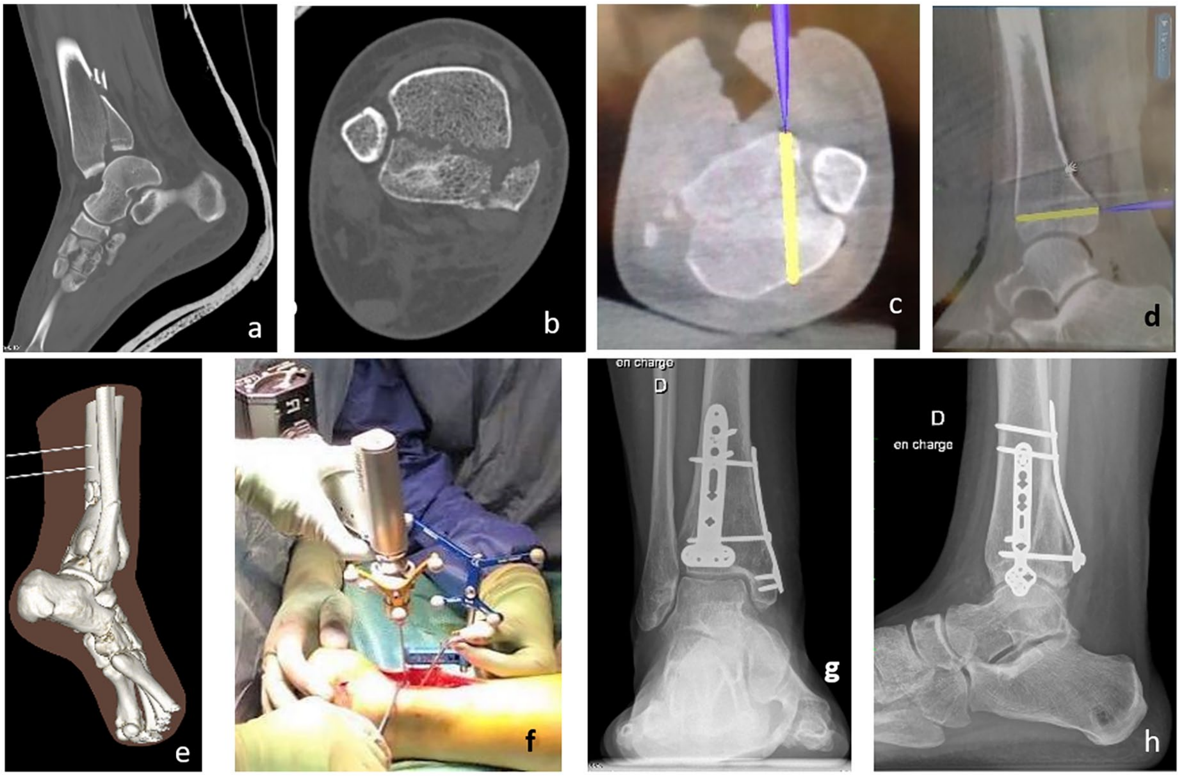

Fig. 6 Pilon fracture fixation. (a, b) Computerized tomography (CT) scan of the ankle, sagittal and axial views. (c, d) Navigation trajectory on the CT scan (blue line, entry point; yellow line, trajectory and length. (e) K-wire insertion for reference frame fixation (3D reconstruction). (f) Navigated power drill use. (g, h) One-year postoperative full-weight-bearing radiographs, AP and lateral views.

Tibia postsurgical malrotation: derotation osteotomy

CAOS is also useful when dealing with complex revisions after less than optimal treatment of trauma or elective surgery. Its use is illustrated in the following derotation osteotomy of the distal tibia. The following case presents a tibial iatrogenic malrotation at six months after index surgery, with a fracture on the lower third of the tibial shaft and an intramedullary (IM) nail fixation. Clinical examination revealed excess external rotation of 26° of the distal tibia in relation to the proximal tibia when compared to the contralateral leg, supported by a comparative CT scan (Fig. 7 a, b, c).

The recreation of the original fracture line as well as the exact needed derotation (in this case 26° internal derotation) are the two key elements. The distal tibia can be navigated as a whole in relation to the proximal tibia where the reference frame is positioned. Navigation of the tracker fixed in the axial plane into the distal tibia ensures exact derotation of 26° around the axis. A percutaneous burr is used to achieve a less-invasive osteotomy of the fibula. The IM nail can be kept in place while the distal locking bolts are removed. An anteromedial approach is used over the original fracture site. A chisel can be used to recreate the transverse fracture around the IM nail.

A 2.5 mm K-wire is calibrated using the adapter, and then carefully fixed to the distal tibia at the mid-malleolar distance using a light hammer (Fig. 7 d). A tracker is then fixed on the K-wire allowing for tracking of the distal tibial around its axis when rotating. The navigation programme is used to create a 3D illustration showing the angle of rotation needed to achieve the desired axis correction (Fig. 7 e). When the desired correction is obtained, the osteotomy site is then secured by a two-hole 1/3 tubular plate by the use of monocortical screws. The IM nail can be then locked distally with three locking bolts to ensure stability of the construct. Postoperative standard radiographs reveal satisfactory coronal alignment (Fig. 7 f, g), and clinical alignment must be identical to the contralateral side.

Retrograde grafting for an osteochondral pilon lesion

Osteochondral lesions of the ankle joint represent a challenge both for the patient population and for the treating specialist in absence of a gold-standard treatment, often with persisting pain after multiple attempts at conservative and operative treatment. One accepted strategy is cystic debridement and grafting. The use of CAOS is presented with a case of cystic osteochondral lesion in the tibial pilon with over two years of moderately effective non-operative

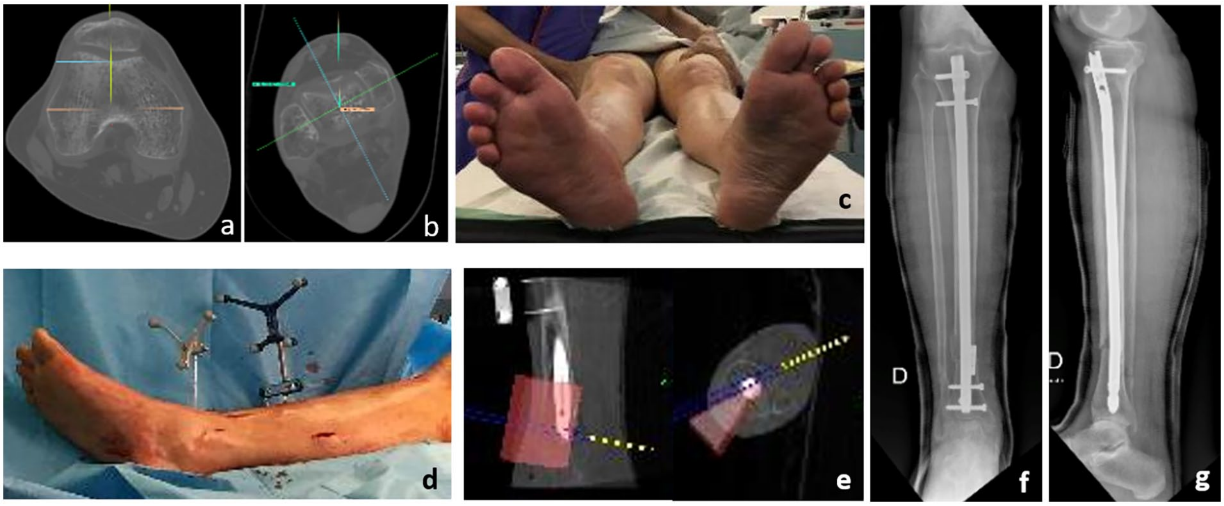

Fig. 7 Tibia derotation osteotomy. (a, b) Computerized tomography (CT) scan of the entire leg revealing excess of external rotation of 26° at the distal segment compared to the proximal segment of the tibia. (c) Clinical comparison with the contralateral leg. (d) To track distal tibia derotation the whole distal segment is navigated using the tracker fixed on it with a 2.5 mm K-wire. (e) The navigation screen showing the angle calculation and the tracking of the distal tibia. (f, g) Postoperative non-weight-bearing radiographs, leg AP view; sagittal view.

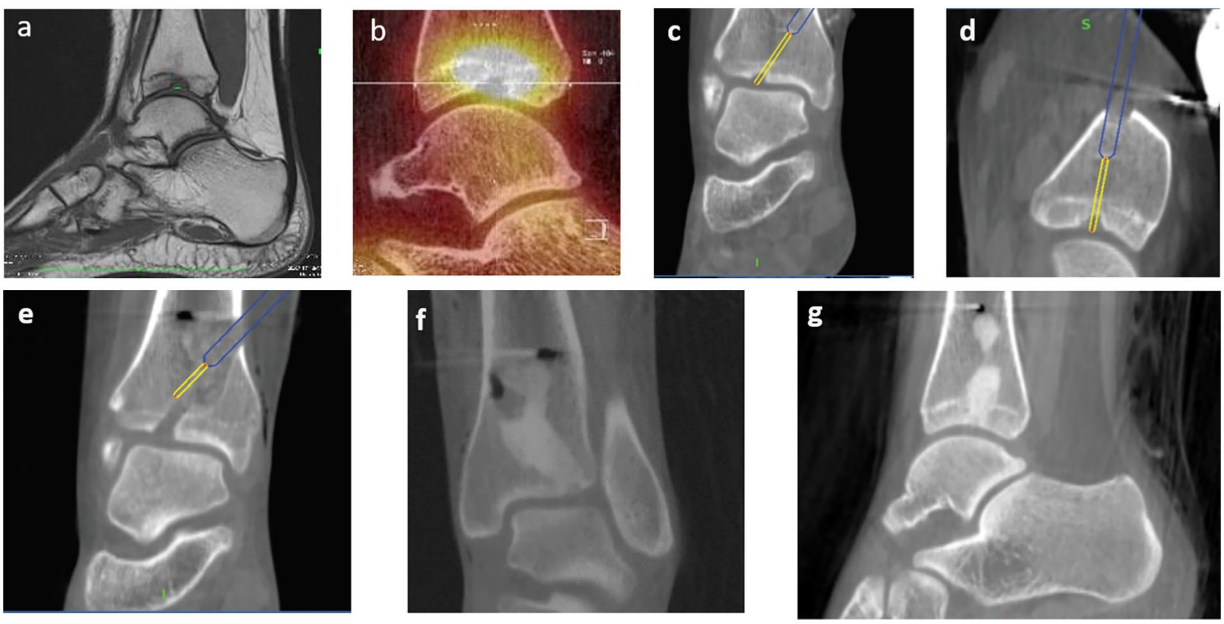

Fig. 8 Distal tibia osteochondral lesion retrograde grafting. (a) Ankle MRI shows a distal tibial osteochondral lesion combined with a cyst. (b) SPECT-CT shows a high uptake zone at the lesion site. (c, d, e) Navigation of the tunnel drilling as seen on the screen. (f, g) Intraoperative CBCT ensuring optimal lesion filling, coronal and sagittal views.

Note. MRI, magnetic resonance imaging; SPECT, single photon emission computed tomography; CT, computerized tomography; CBCT, cone beam computed tomography.

treatment, including immobilization and footwear adaptation (Fig. 8 a, b). The surgical challenge is mainly to access the lesion site without disturbing the ankle joint, as well as an adequate debridement and filling of the cyst with accurate autograft impaction exactly at the level of the bone cyst, without violation of the tibiotalar joint.

The power drill is calibrated using the adapter and navigated, allowing for optimal entry (Fig. 8 c, d, e). The cyst can be debrided without violation of the talar side of the joint. An autologous cancellous bone graft can be harvested from the ipsilateral proximal tibia and then impacted deep in the tunnel. An intraoperative CBCT scan is obtained to confirm adequate filling of the cyst site and a smooth articular surface (Fig. 8 f, g).

Conclusion

The introduction of CAOS with intraoperative navigation in our practice has simplified complex surgeries and increased accuracy of reduction and fixation in many lower limb surgeries. It has broadened the indications for LIS and yet still enable us to achieve the aims of our surgical plan with precision.

CAOS provides multiple advantages for foot and ankle surgeons. It facilitates anatomic reduction in LIS with better image resolution in CT images compared to fluoroscopy images. In addition, it allows intra-operative real-time evaluation of reduction and fixation and hence immediate correction if needed. This avoids unnecessary revision surgery related to bony malreduction or implant malposition. Furthermore, it reduces theatre personel`s net exposure to radiation. This is based on the set-up that allows staff to leave the room while acquiring the few scans as opposed to direct fluoroscopy that required multiple shots. This technique is useful for less experienced surgeons as an aid for immediate assessment and correction of malpositioning and hence shortening the learning curve.

After an experience of more than 1000 surgical cases done at our institution since 2008, the benefits as mentioned above have justified the continued use of CAOS. New software and user-friendly equipment could be developed to facilitate the more widespread adoption of this technology.

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