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Preoperative Guidance With Weight-Bearing Computed Tomography and Patient-Specific Instrumentation in Foot and Ankle Surgery

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Abstract
The use of preoperative and intraoperative guidance in foot and ankle surgery has grown substantially in recent years. Weight-bearing computed tomography (WBCT) and patient-specific instrumentation (PSI) are used in total ankle arthroplasty (TAA) to achieve precise bone cutting and implant positioning, and intraoperative 3-dimensional (3D) imaging has been used to reduce complications and improve clinical outcomes in other foot and ankle surgical procedures. This narrative review of the literature focuses on the evidence supporting the use of WBCT and PSI in TAA and looks at other promising technologies used to guide foot and ankle surgery.

Keywords
robotics/CAOS, basic science, navigation, guidance, ankle, arthroplasty

Introduction

In recent years, several preoperative and intraoperative guidance techniques have emerged in foot and ankle surgery. Although intraoperative robotics and navigation are not currently used in foot and ankle surgery, new guidance techniques have contributed to an increase in the information accessible to surgeons. Weight-bearing computed tomography (WBCT) can be used to create patient-specific instrumentation (PSI) for surgery. The implementation of WBCT, PSI, and intraoperative imaging has been valuable in total ankle arthroplasty (TAA), as well as in other foot and ankle procedures.

Arthritis of the ankle joint affects about 1% of the population [7]. End-stage ankle arthritis can give rise to debilitating outcomes that compromise quality of life—for example, pain and swelling that limits work and daily function and creates emotional and mental distress [15]. Recently, TAA has emerged as a valid alternative to ankle arthrodesis, which was historically the gold-standard treatment for ankle arthritis [35]. The number of total ankle replacements performed annually continues to rapidly increase [30]. This increase is linked to improvements in implant design and surgical techniques, which have led to improved implant longevity and expanded patient candidacy.

Proper bony alignment and implant positioning are crucial to optimize postoperative outcomes following TAA [5]. Even minor malpositioning can significantly affect motion and contact pressure, potentially leading to implant failure [18,39,45]. Implant positioning is critically dependent on the quality of cuts of the distal tibia and proximal talus. Cuts that are inappropriately varus, valgus, internally rotated, externally rotated, dorsiflexed, plantarflexed, or uneven (and therefore cause the implant to not seat fully on bone) can all increase micromotion, bony strain, and the risk for implant failure [44]. Recent innovations in TAA have allowed surgeons to provide more accurate component positioning using PSI with individualized cutting guides generated from WBCT scans [12]. These advancements allow for improvements in bone cutting precision prior to implant insertion.

This review article includes a brief discussion of innovations in foot and ankle procedures outside of TAA, in which similar imaging techniques are being used to

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provide surgeons with a more complete understanding of patients' unique anatomical features. This information can help guide preoperative planning and operative decision-making. For example, in procedures such as arthrodesis and open reduction internal fixation (ORIF), the use of PSI and novel intraoperative imaging techniques—such as 3-dimensional (3D) fluoroscopy and computed tomography (CT)—can help surgeons by providing guidance that enables them to make better-informed decisions during surgery, ultimately improving clinical outcomes.

Preoperative Imaging

Use of WBCT in Foot and Ankle Surgery

WBCT involves CT imaging of the loaded foot and ankle while the patient is standing upright. It is used to identify underlying pathologies, such as malalignment and impingement, that may not be fully appreciated when the joint is offloaded. WBCT uses cone-beam CT technology, rather than conventional multidetector CT configurations, to allow the detector to move around the upright patient while he or she remains stationary [31].

Compared to other imaging modalities, WBCT has demonstrated substantial advantages. Conventional X-rays have demonstrated limitations in terms of perspective, rotational and fan distortion, and reproducibility [4,6,31]. In addition, the complex architecture of the foot and ankle present challenges when using X-rays to visualize the anatomy, even if loads are borne during capture. Conventional CT can compensate for some of these limitations, but it does not allow for weight-bearing capability, rendering it somewhat misrepresentative of the articular configuration when a patient is loading the joint. Without loading the foot, pathological severity is often underestimated and clinical manifestations may appear less severe or even undetectable [21]. To fully understand the function of the foot and the relationships of structures, the joint must be in the appropriate weight-bearing position. WBCT enables this, providing a more accurate representation of the true orientation of the ankle during loading [11]. As a result, it has the potential to improve clinical outcomes in complicated foot and ankle disorders.

This technology has applications in TAA and in numerous other areas of foot and ankle surgery, including adult-acquired flatfoot deformity (AAFD), hallux valgus, injury at the syndesmosis, and lateral ankle instability, among others [11]. In patients with AAFD, WBCT can identify with greater sensitivity subtalar and subfibular impingement, potentially providing insight into which patients might fail a flatfoot reconstruction [26,32]. In patients with hallux valgus, WBCT can be used to identify the degree of pronation of the first metatarsal to guide surgical management [9,29].

Use of WBCT in TAA

Preoperative CT-derived PSI alignment guides allow for optimal bone cuts in TAA [48]. These guides are designed using 3D imaging from the patient's preoperative WBCT. The cutting guides are constructed based on the patient's unique anatomy, thus offering the potential to improve ankle alignment and reproducibility of the prosthesis placement [7,23].

The use of CT-based cutting guides and implants may enable more accurate and reliable bone cutting [20]. While there is no current intraoperative navigation system for use in TAA, incorporating WBCT into the preoperative planning process allows for modeling of potential implant sizes and positions. Computer models are able to account for the degree of deformity, retained hardware, and the presence of large cysts or osteophytes [23]. This all allows for more comprehensive preoperative planning and, ultimately, less variability in the operating room.

Preoperative WBCT is also useful in the evaluation of ancillary procedures to be done alongside TAA, including calcaneal osteotomies, ligamentous reconstruction, and adjacent joint arthrodesis [13]. This is clinically significant, as 73% of ankles with varus deformity greater than 5° require ancillary procedures [43]. Understanding the functional loading anatomy of the foot and ankle using preoperative WBCT is critical to developing a preoperative plan for intraoperative reconstruction.

Due to the novelty of WBCT technology, there are limited data on its usefulness in reducing postoperative complications, and further clinical studies are warranted. While correlations between implant positioning and outcomes have been reported [8,33,42], further investigation is needed to determine the position that yields optimal outcomes. The available evidence shows that using preoperative WBCT for intraoperative procedures can both decrease operative time and increase rates of implant survival [1,41]. Moreover, both preoperative WBCT and PSI have the potential to improve accuracy and reproducibility of component alignment, thus resulting in more appropriate correction of deformities as more is learned about optimal implant positioning and alignment. This can in turn decrease the need for corrective osteotomies, ultimately lowering the burden for patients [48].

Intraoperative Guidance

PSI

Several PSI systems on the market used in TAA aim to facilitate the installation of the implant using customizable modules created from CT imaging. The most widely used is PROPHECY (Wright Medical Technology, Memphis, TN), which is most commonly used for preoperative navigation

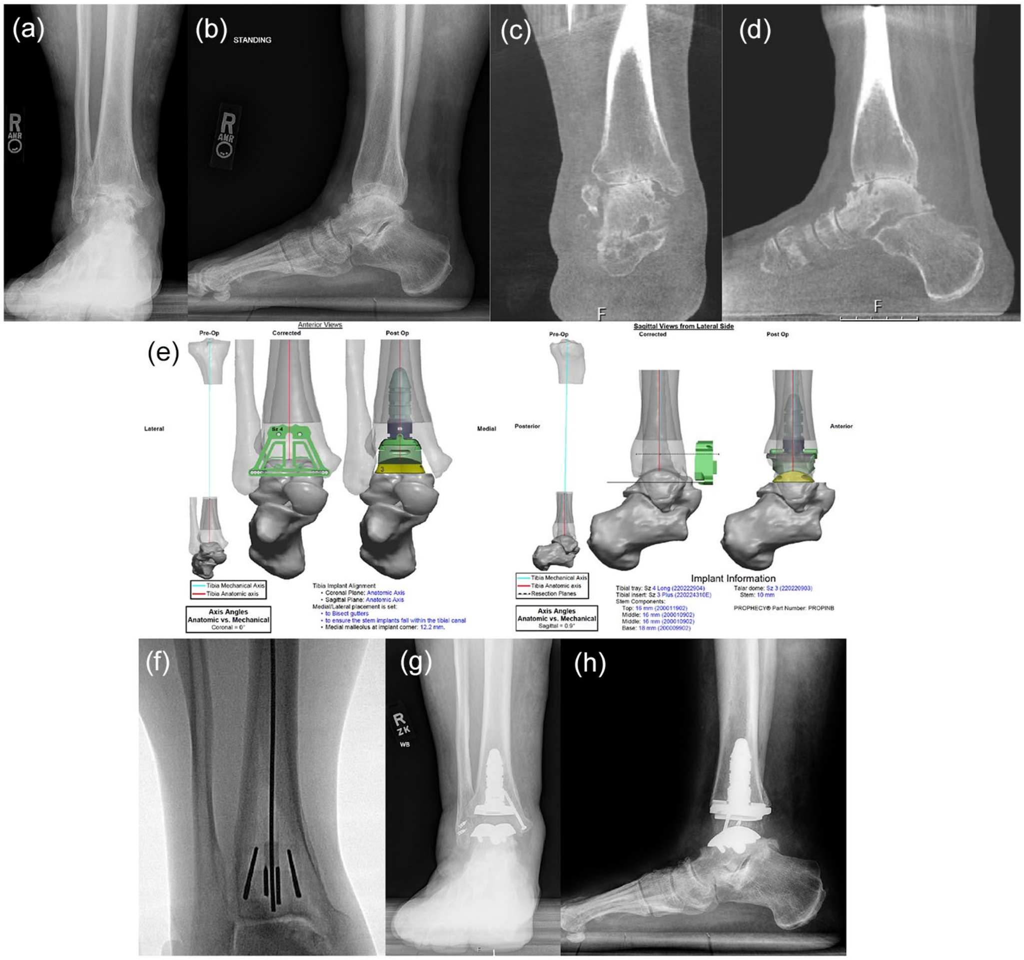

Fig. 1. An INBONE total ankle replacement in a 48-year-old man with end-stage ankle arthritis: preoperative standing radiographs (a: anteroposterior [AP], b: lateral); preoperative weight-bearing computed tomography (c: coronal, d: sagittal) used to create patient-specific instrumentation with customized cutting guides and a preoperative surgical plan (e); intraoperative fluoroscopy (f) used to confirm adequate position of the cutting guides; postoperative weight-bearing (WB) radiographs (g: AP, h: lateral) showing excellent positioning and adherence to the preoperative plan.

with the INFINITY (Wright Medical Technology) total ankle system, a modular prosthetic. However, PROPHECY can also be used alongside the INVISION and INBONE II (Wright Medical Technology) modular prostheses; these are commonly used in TAA revision, as well as in TAA cases with extensive deformity. WBCT imaging has recently been used alongside PROPHECY [48]. The PROPHECY system optimizes accuracy; with INBONE, it was found to produce an average variation between preoperative planned implant placement and postoperative actual implant placement of less than 2° and less than 1.4 mm [7]. A case example with INBONE is shown in Fig. 1, and a case example with INFINITY is shown in Fig. 2.

In addition, PSI systems can improve accuracy and precision in cases of extensive tibial deformities or existing implants. In implant systems like Vantage (Exactech, Gainesville, FL)—which uses an extra-medullary alignment guide anchored at a proximal pin at the tibial tubercle—deformity at the knee or tibia may make it difficult to assess alignment for bony cuts. A case example with Vantage is shown in Fig. 3. Moreover, implants proximally such as a total knee arthroplasty (TKA) prosthesis may further complicate this process and necessitate alternative methods for judging bony resection. In cases such as these, PSI provides an opportunity to ensure satisfactory bony cuts and implant position while minimizing complications. Another PSI system newly available on the market is the APEX 3D (Paragon28, Englewood, CO), which is designed for maximal rotational stability during natural motion of the ankle [2,19]. Further research regarding the accuracy and precision of these PSI systems is warranted.

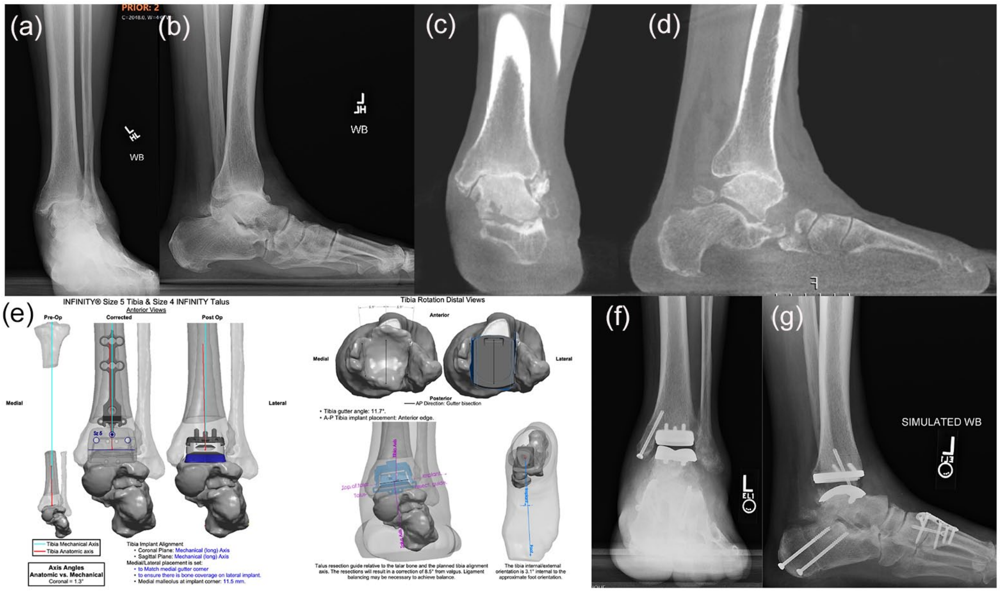

Fig. 2. An INFINITY total ankle replacement in a patient with end-stage ankle arthritis and valgus deformity of the hindfoot: preoperative anteroposterior (AP) (a) and lateral (b) weight-bearing (WB) radiographs; preoperative WB computed tomography (c: coronal, d: sagittal) used for preoperative planning (e) that includes customized cutting guides and guidance for implant position; postoperative standing AP (f) and lateral (g) radiographs confirming position of the implant and of the hindfoot (the patient also underwent concomitant calcaneal osteotomy and first tarsometatarsal fusion to realign the foot).

Intraoperative Imaging

While not yet approved for use in TAA, advanced intraoperative radiologic techniques have already improved surgical methods for multiple procedure types in foot and ankle surgery [33,41]. Unlike traditional fluoroscopy, which produces 2-dimensional (2D) images, intraoperative 3D fluoroscopic imaging uses a mobile isocentric C-arm to obtain CT-like 3D images. This has improved outcomes in foot and ankle surgery, specifically in operative treatment of osteochondral lesions of the talus [22]. In fixation of both ankle and pilon intraarticular fractures, 3D fluoroscopy helps prevent revision procedures [3]. Intraoperative guidance using 3D imaging provides novel information: Richter [41] found that in about one-third of fracture reduction and fixation cases, it illuminated the need for reduction/correction and/or implant repositioning.

Another type of intraoperative imaging system that uses CT, known as the O-arm, is used for ORIF of calcaneal fractures and syndesmotic injuries, allowing for more accurate visualization of bony anatomy and implants. Intraoperative use of the O-arm has been shown to improve patient outcomes, including wound healing and revision rates [10]. The O-arm can also be used intraoperatively to identify diastases of the syndesmosis that would otherwise be missed [16]. It also improves the detection of necessary intraoperative re-reduction in ankle ORIF and the quality of resection in talocalcaneal coalitions in children, a procedure in which 3D fluoroscopy is less contributive [17,27].

Imaging can also be used to make 3D models of a joint for intraoperative guidance in a technique known as computer-assisted surgery (CAS). The use of CAS in arthrodesis of foot and ankle deformities allows for rapid correction and improved accuracy, potentially leading to improved clinical outcomes [14,41]. CAS guidance uses 3D fluoroscopy or CT for intraoperative navigation to provide immediate control of surgical treatment. It has improved accuracy, procedure speed, and clinical outcomes in the correction of deformities of the ankle, hindfoot, and midfoot/tarsometatarsal [12].

Future Applications

Intraoperative navigation been used in other orthopedic procedures for decades. Since first being used for TKA in the 1990s, CAS has improved the accuracy of tibial preparation, coronal alignment, and implant survival [1,28,47]. When it is used in total hip arthroplasty (THA), CAS results in better positioning of the implants and may reduce intraoperative complications [34,38,40].

Intraoperative navigation in TAA has significant potential benefits, as described by its use in TKA and THA. The Mako (Stryker, Kalamazoo, MI) is a robotic-arm assisted surgery system that enables accurate execution of the

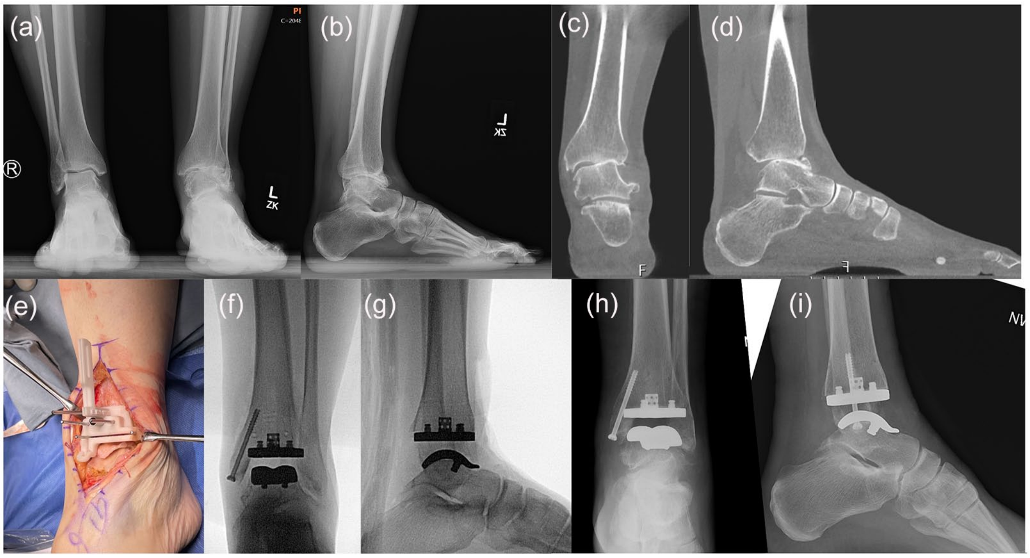

Fig. 3. A vantage patient-specific instrumentation total ankle replacement in a 54-year-old woman with debilitating left ankle arthritis: preoperative standing radiographs (a and b); preoperative weight-bearing computed tomography (c: coronal, d: sagittal) used for preoperative planning and creating patient-specific cutting guides; intraoperative photograph (e) of the customized cutting guide pinned into place; intraoperative fluoroscopy (f: anteroposterior, g: lateral) demonstrating the implant; early postoperative non-weight-bearing radiographs (h: anteroposterior, i: lateral) showing excellent implant position.

surgical plan and protects against soft tissue damage in TKA and THA [46]. KneeAlign and HipAlign (OrthAlign, Aliso Viejo, CA) are intraoperative navigation systems that provide information on where to cut the distal femur and proximal tibia in TKA and on cup placement and leg length in THA [36,37]. Intellijoint KNEE and Intellijoint HIP (Intellijoint Surgical, Kitchener, ON) are navigation tools that provide real-time intraoperative measurements for accurate TKA and THA implant alignment [24,25]. The use of these technologies in TAA, alongside WBCT planning, has the potential to offer precise and accurate implant positioning. While current WBCT and PSI allow for precise tibial and talar cuts, there is still the risk for subsequent implant malrotation or malposition. An additional direction to explore is to validate the measurements that have been collected using existing deep learning and artificial intelligence algorithms. This would entail using measurements recorded by WBCT, for example, to develop models that can predict clinical outcomes. Using these methods, the measurements will become increasingly accurate as additional data are collected.

Finally, an ultimate goal for intraoperative guidance would be the implementation of WBCT techniques in the operating room. Currently, surgeons simulate loading using 2D imaging, but this has limited efficacy. Simulated weight-bearing with a 3D imaging modality could provide accurate and immediate feedback on implant positioning, joint alignment, and projected function.

In conclusion, recent technological advancements in orthopedic surgery have led to the incorporation of operative navigation and preoperative planning to improve clinical results. In TAA, preoperative WBCT has helped surgeons better understand the orientation and specifications of patients' joints, and it allows for the development of individualized cutting guides that are both reliable and reproducible. In other areas of foot and ankle surgery, intraoperative fluoroscopic and CT imaging has improved postoperative outcomes, reducing complications and revisions. Future work in TAA will ideally lead to intraoperative navigation to further improve implant positioning and maximize outcomes.

Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: S.E. has relationships with Paragon 28, Stryker, Wright Medical Technology, American Orthopedic Foot and Ankle Society, and *Foot and Ankle Orthopedics*. J.Z. and J.H. declare no potential conflicts of interests.

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Level of Evidence

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Required Author Forms

Disclosure forms provided by the authors are available with the online version of this article as supplemental material.

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