

Review

Multimodal analysis and reconstruction of medical images in the evaluation of foot and ankle pathologies: Clinical and technological perspectives

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Abstract

Objective: To analyze recent literature on 3D reconstruction technologies and multimodal fusion of medical images in orthopedics, with a focus on foot and ankle applications, and to discuss their potential, limitations, and future directions.

Methods: This narrative review included original articles from 2010 to 2024 from PubMed, Scopus, and IEEE Xplore databases, using keywords related to “foot,” “ankle,” “3D reconstruction,” “weight-bearing computed tomography,” “machine learning,” “augmented reality,” and “multimodal fusion.” Studies on 3D reconstruction, image evaluation algorithms, and integration of imaging modalities in orthopedics were selected, with particular emphasis on those related to the foot and ankle. Those not affiliated with the medical field or specialty were excluded. The extracted data covered authorship, year, imaging modality, population, objective, and main conclusions.

Results: Twenty-one studies were included in four categories: (1) standing weight-bearing computed tomography (WBCT) of the ankle and knee (4 studies), with greater precision and reproducibility than 2D radiographs; (2) 2D-3D algorithms (6 studies) based on neural networks and statistical models, capable of generating 3D models from conventional exams; (3) machine learning (3 studies) for fracture classification and ligament diagnosis, with high accuracy in automatic detection; and (4) augmented/mixed reality (8 studies) applied to surgical navigation and training, improving accuracy, reducing surgical time and radiation, in addition to showing educational potential.

Conclusion: 3D reconstruction and multimodal fusion technologies provide new tools for evaluating foot and ankle pathologies. WBCT remains the gold standard for visualizing dynamic changes, but its restricted access can be mitigated using artificial intelligence for 3D reconstructions from conventional examinations. Advances in augmented reality and multimodal image fusion will permeate surgical diagnosis, planning, and execution, adding precision and safety in clinical practice.

Level of evidence V; Expert opinion; Therapeutic studies - investigating the results of treatment.

Keywords: Foot; Ankle; 3D reconstruction; Weight-bearing; Computed tomography; Artificial intelligence; Augmented reality.

Introduction

The foot and ankle joints play an essential role in distributing body weight during gait. Due to its intricate anatomy and significant dynamic changes, multiple imaging modalities are often required for complete three-dimensional (3D) vi-

ualization of the structures involved, especially when observing structural changes in weight-bearing situations^(1,2).

In this context, although computed tomography (CT) and magnetic resonance imaging (MRI) are widely employed, their limitations include the supine position during the exa-

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mination, which makes functional assessment without weight-bearing unfeasible. Advances such as weight-bearing CT (WBCT) have demonstrated improved results, although cost and limited availability limit its widespread adoption⁽³⁻⁵⁾.

Recent advances in artificial intelligence (AI), machine learning, and augmented reality (AR) have enabled 3D reconstructions from two-dimensional (2D) images and the integration of multiple imaging modalities. Convolutional neural networks have been applied for automatic segmentation and volumetric reconstruction of bones from conventional radiographs or tomographies. Multimodal fusion methods combine CT, MRI, and radiographic information to generate more detailed 3D models, while AR systems aid surgical navigation and the teaching of orthopedic procedures⁽⁶⁾, thereby improving diagnostic and surgical accuracy.

This study aims to demonstrate the practical applications of AI in foot and ankle surgery and to highlight advances in related fields, thereby informing new research directions. Such projects may be the key to solving one of the great challenges of orthopedic surgeries, especially in foot and ankle surgery, which is that the clinical analysis of the pathologies is performed with the limb in orthostasis and with weight-bearing, but the corrective surgeries and complementary exams are performed with the patient in the decubitus position and without weight-bearing.

Therefore, the objective of this narrative review is to analyze recent literature on 3D reconstruction technologies and multimodal fusion of medical images in orthopedics, with a focus on foot and ankle applications, and to discuss their potential, limitations, and future directions.

Methods

This is a narrative review of the literature. The searches were conducted in the PubMed, Scopus, and IEEE Xplore databases between January and April 2025, using combinations of keywords in Portuguese and English: “pé,” “tornozelo,” “pé plano,” “weight-bearing CT,” “tomografia com carga,” “reconstrução 3D,” “realidade aumentada,” “machine learning,” and “multi-modal image fusion.” The references of the included articles were also analyzed to identify additional studies.

Original studies on: (1) 3D reconstruction applied to foot, ankle, or lower limb exams; (2) AI algorithms or neural networks for segmentation, classification, or measurement of bone and joint structures; (3) multimodal fusion involving CT, MRI, radiography or WBCT; and (4) AR applications in surgical navigation or orthopedic training were included. Opinion articles, letters to the editor, and studies unrelated to orthopedics were excluded.

The screening consisted of reading titles and abstracts, followed by a full analysis of eligible texts. The extracted data included authors, year, study type, imaging modality, technology employed (WBCT, AI, AR, multimodal fusion), and main findings. Methodological evaluation metrics were not applied, given the descriptive nature of the review.

Results

Two hundred and thirteen records were retrieved, of which 32 articles were evaluated in full and 21 were included in the final synthesis. The studies were divided into four categories: (1) WBCT; (2) 2D-3D image reconstruction; (3) machine learning to evaluate fractures and ligament injuries; and (4) augmented/mixed reality. Table 1 presents its main characteristics.

After synthesizing the studies, it was observed that, despite the current superiority of WBCT in 3D evaluation, the limited availability and cost of the devices restrict their routine use. 2D-3D reconstruction algorithms have demonstrated that statistical models and convolutional networks can generate 3D reconstructions with millimeter-level accuracy, enabling the simulation of weight-bearing examinations from conventional radiographs. Machine learning studies on fracture and ligament injury detection have achieved accuracies greater than 90%^(7,8), suggesting that AI can assist radiologists and surgeons in decision-making. Augmented reality applications have shown reductions in surgical time and radiation exposure, as well as greater accuracy in surgical navigation^(9,10) and improved resident teaching⁽⁶⁾.

The analysis of the included studies highlights the growing application of AI, 2D-3D reconstruction algorithms, multimodal fusion, and AR in orthopedics, with consistent performance in terms of accuracy, reproducibility, and clinical applicability.

Discussion

This review shows that the use of digital technologies in foot and ankle care has evolved consistently over the last decade, particularly in WBCT, 2D-3D reconstruction algorithms, machine learning, and AR. Despite the methodological heterogeneity of the included studies, there is a clear tendency to incorporate tools to assess image-based evaluation of real weight-bearing conditions and to improve diagnostic and therapeutic accuracy.

WBCT is established as the gold standard for 3D evaluation of orthostasis, enabling more accurate characterization of orthopedic deformities than conventional radiographs and other non-weight-bearing examinations^(11,12). However, the studies analyzed demonstrate that its high cost and restricted availability limit its routine use, particularly in resource-constrained health settings. In this scenario, 2D-3D reconstruction algorithms emerge as a promising alternative, enabling the generation of 3D models from widely available exams^(13,14) and offering a pathway to expand access to 3D analysis in services without WBCT infrastructure.

The generation of 3D models from examinations involves critical steps: segmentation, in which the structures of interest are identified and separated from the others; registration, which aligns images in the same coordinate system, especially when different modalities are combined; and volumetric reconstruction, in which software transforms the data into a manipulable 3D model. Figure 1 presents a flowchart illustrating how the process would proceed.

These steps, intuitive to the human observer, pose technical challenges for AI algorithms, which need to be trained to distinguish anatomical boundaries within complex color scales. When such barriers are overcome, the resulting models can be applied to surgical planning, intraopera-

tive navigation, and even 3D printing for educational and therapeutic purposes.

Machine learning, in turn, has shown potential to reduce interobserver variability and to accelerate the diagnosis of fractures and ligament injuries⁽¹⁵⁻¹⁷⁾. However, most of the

Table 1. Summary of articles evaluated

No.	Study	Study design	Objective	Imaging tests used	No. of exams/cases evaluated
1	Astolfi et al. (2023)	Comparative retrospective diagnostic study	Compare expert accuracy vs. machine learning algorithm in detecting anterior talofibular ligament ankle injury	Magnetic resonance imaging (MRI)	321 images (ATFL lesion and normal)
2	Burssens et al. (2016)	Observational study	Validate a new method for measuring forefoot angles in WBCT scans, comparing with weight-bearing radiographs	WBCT and radiographs	60 exams
3	Butler et al. (2023)	Prospective case series (Augmented Reality in spine surgery)	To evaluate the efficiency and complications of AR in the percutaneous placement of vertebral pedicle screws	Intraoperative imaging + CT	164 cases, 606 screws
4	Cao et al. (2022)	Descriptive/anatomical study	Reconstruct three-dimensional fractures of the lateral malleolus and evaluate parameters to predict preoperative syndesmosis lesions	TC	148 cases
5	Godoy-Santos (2018)	Narrative review	Update on the use of WBCT on the foot and ankle	Not applicable	Not applicable
6	Kim et al. (2023)	Retrospective neural network validation study	Evaluate the utility of a neural network to perform a multivariate analysis of parameters present in ankle radiographs	Radiographs	1493 exams
7	Leão et al. (2024)	Prospective pilot study	Test parameters measured in WBCT to assess the instability of knees with chronic ACL injury	WBCT	05 cases
8	Lee et al. (2017)	Proof of concept/method	Demonstrate a real-time multimodal image fusion AR method to guide orthopedic procedures	Fluoroscopy + CT	Not applicable
9	Li et al. (2021)	Computational method development	Compare a new multimodal image fusion method with established methods	MRI + PET-MRI + SPECT + CT	12 pairs of exams
10	Li et al. (2023)	Narrative review	Describe historical and technical aspects of the creation, development, and evolution of surgical navigation systems	Not applicable	Not applicable
11	Matthews (2021)	Narrative review	Review the literature on clinical application of AR in orthopedics	Not applicable	Not applicable
12	Montemagno et al. (2024)	Randomized clinical trial	To compare the performance of residents vs. attending physicians in the diagnosis of acetabular fractures with AR vs. 3D printing vs. CT	CT	Not applicable
13	Nguyen et al. (2023)	Technical methodological study	Develop for 3D reconstruction of lower limbs from orthogonal biplanar radiographs	Radiographs	13 pairs of radiographs
14	Olczak et al. (2021)	Retrospective study	Demonstrate the accuracy of a deep learning model in the radiographic classification of ankle fractures according to the AO/OTA 2018 classification	Radiographs	4941 exams
15	Ortolani et al. (2021)	Cross-sectional observational study	Demonstrate the advantages of measuring deviations and angles in the flatfoot through the use of 3D image reconstruction and WBCT	WBCT	21 patients
16	Pei et al. (2021)	Algorithm development study	Measure the hip-knee-ankle angle through a deep learning algorithm in lower limb radiography	Radiographs	398 exams
17	Polt et al. (2024)	In vitro comparative experimental study	Compare the technical accuracy of the conventional vs. AR-assisted method in calcaneal elongation with osteotomy using a bone model	Not applicable	120 models
18	Shiode et al. (2021)	Computational method development	Develop and test a neural network model to reconstruct 3D models of the distal portion of the forearm from radiographs	CT + Radiographs	173 CTs + 105 radiographs
19	Tu et al. (2021)	Pilot study/proof of concept	Evaluate AR navigation with HoloLens 2 to guide intramedullary distal stem block	Not applicable	Not applicable
20	Wang et al. (2016)	Technical-clinical pilot study	Demonstrate the benefits of the insertion accuracy of sacroiliac screws in cadaver models from the use of AR systems	CT + AR	06 cases
21	Zhao et al. (2020)	Technical experimental study	Evaluate CT cone beam performance with tilted rotary shaft in phantom/technical manipulation	CT	Not applicable

WBCT: Weight-bearing computed tomography; CT: Computed tomography; AR: Augmented reality; MRI: Magnetic resonance imaging; SPECT: Single photon emission computed tomography; PET: Positron emission tomography

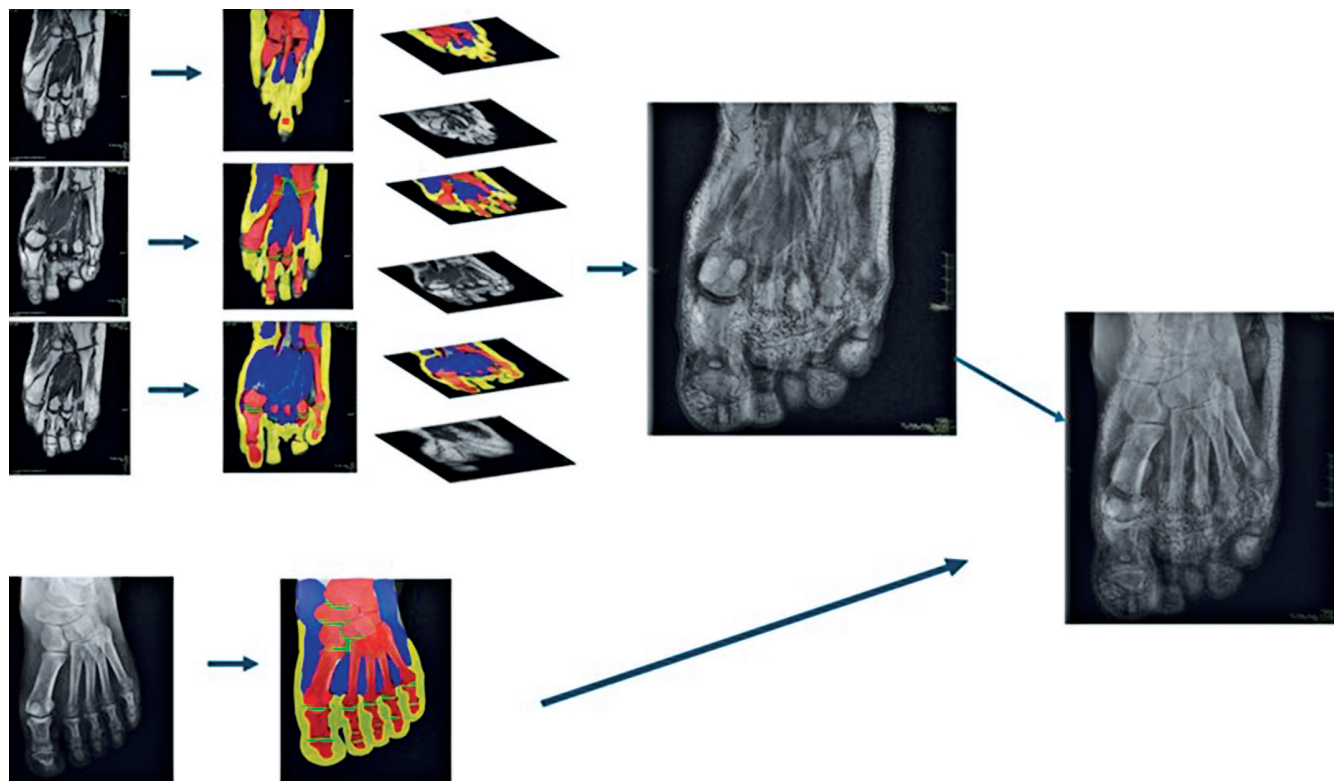


Figure 1. Flowchart of the steps for image fusion.

revised algorithms were trained on relatively small databases, lack external validation, and do not present impact assessments on clinical outcomes or cost-effectiveness. Thus, the routine incorporation of AI in orthopedic practice depends on prospective studies that overcome these limitations.

Fusion of images from different modalities (CT, MRI, radiographs) has been shown to be useful for optimizing soft-tissue visualization and guiding minimally invasive procedures, while AR systems have demonstrated greater accuracy in surgical navigation⁽¹⁸⁻²¹⁾, reduced fluoroscopic exposure, and increased use in immersive training. However, most available studies address the spine, pelvis, or hip; in the foot and ankle, evidence remains incipient, limiting clinical extrapolations.

The practical implications of this review indicate that, although such technologies already demonstrate clear benefits, the field remains in a state of consolidation. For the foot and ankle orthopedist, this means access to tools with the potential to refine diagnosis, optimize surgical planning, and reduce complications, but which do not yet have robust clinical validation.

Among the research priorities identified are (1) clinical trials that evaluate the accuracy, applicability, and functional impact of technologies; (2) cost-effectiveness and accuracy studies that determine the feasibility and benefit of reconstruction

algorithms to replace WBCT; and (3) multimodal fusion protocols based on broad datasets, increasing their validity and accuracy.

Therefore, although advances in 3D reconstruction, machine learning, and AR represent a milestone in the evolution of surgical diagnosis and planning, their incorporation into clinical practice still depends on the consolidation of evidence demonstrating not only technical performance but also direct patient benefit.


Conclusion

Three-dimensional reconstruction and multimodal image fusion represent significant advances in orthopedics, particularly for the evaluation of complex joints such as the foot and ankle. This review showed that such technologies increase diagnostic accuracy, favor surgical planning, and have potential for integration into navigation and training strategies. However, its large-scale clinical adoption remains limited by barriers including the scarcity of clinical studies, computational complexity, and the absence of standardized protocols.

From a clinical perspective, these tools may, in the future, aid the analysis of complex deformities and the performance of minimally invasive procedures with greater safety and reproducibility. For this potential to translate into real

patient benefit, research efforts should focus on developing accessible and reproducible algorithms and creating robust databases for training and external validation. Studies

focusing on clinical outcomes and cost-effectiveness will be fundamental to consolidating the application of these technologies in orthopedic practice.

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