Application of New Technologies

Patient-specific Instrumentation and Artificial Intelligence in the Field of Foot and Ankle

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KEYWORDS

- Patient-specific instrumentation • Artificial intelligence • Area under the curve
- Open reduction and internal fixation • CT

KEY POINTS

- New technologies and use of artificial intelligence is still in the very early stages in the field of foot and ankle.
- Patient-specific instrumentation is the most advanced form of this technology.
- Most studies in artificial intelligence in foot and ankle show good modeling performance, but these are simplistic models.
- Use of artificial intelligence in the clinic is still evolving with foot and ankle applications not much different than the rest of orthopedic fields currently.

INTRODUCTION

New technologies, namely patient-specific instrumentation (PSI) and artificial intelligence (AI) are being utilized in the orthopedic foot and ankle world in an increasing number of ways in both in the clinic and operating room settings.

PSI in the foot and ankle is based on advances seen in the field of joint replacement. AI in the foot and ankle is mainly based off of deep learning algorithms.

Deep learning algorithms are a class of machine learning models that use artificial neural networks with multiple layers to learn complex patterns from large amounts of data. Unlike traditional machine learning models, deep learning does not require manual feature extraction, and learn automatically from raw data, rather than machine learning models that require the input of preselected features or characteristics.

A deep learning model typically has 3 types of layers. The input layer receives raw data. The hidden layer processes data through "neurons" that apply mathematical operations to detect patterns. The output layer produces the final analysis.

AI-based systems are measured by area under the curve (AUC) values. A higher AUC value indicates better model performance, with an AUC of 1.0 signifying a perfect model and 0.5 indicating a model that performs no better than the flip of a coin. Langerhuizen and colleagues[1] in a systematic review found AUC's ranging from 0.95 to 1.0 for the studies included in their review.

DISCUSSION

Artificial Intelligence in Operating Room

Operative uses of new technologies and AI are most extensive in the operating room. AI learning models can assist in preoperative planning by simulating surgical techniques and

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Abbreviations	
3D	3 dimensional
AI	artificial intelligence
AUC	area under the curve
BMI	body mass index
CT	computed tomography
PSI	patient-specific instrumentation

scenarios as well as optimizing implant selection and placement. The 2 most common practices currently in foot and ankle are using AI models to help with PSI in total ankle and total talus replacements.

The standard expectation of most ankle replacement systems is that there is the capability of PSI. The initial studies and the majority of this application of PSI for ankle replacements were and are still based on nonweight-bearing computed tomography (CT) scans. PSI for ankle replacements have been shown to have improved alignment and other operative metrics.

In a study of 159 patients undergoing 168 Infinity AA (61 PSI, 107 non-PSI), there was a statistically significant decrease in tourniquet time and reduced radiation exposure in the PSI group versus the non-PSI group. The angular correction of ankle arthritis deformity was also more accurate.[2] Furthermore, another study evaluating PSI versus non-PSI ankle replacements in 99 patients (75 PSI, 24 non-PSI) showed similar reduced operative time and fluoroscopy time in the PSI group as well. Tibial component alignment was similar in both groups, but the authors noted that the PSI preoperative plan reports were poor predictors of implant sizing.[3]

There have been a smaller cohort of studies looking at using weight-bearing CT scans for PSI for total ankle replacement. Ten patients who underwent ankle replacement after weight-bearing CT scans showed that postoperative coronal and sagittal plane alignment of the implants were within target goal of 5° or less, suggesting that PSI can be printed using nonweight-bearing or weight-bearing CT scans.[4] The lack of access to weight-bearing CT scans makes this still difficult to obtain for many surgeons and patients.

Another application of technology to improve surgical outcomes has been seen in treating bone loss in the talar. Total talar replacements are valuable as a treatment for a very difficult problem to treat otherwise. These issues are not very common, and finding large trials is difficult. However, these implants have a higher rate of complication than those PSI for total ankle replacements.

The first talar replacement prostheses were implanted in 1974 in Thailand. This partial replacement of the talar body was made from plain radiographs and manufactured with 316L stainless steel.[5]

One of the largest studies on total talus replacement was done on ceramic replacements. In 18 patients with mean follow-up of 152 months, there were no failures. This study also saw improvement in range of motion (ROM) from 25° to 45°. However, this cohort had a low body mass index (BMI) of 22.9, which the authors noted was not applicable to all populations.[6]

Another study used CT scans based on the contralateral talus. This study had 5 patients, 4 who had stainless steel talar replacement and 1 with a titanium replacement. After 18 months follow-up, complications in this small study were stiffness in the subtalar joint in 1 patient and pain with weight-bearing in 1 patient.[7]

One of the largest studies included 27 patients with custom 3 dimensional (3D)-printed talus based on either contralateral talus if there was collapse, or the ipsilateral talus if no collapse. Follow-up was 22 months. These implants were cobalt chromium with titanium nitride coating. There was no change in preoperative versus postoperative dorsiflexion, plantarflexion, or total ROM. Visual analog scale (VAS) pain scores decreased and foot ankle outcome scores (FAOSs) improved. There were 3 complications in this study. There was 1 case of distal tibial avascular necrosis (AVN), 1 superficial infection, and 1 superficial peroneal nerve neuroma. This patient with neuroma required excision 2.5 years postop. The AVN patient was converted to a tibial replacement with revision total talus. The infected patient underwent below knee amputation for residual pain even after a cavovarus reconstruction.[8]

A study of 15 custom cobalt chromium 3D-printed talus based on scan of contralateral talus. VAS and FAOSs scores showed significant improvement at 1 year follow-up. One patient required an incision and drainage of a wound dehiscence.[9]

Another study included 8 patients with custom titanium 3D-printed talus based on scan of contralateral talus. The mean age was 46 years and pathologies were multifactorial. Follow-up was 23 (12–49) months. At time of the publication, no revisions had been done. Seven patients had a mild gait abnormality, and 1 patient had a moderate abnormal gait. Seven patients had decreased ROM, 3 had rigid hindfoot varus, and 3 had discomfort with ankle ROM. The authors concluded that short-term to medium-term follow-up showed total talus replacement was a reasonable treatment.[10]

In a small study of 6 patients, total talus replacements have been used acutely to treat talus fractures with bone loss. The authors commented that external fixation was necessary in some patients to keep soft tissue tension as it took 5 weeks to print the talar replacements. One patient required a posterior capsule release and Achilles tendon lengthening at 10 months. This patient developed tibial sided arthritic changes and required ankle replacement conversion. A second patient also required ankle replacement due to arthritis.[11]

Combining PSI for ankle replacement and total talus replacement has also been done. In patients with an arthritic tibiotalar joint that would otherwise be a contraindication to a total talus replacement, an option combining these technologies is known as combined total ankle replacement (total talus implants used in conjunction with the tibial component of a total ankle replacement). One study had 22 patients with tibial component mated to a total talus based on CT scan of contralateral talus. They had mean follow-up of 35 months and the mean age was 72 years. The range of motion improved from 4° to 14.4° dorsiflexion and from 23.8° to 32.0° in plantarflexion. Three patients had delayed wound healing and 4 patients had medial malleolus fractures.[12]

Another study compared 10 patients with combined total ankle arthroplasty (TAA) with 12 patients who had standard TAA. The combined TAA had a TNK tibial component and an alumina ceramic talus. The mean age in the combined TAA was 71 years and the age in the standard TAA group was 75 years. Follow-up was 58 months in the combined TAA and 64 months in the standard TAA (48–88), respectively. They noted significantly higher postoperative outcome in the Japanese Society for Surgery of the Foot ankle-hindfoot scale in the combined TAA group (Tables 1 and 2).[13]

Three dimensional printing is currently the technology most commonly used in the operating room. The future of AI in the operating room is still theoretic in the field of foot and ankle. However, advances in augmented reality displays with integrated AI systems are emerging to provide real-time feedback and visualization intraoperatively.

Table 1
Studies on total talus replacement

Study	Number of Patients	Follow-up (Months)	Outcomes
Morita et al,[6] 2022	18	152	Low BMI of 22.9 with no failures ROM improved from 25° to 45°
Angthong et al,[7] 2020	5	18	One patient had stiff subtalar joint One had pain with weight-bearing
Kadakia et al,[8] 2020	27	22	No change in ROM preop vs postop VAS pain scores decreased and FAOSs improved Three complications: distal tibial AVN, superficial infection, and superficial peroneal nerve neuroma
Scott et al,[9] 2020	15	12	VAS and FAOSs showed significant improvement One patient required irrigation and debridement (I&D)
Abramson et al,[10] 2021	8	23	Eight patients with abnormal gait Seven had decreased ROM—3 had rigid hindfoot varus Three had discomfort with ankle ROM
Katsui et al,[11] 2020	6	47	Two required conversion to total ankle One required posterior capsule release/Achilles tendon lengthening

There are not many studies, and they are small with variable outcome reporting.

Table 2
The studies on the benefits of patient-specific instrumentation in total ankle replacement

Study	Number of Patients	Conclusions
Yau et al,[2] 2023	168 ankle replacements in 159 patients (61 PSI, 107 non-PSI)	Decreased tourniquet time, reduced radiation exposure, and improved angular correction of deformity in PSI group
Saito et al,[3] 2019	99 patients (75 PSI, 24 non-PSI)	Reduced operative and fluoroscopy time in the PSI group Tibial component alignment postop was similar in both groups. PSI preoperative plan was poor predictor of implant sizing
Thompson et al,[4] 2021	10 patients with weight-bearing CT scans	Coronal/sagittal plane alignment within target goal of 5° or less Concluded PSI can be used from nonweight-bearing or weight-bearing CT scans

Postoperatively, these same AI models can be used to support patient monitoring, detection of complications early, and individualized rehab protocols Meta-analysis by Misir and colleagues[14] showed that deep learning predictive models for complications were outperforming traditional scoring systems with AUC improvements between 0.1 and 0.15. Regarding applications for rehab, a meta analysis of 29 studies with a total of 164 patients by Zhang and colleagues[15] demonstrated that ankle function and gait were improved after the use of robot-assisted rehab devices. Robotic and AI-assisted technologies continue to be explored for intraoperative guidance and postoperative rehabilitation but use and outcomes specific to foot and ankle are limited mostly because of the wide scope of foot and ankle surgery and most evidence is extrapolated from higher volume arthroplasty procedures.[16]

Artificial Intelligence in the Clinic

AI is being increasingly used to provide predictive analytics used to gauge surgical outcomes, implant survivorship, and risk of complications. This is accomplished through integrating patient data including gait analysis, imaging, and electronic health records. In the foot and ankle world, AI tools are being primarily validated for imaging interpretation, fracture detection, and biomechanical analysis.

The performance of AI is increasingly being used to streamline clinic flow for patients and providers, particularly through scribe technology and automated documentation tools. Commercially available scribe platforms utilize large language models to transcribe and structure clinic notes from audio recordings of patient encounters. These systems will integrate with electronic health records, allowing the provider to record patient encounter visits and generate a draft of a clinic note, which includes the history, physical examination, assessment, and plan all within a minute for review and attestation.[17,18] This approach has demonstrated the potential for reduction in documentation burden and improved provider efficiency. This is not without limitations such as lack of regulatory oversight, interoperability, and confidence in the AI-generated outputs.[17,18]

Artificial intelligence in foot and ankle research

There have been AI models developed for total hip arthroplasty revision, blood transfusion after total knee arthroplasty, and detecting cervical spine cord compression on MRI. However, the majority of AI for lower extremity orthopedic injuries is fracture-based. Developing AI-based systems can automatically detect and classify foot and ankle fractures on radiographs and other imaging modalities with AUC values comparable to expert clinicians.

There have been a multitude of studies that have looked at detecting ankle fractures from plain radiographs. Ashkani-Esfahani and colleagues[19] validated ankle fractures from radiographs. Kitamura and colleagues[20] validated 5 separate convolutional neural networks (CNNs) for detecting ankle fractures from plain radiographs and achieved a fair fracture detection accuracy of 81%. Prijs and colleagues[21] validated a model for detecting, classifying, and localizing ankle fractures from plain radiographs and achieved an excellent AUC of 0.92 and an accuracy of 99% on external validation. Guermazi and colleagues[22] internally validated a DL model for detecting fractures from foot and ankle plain radiographs, which performed excellently with an AUC of 0.97, sensitivity per patient of 93%, and specificity per patient of 93%. Olczak and colleagues[23] internally validated neural network models for classifying ankle fractures from radiographs according to the AO Foundation/Orthopaedic Trauma Association 2018 classification, which showed fair to excellent performance with AUCs ranging from 0.79 to 0.99 in classifying AO types. Pinto Dos Santos and colleagues[24] internally validated a CNN for detecting fractures in anteroposterior ankle radiographs, which performed well with an AUC of 0.85.

Ashkani-Esfahani and colleagues[19] also validated 2 deep convolutional neural networks (DCNN) models for detecting Lisfranc instability from single-view (anteroposterior) and 3 view radiographs (anteroposterior, lateral, and oblique), which performed excellently with AUCs ranging from 0.925 to 0.994.

Aghnia Farda and colleagues[25] internally validated a CNN model for classifying calcaneal fractures on CT images into the Sanders system, which performed well with a classification accuracy of nearly 72% after augmenting the data.

Pranata and colleagues[26] internally validated 2 separate DCNN models for detecting the presence or absence of calcaneal fractures on CT images and achieved an excellent accuracy of 98%.

Multiple studies have been able to evaluate tibial shaft fractures with posterior malleolus fractures.

Hendrickx and colleagues[27] internally validated 4 machine learning and deep learning models for predicting patients with tibial shaft fractures and associated occult posterior malleolar fractures. The models performed well with AUCs ranging from 0.81 to 0.89.

Oosterhoff and colleagues[28] internally validated 5 models for predicting posterior malleolar involvement in distal tibial shaft fractures using the same data set as that in the previously described study by Hendrickx and colleagues. They found that all the models performed well with AUCs 0.80 (highest 0.89) and 4 of 5 having a Brier score of 0.11.

Merrill and colleagues[29] internally validated a logistic regression and gradient boosting model for predicting short-term complications, including mortality and readmissions, in patients who have undergone open reduction and internal fixation in acute ankle fractures.

Tendinopathies

There are many more studies so far on AI with regards to fractures than tendinopathy. There are a couple models looking at Achilles pathology.

Wang and colleagues[30] validated models for diagnosing Achilles tendinopathy from ultrasonographic images in skiers and achieved an excellent AUC of 0.99, 90% sensitivity, and 100% specificity.

Kapiński and colleagues[31] internally validated several DL models to classify Achilles tendons injuries on MRI scans, achieving a maximum accuracy of 97.6%, a sensitivity of 98.3%, and a specificity of 99.5%.

Gait

Chaabane and colleagues assembled a large database of 734 patients (115 adults, 619 children) encompassing 1459 gait sessions and 53,693 gait cycles, to predict future change in gait quality using 2 neural network approaches. Both approaches achieved an AUC above 0.72 for gait improvement versus deterioration. This study showed that AI can forecast gait quality progression from baseline kinematics.[32]

Özateş and colleagues[33] studied 6 common foot pathologies from 3D gait analysis data with by combining gait features with AI visualization. This study showed strong potential for objective, data-driven gait assessment in foot and ankle practice. However, external validation and prospective testing are needed before clinical implementation to ensure generalizability and true biomechanical relevance.

Future of Technology and Artificial Intelligence

There is a lack of multicenter prospective validation and standardized outcome reporting in foot and ankle applications. Most research so far focuses on technical performance rather than patient-centered outcomes. In summary, while AI as a diagnostic tool for foot and ankle surgery are highly accurate in retrospective and external validation studies focusing on fracture detection and gait analysis, there is not yet robust prospective or randomized controlled trial evidence demonstrating improved patient outcomes compared to standard practice. The current evidence demonstrates that AI as a diagnostic tool for foot and ankle surgery has shown high accuracy in retrospective studies, but prospective clinical validation and real-world impact on patient outcomes remain limited.

SUMMARY

PSI has been shown to be effective in decreasing surgical time, decreasing exposure to radiation, and allowing for very accurate placement of hardware.

AI in orthopedics has largely focused on imaging interpretation, fracture detection, and outcome prediction. These early models have been shown to match or exceed expert clinicians in retrospective studies. However, this is primarily in controlled settings, and most studies are retrospective and there is a lack of large-scale prospective validation.

AI shows promise in these areas and has shown to be helpful in the clinic setting in the way of scribe technology and automated documentation tools, further prospective research is needed to validate the ability of AI in these domains.

CLINICS CARE POINTS

- PSI has been shown to positively affect operative outcomes.
- AI models show promise as AUC shows equivalent or better reproducibility than expert clinicians.
- However, AI in the field of foot and ankle surgery has a long way to go with very few current clinical applications.
- With further validation, training, and advancement of AI tools and models, the role of AI within the orthopedic specialty has huge potential.

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