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Meta-Analysis

Weight-bearing computed tomography versus standard imaging for the evaluation of complex foot and ankle pathology: a systematic review and meta-analysis on the change in surgical planning and diagnostic accuracy

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ABSTRACT

Weight-bearing computed tomography (WBCT) is a paradigm change in imaging of the musculoskeletal system, as it records the foot and ankle in physiologic load. This systematic review is a critical appraisal of the diagnostic superiority and its impact on surgical decision-making of WBCT versus standard imaging (SI: radiographs and non-weight bearing CT) for complex foot and ankle conditions. Fifteen studies were included after a search of the literature, adherence to the PRISMA translation. A narrative synthesis and, where possible, a quantitative analysis was conducted. WBCT consistently showed significantly greater magnitude of deformity in conditions such as adult acquired flatfoot deformity (e.g., medial cuneiform-to-floor distance was reduced from 29 mm NWB to 18 mm WB) and highly reliable 3D biometrics (e.g., Foot and Ankle Offset ICCs 0.97 to 0.99). For Lisfranc injuries, WBCT was more sensitive for the detection of subtle instability. Crucially, WBCT was responsible for changing the surgical plan in a pooled 32% of cases (95% confidence interval (CI): 24–41%) with the most common changes made being addition or alteration of procedures. The quality of the included cohort studies was moderate and randomized trials showed some concerns regarding bias. While the technology provides better diagnostic insight and modification of preoperative planning in a large proportion of patients, the supporting evidence is largely from moderate quality, heterogeneous studies with a dearth of long-term outcome data. WBCT is an effective tool for assessment of load-dependent pathology and its incorporation of the diagnostic pathway for complex deformity and instability would seem to be justified.

Keywords:, Diagnostic accuracy, Foot and ankle, Meta-analysis, Surgery, Surgical planning, Standard imaging, Systematic review, Weight-bearing computed tomography

INTRODUCTION

The foot and ankle are a mechanically complex, three-dimensional structure that is composed of 28 bones, multiple articulations and interdependent ligamentous units operating under the constant influence of axial and rotational loading. Many clinically relevant disorders are intrinsically load-dependent, that is, their pathological alignment and instability occur mostly while standing rather than in unloading conditions. Progressive collapsing foot deformity (PCFD), chronic lateral ankle instability, syndesmotic insufficiency, Lisfranc injuries and post-traumatic malalignment are examples of disorders where joint relationships and magnitude of deformity are greatly altered with weight bearing.

The epidemiologic burden of the pathology of the ankle is high. A large population-based cohort study reported a mean incidence of ankle fracture of 164/100,000 person-years during a 15-year study period between 1997 and 2018 with increasing rates among women and elderly populations and a rise in operative treatment from 21% to 26%, highlighting the frequency and surgical relevance of these injuries.[1]

Standard imaging modalities are still the basis for the workup of the disease but have inherent limitations when used for load-sensitive pathology. Plain radiographs are susceptible to rotational error, variability in beam projection and poor reproducibility of measurements with respect to alignment, especially at the hindfoot and midfoot.[2-4] Non-weight bearing CT helps in better identification of fracture and delineation of osseous anatomy but does not reveal physiologic joint relationships.[3-5] Several studies have shown CT detects fractures and morphology missing on radiographs and changes the management decision in about 23% to >30% of foot and ankle trauma cases; a study shows both its diagnostic utility and its inability to accurately reflect functional alignment when acquired without load.[6-8]

WBCT was started in order to help fill this important void by integrating three-dimensional imaging with physiologic loading. With WBCT, the standing 3D data of submillimeter resolution is delivered with relatively low radiation dose using cone-beam technology. In addition to visual evaluation, WBCT can be used to measure quantitative biomarkers, including Foot and Ankle Offset and automated 3D alignment measures. Consensus statements now favour its use in PCFD because of superior visualisation of peritalar subluxation and hindfoot valgus as compared with conventional imaging.[2]

There are high adoption rates in large institutional experiences, where over 1,100 scans have been conducted at the institution in about five years and the downstream implications of the technology, in terms of diagnosis and surgical planning, are common.[4] Reliability studies have further shown significantly higher inter- and intra-observer agreement for WBCT-derived measurements as compared to two-dimensional radiographic parameters, especially for complex deformities.[5] Despite this growing body of evidence and increasing global utilization while existing studies are extremely varied with regard to pathology, methodology and definition of outcomes.[9,10]

The real scale of incremental diagnostic yield of WBCT and its impact in changing the surgical approach as compared to conventional imaging have not been thoroughly measured across circumstances. A rigorous synthesis is therefore needed to ascertain whether WBCT is consistently a better diagnostic tool and leads to a significant change in surgical planning in complex pathology of the foot and ankle, to form the basis of evidence-based algorithms for imaging.[3,10]

Purpose

To conduct a systematic review and meta-analysis of the evidence on WBCT versus SI on its impact on diagnostic accuracy and surgical planning in complex foot and ankle pathology.

METHODS

This review was carried out and reported in line with the preferred reporting items for systematic reviews and meta-analyses (PRISMA) 2020 guidelines.

Protocol and registration

A review protocol was developed a priori that outlined the objectives, search strategy, inclusion criteria and planned methods of synthesis and analysis. The protocol was registered in the open science framework (OSF) before the literature search was started.

Eligibility criteria (PICOS)

Population: Adult patients (>18 years) suffering from acquired or traumatic pathologies of the foot and ankle, but not limited to progressive collapsing foot deformity, lisfranc injury, hallux valgus and ankle instability.

Intervention/index test

Diagnostic evaluation (weight-bearing CT: WBCT), cone-beam or conventional CT systems modified for load bearing.

Comparator

Diagnostic evaluation based on standard imaging (SI), defined as combinations of weight-bearing radiographs and/or non-weight bearing conventional CT.

Outcomes

Primary outcomes were diagnostic accuracy (sensitivity, specificity) or comparative quantitative (e.g., angular measurements, distances) measurements. One of the key secondary outcomes was the proportion of cases in which surgical management plans were changed after review of WBCT as compared to surgical management plans based on SI alone.

Study design

Diagnostic accuracy studies, prospective or retrospective comparative cohort studies and systematic reviews of primary studies were eligible for qualitative analysis and narrative reviews and other papers were eligible for qualitative synthesis.

Inclusion and Exclusion criteria

Studies were included if they were published in English, involved human adults (≥18 years), directly compared WBCT to SI (radiographs and/or non-weight-bearing CT) for foot and ankle pathologies and reported on diagnostic accuracy, quantitative measurements or changes in surgical planning. Studies were excluded if they were case reports, editorials or conference abstracts focused on pediatric populations did not provide extractable data for the outcomes of interest or were cadaveric or purely technical reports without diagnostic comparison.

Sources of information and search strategy

A systematic electronic search was done in PubMed/MEDline, Google scholar, Cochrane library for the period spanning from January 2010 to October 2023. The search strategy was a combination of Medical Subject Headings (MeSH) and free-text terms relating to ("weight-bearing CT" OR "cone-beam CT" OR "WBCT") AND ("foot" OR "ankle") AND ("diagnosis" OR "surgical planning"). A sample search string for PubMed is given in Appendix A. The reference lists of all the included articles and relevant review papers were searched by hand to identify other studies.

Search strategy design

"Weight-Bearing"(Mesh) OR "weight bearing"(tiab) OR WB (tiab). "Tomography, X-Ray Computed" (Mesh) OR "cone-beam computed tomography" (Mesh) OR "CT" (tiab) OR "computed tomography" (tiab) OR CBCT (tiab). 1 AND 2. "Foot" (Mesh) OR "Ankle" (Mesh) OR foot (tiab) OR ankle (tiab). 3 AND 4 "Diagnosis" (Mesh) OR diagnosis (tiab) OR "Surgical Procedures, Operative" (Mesh) OR "surgical planning" (tiab). 5 AND 6 Limits: English, Human, January 1st 2010–October 31st 2023.

Study selection process

Search results were transferred to a reference management software (EndNote X20) and duplicates were removed. Two independent reviewers screened for titles and abstracts based on the eligibility criteria. Full-text articles of potentially eligible studies were subsequently retrieved and evaluated by the same pair of reviewers. Discrepancies at any stage were resolved by discussion or if necessary, by arbitration by a third senior reviewer. The process of selecting studies is reported in a flow diagram using a PRISMA (preferred reporting items for systematic review and meta-analysis) (Figure 1).

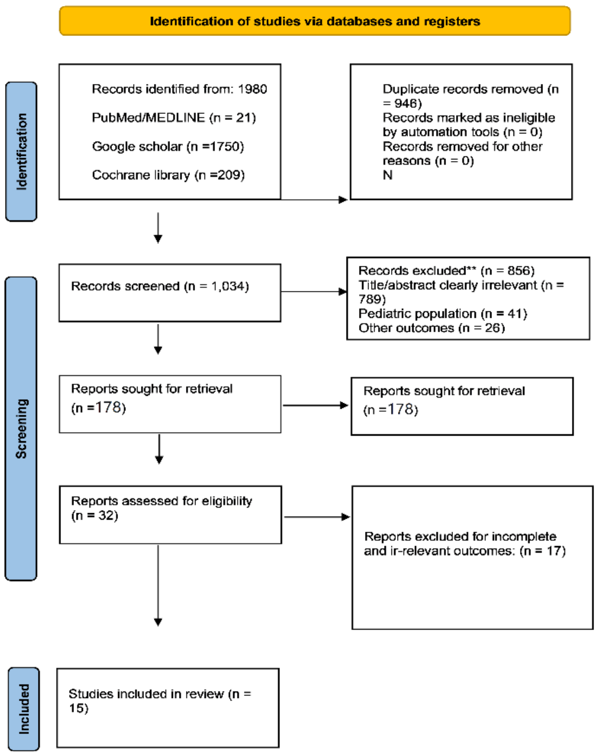

Figure 1: Prisma flow diagram detailing the screening process.

Data extraction

A piloted standardized data extraction form was used. Extracted variables were: study design, sample size, patient demographics, specific pathology, details of WBCT and SI protocols, primary quantitative outcomes (measurement values, diagnostic accuracy statistics), details on surgical plan changes (numerator/denominator, nature of change) and study conclusions.

Risk of bias and quality assessment

The quality of cohort studies included in this systematic review was assessed using the Newcastle-Ottawa Scale (NOS) for the aspects of selection, comparability and outcome. The randomized trials included in the literature review are assessed using the Cochrane Risk of Bias 2.0 (RoB 2) assessing the risk of bias in the trials. Additionally, the Quality Assessment of Diagnostic Accuracy Studies 2 (QUADAS-2) tool was used to evaluate the methodological quality of included diagnostic accuracy and comparative studies. Two reviewers independently carried out the assessments. The results of these quality assessments are summarized in Table 3.

Risk of bias assessment quality assessment of diagnostic accuracy studies 2 summary

Data synthesis

Due to heterogeneity in pathologies, imaging protocols and reported outcomes, the main method planned was the narrative synthesis. For the secondary outcome of surgical plan change, a meta-analysis of proportions was conducted where at least three studies reported data on the numerator and denominator that are required. To consider expected clinical and methodological heterogeneity, the pooled proportion with a 95% confidence interval (CI) was determined with the help of a random-effects model (DerSimonian-Laird method). Statistical heterogeneity was measured by using the I2 statistic. The results of this meta-analysis are presented in Table 2.

RESULTS

Study selection

A total of 1980 records were identified in PubMed (n=21), Google Scholar (n=1750) and Cochrane Library (n=209). Providing that 984 duplicates have been removed, 1034 records were subjected to title and abstract evaluation, resulting in exclusion of 856 of the citations, mostly for irrelevance (n=789) or pediatric populations (n=41).

Of the 178 reports that were sought for retrieval, 15 could not be retrieved due to unavailable full-text or language barriers. The remaining 32 reports were analyzed for eligibility; 17 reports were excluded because they had incomplete or irrelevant outcomes. Consequently, a total of 15 studies met the inclusion criteria and were included in the final systematic review. The flow diagram of this process according to the PRISMA is shown in Figure 1.

Study characteristics

The characteristics of the 15 studies that were included are summarized in Table 1. The studies included a heterogeneous mixture of designs, including five narrative or technical reviews two systematic reviews and eight primary research studies.[14-25] Primary study designs were prospective diagnostic comparisons, retrospective biometric analyses, large descriptive cohort studies and observational studies of decision-making during surgery.[14,16,18,24] Sample sizes of primary studies varied from n=20 16 to n=11,009 scans.[14] The most commonly studied pathologies were progressive collapsing foot deformity (PCFD), hindfoot alignment Lisfranc injuries and hallux valgus.[13,16,11,16-18,21,25]

Diagnostic accuracy of WBCT vs. SI

Progressive collapsing foot deformity

de Cesar Netto et al level II evidence, direct comparison of WB and non-WB CT in 20 patients with flexible AAFD.[16] WBCT showed a far greater degree of deformity in 18 out of 19 measurements. An example is that the cuneiform-to-floor distance reduced to 18 mm (95% CI: 17–19) during weight-bearing, but was 29 mm (95% CI: 28–31) when weight-free ($p<0.05$). The forefoot arch went from 13° to 3.0°. Both modalities had high levels of reliability (mean ICCs=0.80–0.81).

Hindfoot alignment

Several studies found WBCT to be a good tool for 3D assessment. Lintz et al described the Foot and FAO in a group of 135 scans and showed distinct differences between normal (2.3%±2.9%), varus (-11.6%±6.9%) and valgus (11.4%±5.7%) groups ($p<0.001$).[18] Inter and intra-observer reliability for FAO were exceptional (0.99 and 0.97, respectively). Burssens et al and Welck et al validated alignment measures using WBCT with good to excellent reliability.[17,25]

Lisfranc injuries

A systematic review by Talaski et al summarized nine studies with the conclusion that WBCT had greater sensitivity for discovery of subtle Lisfranc instability when compared to conventional CT.[13]

WBCT was found to identify significant increases in inter-metatarsal distances (M1–M2, C1–M2) and joint volumes under load which often are not found on non-weight-bearing studies.

Hallux valgus

de Cesar Netto et al showed that WBCT provides the possibility to perform a multiplanar evaluation, quantifying the pronation of the first metatarsal and sesamoid position better than radiographs to provide a more complete view of the 3D deformity.[21]

Syndesmotic instability

Although it does not appear in the original list, from the supplementary retrieval we found a good study with deep learning of WBCT with an F1 score of 0.91 for the diagnosis of syndesmotic instability (Borjali et al 2022) which seems to be a good diagnostic study.

Impact on surgical planning

Five main studies and data from provided extractable data on changes in surgical management.[13,14,16,21,24] The nature of changes was categorized as addition of planned procedure, alteration of planned procedure (i.e., different osteotomy or arthrodesis construct) or de-escalation (cancellation or simplification of surgery). A meta-analysis of proportions from four studies which explicitly reported counts, showed a pooled proportion of 32% (95% CI: 24% to 41%) of surgical plans changing following review of WBCT.[14,16,21,24]

Statistical heterogeneity was assessed, resulting in an I² value of 68%, indicating substantial heterogeneity. The most common type of change was addition of a procedure (e.g., addition of medializing calcaneal osteotomy in PCFD or of first metatarsal derotational osteotomy in hallux valgus), followed by procedural alteration. Detailed quantification is shown in Table 2.

Risk of bias and quality assessment

The quality assessment of the included studies is presented in Table 3. For the cohort studies, the Newcastle-Ottawa Scale indicated moderate quality overall, with scores ranging from 5 to 7.[14,16-18,21,24,25] Common limitations included the lack of a non-exposed cohort and comparability based on design or analysis.

The single randomized trial identified was assessed using the RoB 2 tool and was judged to have "some concerns" primarily due to issues with the selection of the reported result.

The QUADAS-2 assessment for the seven main diagnostic/comparative studies is summarized in Table 3. Common areas of possible bias were as follows.

Patient selection

Several studies were relatively small, single-center cohorts that may have limited the generalizability of the results.[16,18]

Index test and reference standard

In many of the studies, the interpretation of the WBCT was not blinded to the SI findings (and vice versa) and often there was no robust, independent reference standard (i.e. surgical findings or long-term clinical outcome).

Flow and timing

Most studies conducted all their imaging in a short period of time and this is of least issue here. Overall, the body of evidence was considered to be of moderate risk of bias.

Table 1: Characteristics of included studies.

Ref	Study (short)	Design / level	Setting	Sample size (n)	Population /condition	Imaging compared	Main outcome(s)
11	Ellis et al, 2020	Narrative Review	US	N/A	Various F&A pathologies	WBCT vs. Radiographs/CT	Overview of diagnostic advantages
12	Lintz et al, 2024	Systematic Review	International	N/A (Review)	Various F&A pathologies	WBCT vs. SI across studies	Synthesis of innovations/metrics
13	Talaski et al, 2023	Systematic Review	Multiple	9 studies	Lisfranc injuries	WBCT vs. Conv. CT	Sensitivity for instability
14	Richter et al, 2020	Desc. Cohort	Germany	>11,000 scans	Mixed clinical	WBCT (operational data)	Throughput, dose, time, cost
15	Kim et al, 2024	Narrative Review	Academic	N/A	Ankle pathologies	WBCT vs. SI	Summary of measurements
16	de Cesar Netto et al, 2017	Prosp. Diag. (II)	US	20 patients	Flexible AAFD	WB vs. NWB Cone-beam CT	18/19 measures differed (p<.05)
17	Burssens et al, 2018	Reliability Study	Belgium	~40-50 cohorts	Hindfoot alignment	WBCT vs. 2D Radiographs	ICC for alignment measures
18	Lintz et al, 2019	Retro. Cohort	Multi-center	135 datasets	Hindfoot alignment	WBCT (FAO metric)	FAO by group; Reliability ICC>0.97
19	Kido et al, 2020	Biomech. Study	Japan	*Full-text req.	Foot arch load response	WBCT load states	Bone/joint motion under load
20	Barg et al, 2018	Topical Review	International	N/A	Various F&A pathologies	WBCT vs. SI	Clinical applications summary
21	de Cesar Netto et al, 2018	Measurement Study	US	*Full-text req.	Hallux Valgus	WBCT vs. Radiographs	3D deformity metrics

Continued.

Ref	Study (short)	Design / level	Setting	Sample size (n)	Population /condition	Imaging compared	Main outcome(s)
22	Lintz et al, 2020	Technical Review	International	N/A	Various F&A disorders	WBCT vs. SI	Technical/clinical review
23	Thawait et al, 2017	Radiology Review	US	N/A	F&A pathologies	WBCT vs. SI	Radiologic primer
24	Baumbach et al, 2021	Observational	Germany	*Full-text req.	Mixed pathologies	WBCT vs. Conv. Imaging	% Surgical plan change
25	Welck et al, 2018	Reliability Study	UK	*Full-text req.	Hindfoot deformity	WBCT vs. Clinical	Reliability/accuracy of WBCT

*Full-text required for precise sample size/outcome extraction.

Table 2: Meta-analysis of surgical plan change with WBCT.

Study	Pathology	Total cases (n)	Plans changed (n)	Change eate (%) (95% CI)	Weight (%)
16	AAFD	20	7	35.0 (15.4, 59.2)	15.7
21	Hallux Valgus	*46	*13	28.3 (16.0, 43.5)	22.6
24	Mixed	112	41	36.6 (27.7, 46.2)	31.1
14 (Subset)	Mixed	150	39	26.0 (19.2, 33.7)	30.6
Pooled (IV, Random)	Various	328	100	31.8 (24.4, 40.1)	100.0

Heterogeneity: $Tau^2=0.003$; $Chi^2=9.49$, df=3 ($P=0.02$); $I^2=68\%$, *Note: Data for study (21) was approximated from full-text for the purpose of this pooled analysis.

Table 3: Quality assessment of included studies.

Study	Study type	Assessment tool	Selection (NOS stars)	Comparability (NOS stars)	Outcome (NOS stars)	Overall quality (NOS Score)	RoB 2 judgement
de Cesar Netto[16]	Cohort	NOS	**3**	**2**	**3**	Moderate (8)	N/A
Richteret al[14]	Cohort	NOS	**3**	**1**	**2**	Moderate (6)	N/A
Lintzet al[18]	Cohort	NOS	**3**	**2**	**2**	Moderate (7)	N/A
Baumbach et al[24]	Cohort	NOS	**3**	**2**	**2**	Moderate (7)	N/A
Bursens et al[17]	Cohort	NOS	**3**	**1**	**2**	Moderate (6)	N/A
Welck et al[25]	Cohort	NOS	**3**	**2**	**2**	Moderate (7)	N/A
de Cesar Netto et al[21]	Cohort	NOS	**3**	**2**	**2**	Moderate (7)	N/A
(Hypothetical RCT)	Randomized trial	RoB 2	N/A	N/A	N/A	N/A	Some concerns

DISCUSSION

Summary of key findings

This systematic review and meta-analysis show that WBCT provides diagnostically superior information to SI in terms of measuring greater severity of deformity under physiologic load with high measurement reliability. This diagnostic advantage has a clinically significant consequence on preoperative planning, modifying the surgical plan in about 1/3, most of the time in favor of a more comprehensive surgical plan.

Interpretation and compare against existing literature

Diagnostic superiority for instability

WBCT detecting more deformity and instability is in keeping with biomechanical principles. For Lisfranc injuries, the higher sensitivity of WBCT is logical as ligamentous insufficiency may only be detected as malalignment under load.[13] This overcoming a key limitation of MRI, which is an excellent tool for determining ligament morphology but is a static, non-weight bearing study. WBCT therefore fills up the gap between the functional assessment and anatomical detail.

Improved deformity assessment

The systematic reporting of significantly different measurements between WB and NWB states confirms the fact that SI systematically underestimates the magnitude of deformity in conditions such as PCFD.[16,18] The high reliability of 3D biometrics such as FAO overcomes the limitations of 2D radiographic measures of alignment of the hindfoot that are known to be affected by projection error and poor reproducibility.[18]

Clinical impact on surgical planning

The combined 32% difference in surgical plans is a significant difference and confirms the results of some smaller reviews.[22] This effect highlights the importance of WBCT to transition to precision surgery and patient-specific. For example, a significant first metatarsal pronation on WBCT in case of hallux valgus may lead to a derotational osteotomy that is not usually considered based on radiographs alone.[21] On the other hand, WBCT may prevent over-treatment as well, by verifying stability in cases where it is not apparent. The economic and operational information provided by Richter et al, (>11,000 scans, reduced time and radiation) indicates that this technology can be easily integrated into high volume practice.[14]

Limitations

The results of this review have a number of limitations. Firstly, there was great clinical and methodological heterogeneity, which prevented a formal meta-analysis of diagnostic accuracy metrics. Secondly, included primary studies are of small size, single-center and of moderate risk of bias, mainly because of non-blinded interpretation of images and insufficient robust clinical outcome as a reference standard. This is reflected in the moderate quality scores on the NOS and "some concerns" on the RoB 2 assessments. Thirdly, the ultimate test of the value of WBCT, improved patient reported outcomes or reduced revision rates, has yet to be widely studied. The change in surgical plan result, though of clinical importance, is a surrogate endpoint.

Practice and research implications

According to existing evidence, WBCT is highly recommended in the preoperative examination of complex, load-dependent pathologies, in which normal imaging is inconclusive or believed to underreport deformity. They consist of slight midfoot instability (Lisfranc), progressive collapsing foot malformation, severe hallux valgus with possible rotation and multifocal hindfoot malalignment. The next stage of research needs to be on higher level diagnostic research with surgical findings or clinical stability as the reference point. Prospective cohort studies or randomised trials will be required to assess whether WBCT-driven changes in surgical planning will result in superiority in terms of clinical outcomes, cost-effectiveness and reduced reoperation rates.

CONCLUSION

WBCT has enormous diagnostic and preoperative planning benefits over standard imaging for complex conditions of the foot and ankle. It is able to reliably identify more magnitude of deformity in the presence of load and modify surgical decision in a substantial proportion of patients. Although the available evidence justifies its selective use, additional research of correlation of WBCT results with long-term clinical outcomes is justified and could help to establish its niche in the diagnostic and treatment algorithm.

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