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REVIEW ARTICLE

Weight-bearing cone-beam CT: the need for standardised acquisition protocols and measurements to fulfill high expectations—a review of the literature

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Abstract

Weight bearing CT (WBCT) of the lower extremity is gaining momentum in evaluation of the foot/ankle and knee. A growing number of international studies use WBCT, which is promising for improving our understanding of anatomy and biomechanics during natural loading of the lower extremity. However, we believe there is risk of excessive enthusiasm for WBCT leading to premature application of the technique, before sufficiently robust protocols are in place e.g. standardised limb positioning and imaging planes, choice of anatomical landmarks and image slices used for individual measurements. Lack of standardisation could limit benefits from introducing WBCT in research and clinical practice because useful imaging information could become obscured. Measurements of bones and joints on WBCT are influenced by joint positioning and magnitude of loading, factors that need to be considered within a 3-D coordinate system. A proportion of WBCT studies examine inter- and intraobserver reproducibility for different radiological measurements in the knee or foot with reproducibility generally reported to be high. However, investigations of test–retest reproducibility are still lacking. Thus, the current ability to evaluate, e.g. the effects of surgery or structural disease progression, is questionable. This paper presents an overview of the relevant literature on WBCT in the lower extremity with an emphasis on factors that may affect measurement reproducibility in the foot/ankle and knee. We discuss the caveats of performing WBCT without consensus on imaging procedures and measurements.

Keywords Cone beam CT · CBCT · Weight-bearing WBCT · Lower extremity · Reproducibility · Test–retest · Standardisation

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Introduction

Our aim in this article is to provide an overview and commentary on the current literature on weight-bearing CT (WBCT) of the lower extremity with emphasis on the foot/ankle and knee. We discuss the need to achieve sufficient scanning repeatability and measurement reproducibility to realise the full potential of WBCT. We also discuss the caveats of using WBCT without consensus as well as the technical challenges in terms of different scanner designs. Lastly, we convey our recommendations on how to ensure adequate reliability.

Since first being described in 1998 by Mozzo et al., cone-beam CT (CBCT) has become well known and well used in the dental industry [1, 2]. Over the last decade, clinical specialists such as orthopaedic surgeons, musculoskeletal radiologists and in some countries, physiatrists and podiatrists have become aware of the potential of CBCT in combination with weight bearing (WB) in the assessment of joints of the lower limb, reflected in the fast growing number of articles on the subject (Fig. 1). CBCT offers a low radiation [3–7], varying slightly between vendors [3, 4, 8, 9] and high resolution imaging with sub-millimetre isotropic voxels [10] (Table 1). This technology allows investigation into the changes between non-weight-bearing (NWB) unloaded positions and WB positions (Fig. 2) and can enhance our three-dimensional (3-D) understanding of joint anatomy, biomechanics and pathology in the lower limb. The dynamic relationship between anatomical structures in a functional setting can be examined under naturally loaded WB conditions, and in different static joint positions [2, 11–13]. This approach may reveal joint pathology that could remain undetectable

Fig. 1 Overview of the increase in articles published concerning CBCT during the last two decades, divided by themes. The themes are ordered after highest amount of publications to smallest amount of publications in 2021

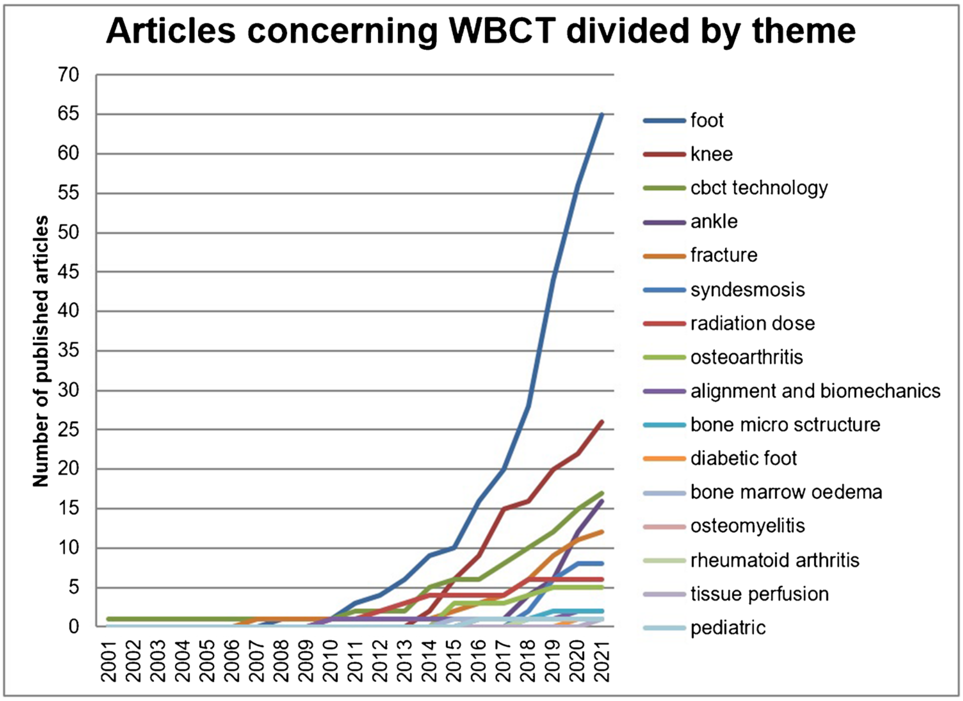

Table 1 Comparison of multidetector CT and cone beam CT of lower extremity

	MDCT	CBCT
Radiation dose [4, 5]*		
• Foot–ankle	21.4–22.9 µSv	1.9–14.3 µSv
• Knee	32.8–48 µSv	2.1–12.6 µSv
Field of view	No limitations	13 × 16 cm–35 × 40 cm
Rotation/exposure time	1 s	25 s
Pixel/voxel spacing	0.6 × 0.6x0.6 mm pixels	0.26 × 0.26 × 0.26 mm voxels
Weight-bearing option	No	Yes

*Radiation doses in comparison: X-ray knee: 5 µSv, US background radiation dose 0.8 µSv, single E-W coast US flight = 35 µSv [7]

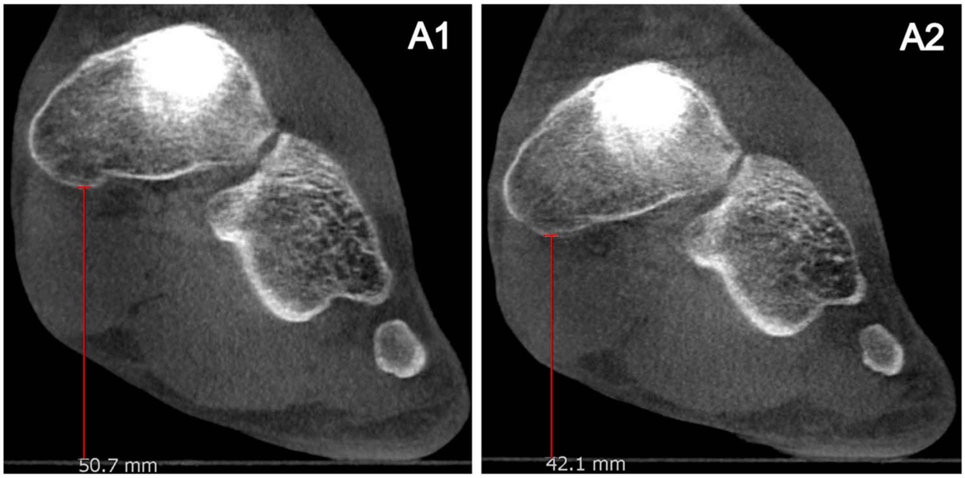

Fig. 2 Measurement of the navicular height on CBCT (**A1**) in NWB unloaded condition and (**A2**) in loaded WB condition

in conventional 2-D radiographic or supine cross-sectional imaging such as subtle Lisfranc or patellofemoral joint (PFJ) instability [14, 15]. As shown in Fig. 1, WBCT is unquestionably receiving significantly increasing scientific attention. WBCT under approximated physiological loading conditions enables the study and quantification of important biomechanical parameters such as the relative positions of bones, angles and alignment between bones, joint space width (JSW) and biomechanical properties with theoretical improved clinical relevance compared to WB conventional radiography [3] or supine cross-sectional imaging [16]. As a gateway example, when assessing patellar instability, WBCT measurements of PF parameters have been shown to be significantly different from conventional supine CT—e.g. tibial tuberosity-trochlear groove distance (TT-TG distance) changes of 2–3 mm in WBCT compared to NWB CT—implying that the effect of mechanical loading on PFJ alignment is far from trivial [11, 17].

Advancements in diagnostic information and caveats in WBCT

There is little doubt that WBCT has provided new insights into certain disorders of the lower limb, which rest on the combined detailed 3-D information of bone and joints and the ability to physiologically load anatomical structures during scanning. Perhaps not surprisingly, measurement of JSW in osteoarthritic knees by WBCT entails more accurate representation of JSW distribution across joint surfaces with increased sensitivity to detect relevant disease-related changes in the joint, exceeding the capabilities of conventional radiography, and importantly demonstrating that radiography may underestimate disease severity [18–20]. In the foot and ankle, WBCT can provide imaging information on rotational dynamics of the distal tibiofibular joint, with measurable changes in configuration from supine to WB position [21], and for assessing adult acquired flat foot deformity, where accurate 3-D measures of hindfoot alignment are crucial for operative planning [22]. Furthermore, the newest addition of commercially available large gantry WBCT scanners that have the ability to scan the pelvis and bilateral hip joints in a weight-bearing position is promising for the future of measurements of hip alignment, pelvic tilt angles and other important measurements of these anatomies. Due to the novelty of such large gantry scanners, there are currently no published results of the usage of WBCT scans of the hip and pelvis.

WBCT has potential to prevent bias from super-imposition of bones, rotational and projectional inconsistencies, and image distortion or magnification artefacts [16, 23] seen with conventional radiography because it is possible to define bone positioning in 3-D [23]. However, it should be recognised that 2-D radiography does still have inherently higher spatial resolving capability, while the lack of a single, preset imaging plane in cross-sectional imaging such as WBCT involves the risk of introducing variability through non-standardisation of review planes between imaging systems and users.

The theoretical advantages in terms of more physiologically relevant imaging information from WBCT have led to a rapid uptake of the technique, but this has been in the absence of strictly standardised imaging protocols and measurement procedures that are required when adding WB to the equation. It is well known that the introduction of new technologies can create a “hype cycle” [24–28]. This predictable effect of a new technology is important to keep in mind since an initial period of “inflated expectations” may occur during which new technology is unlikely to be truly beneficial for patients or clinicians [28] before robust scientific knowledge on its capabilities and drawbacks are widely understood. It is likely that we are currently facing this challenge for WBCT.

The challenges of reproducibility

Despite the perceived advantages of WBCT, it is important to recognise that moving from measurements in 2-D to 3-D introduces a new level of complexity that is further elevated by the introduction of WB. This requires close attention to standardisation, since anatomical landmarks and planes are defined by many more degrees of freedom than in 2-D imaging. Studies have shown that the reproducibility of typical orthopaedic radiological measurements on WBCT can be influenced by multiple factors [29–31] and that measures can vary between separate scanning sessions on separate days and be influenced by confounding factors. One example is the tibial tuberosity-trochlear groove (TT-TG) distance, which has been shown to be influenced both by knee joint position and the magnitude of mechanical loading between scans if left uncontrolled [15]. In the foot, superior day-to-day repeatability of navicular bone position on magnetic resonance imaging (MRI) has also been identified with WB compared to NWB acquisitions [32].

So when assessing reproducibility of WBCT measures, two independent aspects must be addressed: (1) variability in the acquisition of imaging data (i.e. test–retest repeatability); and (2) variability in the analysis method (i.e., intra- and interobserver reproducibility). It seems that often the literature focusses merely on observer variabilities and frequently solely by use of a so-called reliability parameter such as intraclass correlation coefficient (ICC). We wish to stress that in order to fully assess the reproducibility of an imaging technique, the observer agreement as well as repeatability of the method should also be examined: i.e. it must be demonstrated that the technique is able to consistently reproduce measurements between different scanning sessions [33, 34].

A *caveat* of using ICC (and other reliability methods based on correlation) is the dependence of ICC not only on the variation of repeated measurements but also on the composition of the sample being measured: a very homogenous sample will tend to yield lower ICC and vice versa [33, 35, 36]. Ideally, ICC should be accompanied by agreement descriptive statistics such as minimal detectable change (MDC) derived from Bland–Altman analysis [37].

Different vendors, applications and techniques

The market and usages of CBCT are quickly evolving with multiple scanners such as the PlanMed Verity [38] and Curvebeam scanners (PedCat, HiRise, LineUp) [39, 40] now available on the market (Fig. 3). The Carestream Onsight 3-D Extremity system [41] was recently terminated from both US and European markets. Scanning units from different vendors vary in their capabilities, advantages and disadvantages e.g. through varying ability to perform unilateral versus bilateral scans, different field of views (FOV) and different ways of aligning within the scanner itself [10]. Different scanners can also have different modes of usage: some allow scanning at multiple WB joint levels, although this can require repositioning for the different regions. Error can therefore arise from the need to exit the scanner between acquisitions. Some scanners are able to perform bilateral scans but may be restricted to imaging of the ankles and feet [10], while others can only perform unilateral imaging[41]. Differences in scanner gantry layout may also limit optimal standing position depending on body height, BMI, patient mobility and accompanying co-morbidities.

As mentioned, recently emerging large gantry scanner systems are able to perform bilateral scans of the hips, knees and feet in the same scanning session, without the need for patient repositioning [40], which could possibly reduce position change induced variation. However, it is likely that a trade-off exists between optimal image quality and FOV size. These bilateral scans may result in more artefacts but will otherwise deliver novel 3-D information of the lower limb joint alignment during loading [39, 41]. Given the variety of scanner designs, a universal approach to standardisation of image acquisition has not become easy to obtain, yet its necessity has increased accordingly. Ideally, global consensus should be achieved to bridge differences in layout and acquisition procedures for all these current and any emerging scanner types.

Literature on WBCT in the lower extremity

The medical literature databases PubMed (MEDLINE) and Scopus (Elsevier) were searched during April 2021 using the term “Weight bearing CT,” which resulted in 1385 and 1535 publications respectively. Several search strings were used to narrow down: “Weight bearing cone beam CT”, “Weight-bearing CT AND knee”, “Weight-bearing CT AND foot”, “Weight bearing cone beam CT AND knee”, “Weight bearing cone beam CT AND foot”, “Cone beam CT AND knee”, “Cone beam CT AND foot”, “Cone Beam AND knee AND reliability”, “Cone Beam AND foot AND reliability”, “Cone Beam AND knee AND reproducibility” and “Cone Beam AND foot AND reproducibility”. This resulted in 1711 articles across the two databases combined. After removing off-topic articles concerning NWBCT, the upper extremities, conventional CT and weight bearing radiography, as well as duplicate articles, this resulted in 160 relevant final articles.

Fig. 3 **B1** PlanMed® Verity (https://www.planmed.com/), **B2** Curvebeam® PedCAT (https://curvebeam.com/), **B3** Curvebeam® HiRise (https://curvebeam.com/), **B4** Carestream. © Onsight 3-D Extremity system (https://www.carestream.com/en/us/)

These studies concerned various disorders and applications e.g. knee biomechanics [11, 15], foot/ankle biomechanics [12, 42–45], fracture and syndesmosis diagnostics [46–51], evaluation of knee arthroplasty [52, 53], paediatric trauma [54], osteoarthritis [2, 18, 19, 55], rheumatoid arthritis [56] and diabetic foot infection [57]. Despite a broad approach to CBCT in different areas, we found a predominance of articles concerning the foot (Fig. 1). Approximately 1/3 out of the 160 articles addressed inter- and intra-observer variability, e.g. TT-TG distance, patellar tilt and tibiofemoral JSW at the knee [11, 17, 53, 58, 59], and Lisfranc instability, hind-, mid- and forefoot alignment in the foot [12, 21, 60–66]. The consensus across these studies was reported to be good to excellent, most commonly presented by intraclass correlation coefficients (ICCs) [67] (Table 2, but also note the caveat above). However, concerningly, few studies provided a structured report on measurement test–retest repeatability at any region.

Issues and solutions concerning reproducibility and repeatability of WBCT

The studies found in our search revealed that WBCT examination can be affected by posture (the way a person positions and holds their body), stance (the manner, posture or pose in which a person stands) and magnitude of joint loading [32, 59]. We also noted that artefact in the case of FOV limitations that require two (or more) scans to be stitched can be affected by small positional changes [116]. These are all factors that must be controlled prior to imaging since they involve conditions that cannot be optimised after the event. To our knowledge, the day-to-day repeatability of various geometric analyses in the lower extremity by WBCT is largely unknown (or unpublished) for most measurements despite the fact that WCBT is increasingly applied for clinical purposes. This poses a problem since the clinical value of

Table 2 Studies concerning reproducibility of WBCT in the lower extremity

	Author	Theme	Reliability method	Test–retest study
Foot and ankle				
2011	Kido et al. [68]	Foot	Kappa	No
2013	Arunakul et al. [69]	Foot	ICC	No
2014	Hirschmann et al. [12]	Foot	ICC	No
2016	Lepojärvi et al. [21]	Ankle	ICC	No
2016	Krähenbühl et al. [64]	Foot	ICC	No
2016	Lepojärvi et al. [66]	Foot	ICC	No
2016	Burssens et al. [70]	Foot	ICC + Kappa	No
2017	Netto et al. [44]	Foot	ICC	No
2017	Zhang et al. [71]	Foot	ICC	No
2017	Lintz et al. [43]	Foot	ICC	No
2017	Kim et al. [72]	Ankle	ICC	No
2018	Barg et al. [60]	Foot/ankle	ICC	No
2018	Burssens et al.[63]	Foot	ICC	No
2018	Cheung et al. [73]	Foot	ICC	No
2018	Burssens et al.[74]	Foot	ICC	No
2019	Bernasconi et al. [65]	Foot	ICC	No
2019	de Cesar Netto et al. [75]	Foot	ICC	No
2019	Ota et al. [76]	Foot	ICC	No
2019	Jeng et al. [77]	Foot	ICC + Pearson	No
2019	Krähenbühl et al. [78]	Foot	ICC	No
2019	de Cesar Netto et al. [79]	Foot	ICC	No
2019	Krähenbühl et al.[80]	Ankle	ICC	No
2019	Scheele et al.[81]	Foot	Pearson	No
2019	Kang et al. [82]	Foot	ICC	No
2019	Krähenbühl et al. [83]	Foot	ICC	No
2019	Krähenbühl et al. [84]	Foot	ICC	No
2019	Kaneda et al. [85]	Foot	ICC	No
2019	de Cesar Netto et al. [86]	Foot	ICC	No
2020	de Cesar Netto et al. [42]	Foot	ICC	No
2020	Ponkilainen et al. [87]	Foot	Kappa	No
2020	de Cesar Netto et al. [88]	Foot	ICC	No
2020	Burssens et al. [89]	Foot	ICC	No
2020	Lintz et al. [90]	Ankle	ICC	No
2020	de Cesar Netto et al. [91]	Foot	ICC	No
2020	Gabel et al. [92]	Foot/ankle	ICC	No
2020	Patel et al. [93]	Foot	ICC	No
2020	del Rio et al. [94]	Ankle	ICC	No
2020	Sripanich et al. [95]	Foot	Kappa	No
2021	Broos et al.[45]	Foot/ankle	ICC	No
2021	Kvarda et al. [96]	Foot	ICC	No
2021	Shakoor et al. [97]	Foot	ICC + Kappa	No
2021	Zhong et al. [98]	Foot	ICC	No
2021	Haldar et al. [99]	Foot	ICC	No
Knee				
2015	Zbijweski et al. [2]	Knee	Pearson	No
2015	Hirschmann et al. [11]	Knee	ICC	No
2015	Honkanen et al. [100]	Knee	Kappa	No
2017	Nardi et al. [53]	Knee	ICC + Kappa	No

Table 2 (continued)

	Author	Theme	Reliability method	Test–retest study
2017	Segal et al. [55]	Knee	ICC + RMSE	Yes
2017	Hirschmann et al. [58]	Knee	ICC	No
2017	De Medeiros Barbosa et al. [101]	Knee	ICC	No
2017	Marzo et al. [102]	Knee	ICC	No
2018	Jaroma et al. [103]	Knee	ICC + Kappa	No
2019	Brehler et al. [104]	Knee	ICC	No
2021	Turmezei et al. [18]	Knee	LOA + RMSCV	Yes
2021	Lullini et al. [59]	Knee	ICC	No
2021	Dartus et al. [105]	Knee	Kappa	No
Other areas				
2015	Demehri et al. [106]	CBCT technology	Kappa	No
2018	de Cesar Netto et al. [49]	Syndesmosis	ICC	No
2019	Osgood et al. [13]	Syndesmosis	ICC	No
2019	Hagemeijer et al. [107]	Syndesmosis	ICC	No
2019	Dubreuil et al. [108]	Fracture	ICC + Kappa	No
2019	Krähenbühl et al. [109]	Syndesmosis	ICC	No
2019	Sisniega et al. [110]	CBCT technology	ICC	No
2019	Patel et al. [111]	Syndesmosis	ICC + Pearson	No
2020	Jud et al. [112]	Limb loading	ICC	No
2020	Grunz et al. [113]	Fracture	Kappa	No
2020	Bhimani et al. [114]	Syndesmosis	ICC	No
2020	Hamard et al. [115]	Syndesmosis	ICC	No

ICC, intraclass correlation coefficient; LOA, limits of agreement; kappa, kappa statistics; Pearson, Pearson correlation; RMSE, root mean square error; RMSCV, root mean squared coefficient of variation

WBCT will largely depend on the highest possible reliability of the technique. In the next section, we highlight factors that may influence the reliability of WBCT measurements at the foot/ankle and knee.

Foot and ankle

Much scientific emphasis has been placed on WBCT of the foot and to a lesser extent the ankle, over the last two decades (Fig. 1). WBCT is currently used in the assessment of foot disorders such as calcaneal fractures [117], the diabetic foot [22, 118], syndesmotic injuries [114, 115, 119], Lisfranc injuries [87], flat foot deformity [75, 88, 120] and osteoarthritis [96]. In a recent review, Schlickewei et al. (2021) emphasised that WBCT can provide valuable additional information in multiple aspects of the foot such as when evaluating complex underlying deformities, joint alignment, congruence and coverage of articulating facets, impingement, joint degeneration and possible decreases in JSW when standing [121].

Variability in imaging acquisition at the foot/ankle

WBCT acquisitions of the foot/ankle and subsequent analyses are affected by differences in stance, posture and alignment during WB single-leg versus bilateral acquisitions. Since these factors are subject to between-scan variation, analyses obtained from repeated acquisitions may vary due to differences in positioning and load distribution rather than relevant pathology. NWB data from positional MRI have indicated that it can be difficult to position the foot and ankle in the exact same anatomical position in repeat acquisitions [122]. Even the application of a cast-like device did not improve repeatability of tarsal joint motion induced by foot loading [123]. In our experience, some patients suffering from a disorder of the limbs such as cerebral paralysis can also experience an increase in involuntary movements and risk motion artefact.

In order to better understand the repeatability of 3-D measurements at the foot/ankle, it is important to consider the complexity of its joints: especially the tarsal complex —mainly comprised of three joints referred to as the subtalar joint, the talonavicular joint and the calcaneocuboid joint [123] —and the plantar arches[45] that all play a crucial role in bone positioning and orientation. Acquiring images while standing on one foot instead of both feet obviously increases the load of the foot in question. This will result in decreased bone heights and may affect geometric analyses due to pronation of the foot that could preclude comparison to bilateral scans[45]. In the case of separate acquisitions required for the forefoot and hindfoot (for certain scanner types), stitching software is used to fuse multiple volumes [116]. It remains to be established whether it is preferable to acquire imaging of both feet all at once to minimise errors caused by stitching multiple volumes balanced against error that may be introduced due to stance and posture during single-leg acquisitions (Fig. 4). A recent study found average stitching errors of only 1.3° and 1.2 mm in terms of rotational and translational errors [116].

Another concern for WBCT is unaccounted variability in the patient weight and load distribution during scanning. It is well understood that different WB positions differ from NWB foot alignment [45]. Therefore, monitoring of load and weight distribution would seem crucial to repeatable positioning. Consensus on how patients should stand in terms of weight distribution on the medial-, lateral- or hind-foot should be incorporated into any standardised scanning protocol. One way of controlling the positioning of the foot during scanning and discriminating between different known foot positions (i.e. clinically normal, valgus and varus positions) is the use of a "foot tripod" which is defined as the supporting bony landmarks i.e. the most caudal point of the 1st and 5th metatarsal heads and of the calcaneus. Both Lintz [43] et al. and Arunakul et al. [69] applied the concept of the tripod for foot measurements, in the so-called foot and ankle offset (FAO) and the tripod index (TI) attempting to reduce measurement variation in terms of weight and load distribution as the foot is positioned in a controlled fashion with clear reference points. However, test–retest repeatability studies involving such tripod reference systems are lacking. If properly validated, a tripod reference in WBCT protocols could optimise measurement precision. In our experience, the use of a horizontal supporting surface visible on foot images (e.g. a carbon footplate) during scans is a simple way to provide a stable plane of reference for the tripod with minimised risk of measurement variation that should also be considered as part of a standardised protocol.

Variability in imaging analysis at the foot

In general, geometric 2-D and 3-D measures from WBCT are obtained using 3-D volumes, multiplanar reconstructed images or simulated digitally reconstructed radiographs. Advanced patient-specific analyses such as 3-D geometries and kinematics require reproducible segmentation of bones and the use of robust measurement protocols. Manual segmentation of bones can be time-consuming, observer-dependent and may take several hours per patient. The use of latest software enables semi-automatic segmentation of bones in the foot/ankle in several minutes with the opportunity to enhance the clinical applicability patient-specific WBCT analyses through greater reliability and much quicker availability of results [124].

After bone segmentation and allocation, geometric analyses generally consist of calculations of bone heights using caudal or cranial borders, the centre of gravity [44, 45, 60, 125, 126] or angle measurements based on centre lines, anatomical landmarks, gravitational lines or lines perpendicular to bone surfaces in 3-D or multiplanar reconstructions [45, 60, 125, 126]. Distance maps can also be acquired by calculating distances between bones or at joint spaces [127], which may provide valuable clinical information on loading in patients with osteoarthritis [18, 55, 121, 128, 129] (Fig. 5). Lenz et al. [130] stressed the excessive variety of analysis methods in the foot/ankle and the need for creating uniform strategies for the definition of coordinate systems for the tibia/talus/calcaneus, and kinematic mathematical and geometric definitions for the tibiotalar and subtalar

Fig. 4 Differences in stance, posture and alignment of the foot during separate forefoot and hindfoot acquisitions could lead to inaccurate stitches of both volumes. Although most bone structures are aligned correctly in the hindfoot and forefoot acquisitions, soft tissue artefacts and partial bone misalignment are observed in both illustrations, found in both the tibia, the talus and the metatarsal bone

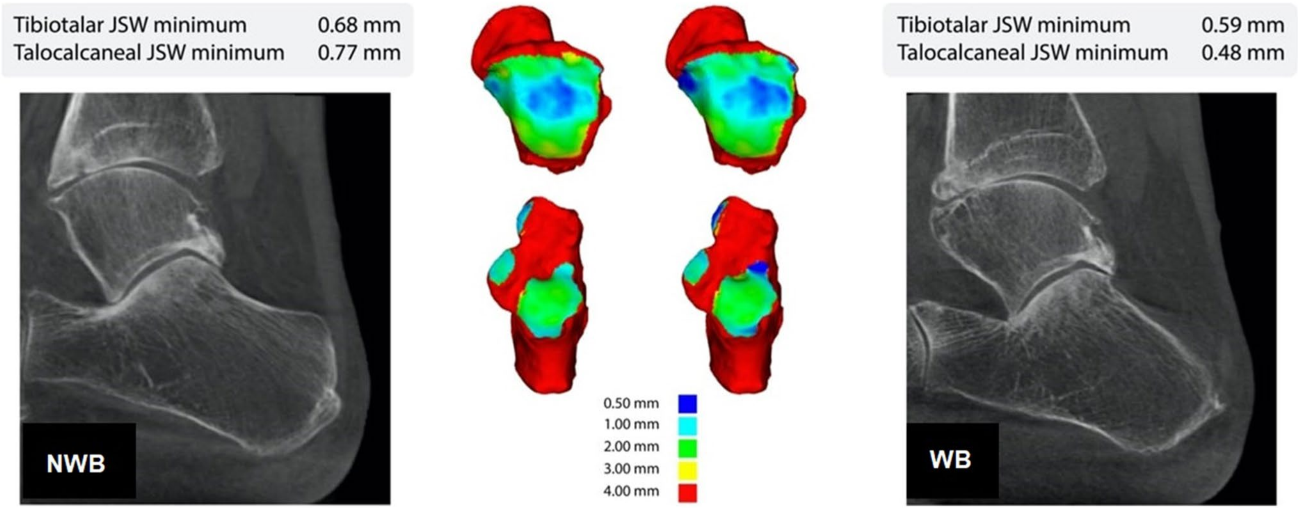

Fig. 5 In this case, severe ankle osteoarthritis is present and joint space widths (JSW) are quantified and visualised using joint space maps in both (NWB) non-weight-bearing and (WB) weight-bearing conditions. Relevant osseous structures were semi-automatically segmented using dedicated software [124] and relative distances were calculated and visualised using in-house developed software [131]. Although the added clinical value of these joint space maps seems clear, the reliability and interpretation depend on the stance and the weight and load distribution during both acquisitions and accuracy of bone segmentation

joints. Furthermore, analyses include the quantification of displacement of bones between WB and NWB conditions, between pre- and postoperative scans, between sequential acquisitions or between left and right feet, all of which can be quantified in 6 degrees of freedom in terms of translation (mm) or rotation (°). Therefore a multitude of factors can influence measurement reproducibility on top of issues regarding acquisition repeatability.

Knee

The number of studies concerning WBCT of the knee is slowly rising and thus so also does the need for consensus on how to perform WBCT reliably at this region. Most importantly, consensus is required for controlling overall knee position, e.g. both flexion, extension and adduction/abduction in order to optimise repeatability. Consensus-based recommendations on the subsequent measurement procedures e.g. regarding the exact choice of anatomical landmark and image plane selections will also be necessary to ensure reproducible measurements.

Variability in imaging acquisition of the knee

Marzo et al. [15, 17], Hirschmann et al. [11, 58] and Lullini [59] et al. amongst others have shown that patellofemoral stability and the corresponding knee measurements are significantly affected by WB. This finding is essential since it underlines the relevance of adding WB to cross-sectional imaging. However, the test–retest reliability of such changes remains to be documented to confidently rely on WB induced changes e.g. in patellar tracking. Knee joint positioning is another important factor to consider in order to obtain maximal reliability of measurements. In particular, knee flexion angle is well known to significantly influence TT-TG distance (Fig. 6) and other radiological measurements of patella position such as patellar tilt, bisect offset and patella height. When measuring the TT-TG distance and patella position, several fixed degrees of flexion have been investigated ranging from 0–30–60–120°, but most studies recommend 30° of flexion for WBCT. Hirschmann et al. [58] reported the influence of flexion on geometric measurements, showing that increasing knee flexion leads to decreased TT-TG distance during flexion ranging from 11.1 ± 3.7 mm at 0° of flexion to − 2.4 ± 6.4 mm at 120° of flexion. Relative abducted (valgus) or adducted (varus) position of the knee, both in supine and WB positions, should also be considered. Although conducted on supine NWB MRI, Smith et al. demonstrated with computational models that valgus or varus position, respectively, increased or decreased the TT-TG distance by 1 mm/1° [132]. In concordance with Smith et al., Egund et al. [133] further showed that measurements of the TT-TG distance on MRI were influenced by the positioning of the knee in either an adducted or abducted position and that the measurement was influenced by systematic technique-dependent errors. Egund et al. suggested aligning images to the craniocaudal centre axis of the tibia on 3-D MRI sequences prior to measurement of TT-TG distance to correct for this error, and discouraged use of routine axial 2-D MRI for TT-TG measurements since image planes cannot be adequately

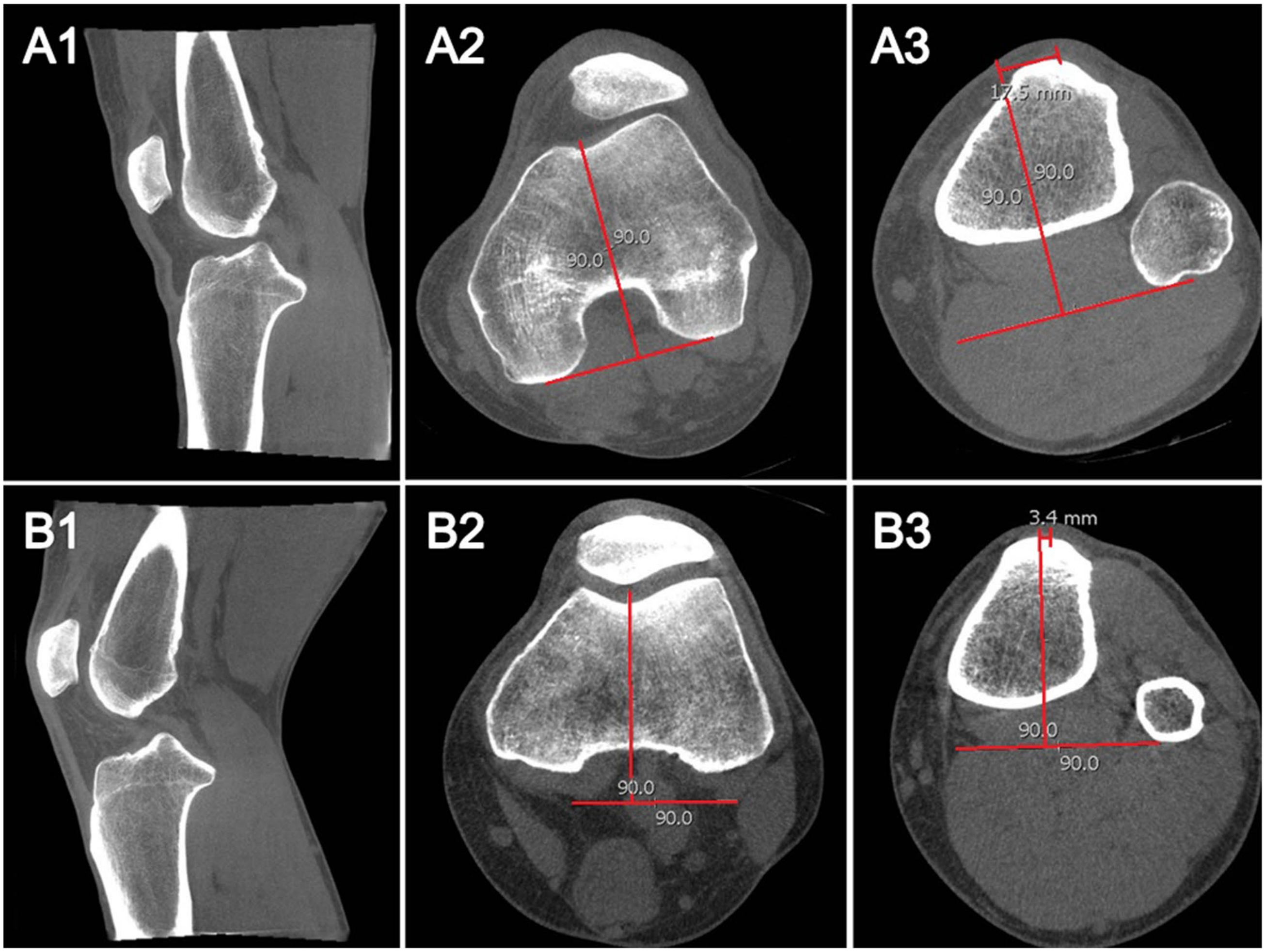

Fig. 6 WBCT in full extension/0° of flexion (**A1**) and in 20° of flexion (**B1**) with their corresponding axial images with the deepest articulating part of the trochlea visible (**A2**, **B2**) and respective TT-TG measurements of 17.5 mm (**A3**) and 3.4 mm (**B3**)

corrected. Results from both studies stressed the need for flexed anatomical scanning positions of the patient [132, 133]. Segal et al. examined WB scans for evaluation of the JSW in osteoarthritis with a test–retest setup. Participants were set with their knee in approximately 20° of flexion in combination with a foot and thigh positioning device. They found that WBCT had the potential to improve evaluation of JSW over standing radiographs [55]; a more recent study by Fritz et al. confirmed the these findings [19]. Across studies, knee flexion has been measured in multiple ways (Table 3).

Only the study by Segal et al. [55] examined knee flexion in a test–retest setup. They found that their joint positioning protocol demonstrated high day-to-day repeatability for measurement of 3-D JSW. Unfortunately, no other WBCT studies were identified that applied a test–retest setup. Turmezei et al. [21] also evaluated test–retest repeatability, but used the same data set as Segal and colleagues [22]. Lullini

Table 3 Methods and degrees of knee flexion in WBCT

	Methods of flexion	Degrees of flexion	Test–retest
Marzo et al. [15]	Fixed-angle goniometer	30°	No
Segal et al. [55]	Syna-Flexer + foot positioning frame	20°	Yes
Hirschmann et al. [58]	Manual goniometer	0°, 30°, 60°, 120°	No
Lullini et al. [59]	Manual goniometer + pressure plate	30°	No
Kothari et al. [134]	Syna-Flexer	20°, 30°	No
Yang et al. [135]	Full extension + squat position	0°, 30°	No

et al. [59] stated that they had planned to make a test–retest but this was precluded by their local ethical committee.

Although they initially seem a realistic solution to issues of positioning variability, external support devices could theoretically reduce the physiological relevance of measurements since they do not replicate the in vivo situation. In theory it could be preferable to rely on “bio-feedback” aids such as real time flexion angle monitoring, e.g. using digital goniometers during scanning, which enables patients to maintain a fixed degree of knee flexion during acquisition. Regardless of the method applied it remains key to improve acquisition repeatability since post hoc correction of variation in knee flexion cannot be corrected post image acquisition.

Another important factor that may induce positional error between acquisitions is the potential for motion artefact blurring bone contours that can influence the accuracy of bony segmentations and landmarks required for measurements. In our experience it can be strenuous for patients, especially those with ongoing pain, to stand in a static flexed knee position even for the shorter scan times that are typically around 20–30 s. The discomfort is likely most pronounced during unilateral loading conditions required in some scanner designs. Even though Maier et al. [136] have proven it possible to reduce movement artefacts in WBCT by marker-free motion correction (involuntary patient movement is estimated with respect to a, motion-free supine reference scan), the accuracy of this correction is not reported and it is not widely adopted.

Variability in imaging analysis at the knee

Although standardised alignment of multiplanar (MPR) reformatting of images is a universal issue in radiology, it is just as important that these are done reproducibly when evaluating WBCT test–retest acquisitions. This is especially important for measurement of landmarks that are identified on two separate cross-sectional slices such as TT-TG distance. If MPR correction of imaging planes is not performed in a standardised manner or a 3-D landmark consensus is not achieved, this could result in unwanted reproducibility error. This source of variability is of course closely related to the aforementioned caveats of scanning in relative abduction or adduction of the knee (Fig. 7).

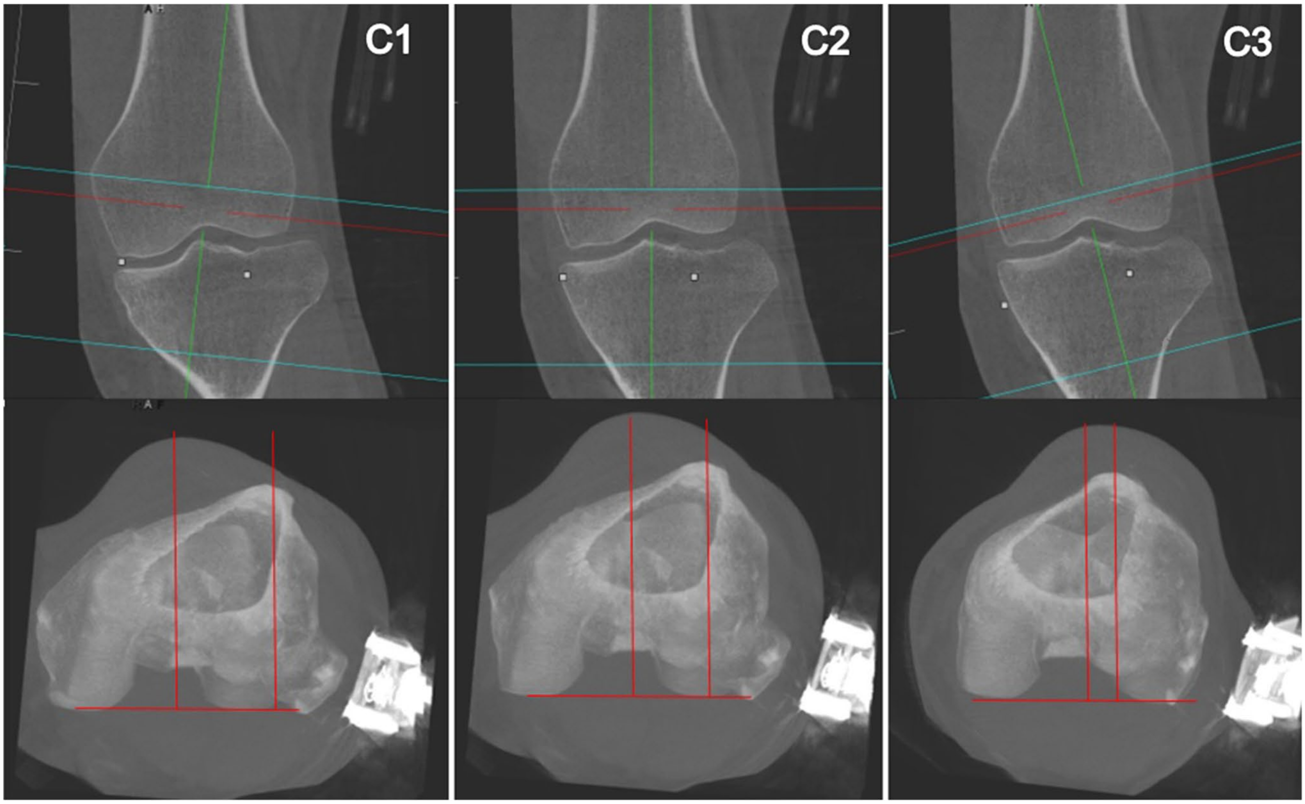

Fig. 7 Volume rendering image showing different TT-TG distances on the same WBCT of the knee joint. The axial plane is adjusted in **C1** abducted, **C2** neutral and **C3** abducted positions yielding correspondingly different TT-TG distances. This call for standardisation of image plane correction prior to TT-TG measurements to ensure reliability

Table 4 Suggestions for future research and expert consensus concerning WBCT in the lower extremity

- Development of guidelines and tools for standardising scanner setup
- Choosing between single *versus* bilateral acquisitions
- Measures to avoid image-stitching and beam hardening artefacts
- Standardised degrees of flexion at the knee ± use of a positioning device
- Standardised positioning at the foot/ankle ± use of a positioning device
- Standardised multiplanar imaging reformatting of image planes prior to geometrical measurements
- Test–retest repeatability studies to optimise robustness of measurements
- Establishing clinical validity of measurements

Future aspects of WBCT

Obtaining repeatable acquisitions in terms of positioning, stance and load distribution will always be challenging, but efforts should be made to provide guidelines of how to best monitor and repeat exact scanning conditions over time. This will require significant future efforts across research and clinical centres in collaboration with vendors of WBCT scanners to standardise the setup for repeatable scanning conditions. In large gantry WCBT we could have some concern about image quality but it seems intuitive, that compared to conventional radiographs many sources of measurement variation could be alleviated if general standardization of measurements is well established. In the pelvis and hips the scanning situation in large gantry scanners is expected to closely resemble the vivo situation and the combination of WB and 3-D imaging can surely add new knowledge to our current understanding of diseases such as hip dysplasia, FAI and osteoarthritis. The predefinition of clinically relevant reference points, axes or anatomical landmarks for measurements of distances, angles, bony displacement and rotation between scans in WB and NWB conditions will undoubtedly improve reproducibility of 2-D and 3-D measurements. This warrants expert consensus exercises and more research (Table 4). Ultimately, these metrics also needs to demonstrate validity in studies that assess usefulness in terms of clinical outcomes.

Conclusion

Acknowledging the risks of adopting new technologies into the clinic, we believe that WBCT, with its low dose of radiation, smaller voxel isotropy and 3-D capability is set to provide important new insights into lower extremity bone and joint morphology, biomechanics and pathology. However, this potential is dependent on standardised acquisition methodologies that optimise test-rest repeatability to allow evaluation of the smallest effects of a given intervention or disease progression. Reproducible 2-D/3-D geometric analyses of these acquisitions are equally essential, and efforts should be made to establish thoroughly tested measurement guidelines, ideally devised by expert consensus panels. Guideline standards should define ideal patient-positioning, loading criteria, uni-versus bilateral acquisition, FOV requirements, standardised image review planes and consensus on valid 3-D anatomical landmarks. It will be a substantial challenge to focus on factors that influence repeatability through strict quality control, and those that influence intra- and interobserver reproducibility from clearly established and technically validated measurement methodologies. With standardised joint positioning/loading, imaging reconstruction and measurement protocols agreed amongst the clinical and research communities, WBCT will be much more likely to deliver on its potential.

Declarations

Conflict of interest The authors declare no competing interests.

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