Radiological assessment of lower limb torsional deformities: a narrative review

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Background and Objective: The evaluation of both femoral and tibial torsional profiles remains a challenge in the orthopedic practice since there is no agreement on the most precise and reliable measurement method and technique. The aim of this review is to collect and critically report the most relevant and up-to-date evidence on the radiological techniques available to determine lower limb torsional deformities and to discuss the advantages and limitations of each technique to better define their optimal field of application.

Methods: Literature research on PubMed, Embase, and Google Scholar databases was performed, utilizing the following search string: "torsion" AND ("lower limb" OR "femur" OR "tibia"). Relevant clinical and preclinical studies evaluating different radiological techniques to assess lower limb torsional deformities, and possibly comparing them, were collected and critically reviewed.

Key Content and Findings: Computed tomography (CT) is still considered the best method to measure both femoral and tibial torsional angles. Its main limitation, the radiation exposure, has been recently addressed with ultra-low dose protocols that were proven to be as accurate as standard protocols. On the other hand, magnetic resonance imaging (MRI) offers a nonionizing, radiation-free option that is now considered almost equivalent to CT. However, MRI consists in a long and expensive procedure that can be hindered by issues linked to metal implants, patient's positioning and measurement variabilities. Lastly, three-dimensional (3D) reconstructions derived from low-dose biplanar radiographies (LD-BRs) have been proposed as a low-radiating, quick and reliable solution to overcome the limitations of both MRI and CT scans.

Conclusions: To date, CT has still to be considered the gold standard for the radiological assessment of lower limb torsional deformities. Nonetheless, MRI and LD-BR have been proven to be valid and reliable alternatives, especially in specific clinical settings.

Keywords: Torsion; femur; tibia; computed tomography evaluation (CT evaluation); lower limb

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Introduction

Background

Torsional deformities of the lower limb are intended as the abnormal twisting in the longitudinal axis of the tibia and/or the femur (1). Femoral torsion is commonly represented by the angle formed by the femoral neck axis and the line tangential to the posterior aspects of the femoral condyles (*Figure 1*) and normally results in internal femoral rotation (IFR) as a result of an excessive femoral anteversion (FAV). On the other hand, tibial rotation is most commonly recognized as the relationship between the tangent to the posterior aspect of the proximal tibial metaphysis and the transmalleolar axis generally resulting in external tibial torsion (ETT) (*Figure 2*). A combination of the two abnormalities can coexist.

Lower limb torsional deformities have been seen to alter the physiological knee biomechanics leading to knee joint alignment alterations and an increase of intra-articular contact pressures (2-4). Indeed, lower values of IFR and lower ETT have been found in osteoarthritic knees (5,6), while higher values of IFR and ETT have been extensively associated with anterior knee pain (3,7) and patellar instability (8-10). As for the latter, the tibial tubercle-trochlear groove (TT-TG) distance is the main value driving surgical decision making but this value has been seen to be influenced by both tibial and femoral torsion (9): an increase in FAV (resulting in an increase of IFR) drives the TG medially thus increasing TT-TG distance similarly to an increase of ETT. As a result, when planning a corrective surgery, it must be kept in mind that the modification of femoral and tibial torsion angles will have an impact on the TT-TG value (11-13). Lastly, torsional abnormalities should be taken in account in the setting of a total knee replacement implantation to avoid postoperative pain and patellar instability (14-17).

Currently, there is no consensus on the cut off between physiological and pathological values of femoral and tibial torsion for none of those knee pathologies (18,19). As a matter of fact, a consensus also lacks on how to precisely measure those parameters: although computed tomography (CT) is widely considered the gold standard to assess such abnormalities (1,20), more than 20 different methods to evaluate FAV on CT have been proposed and are commonly used in the clinical practice and research. This results in physiological values of FAV ranging from 5° to 25° depending on the specific measurement method and significant difference in calculated values of up to 100% (11°–22°) (7,21,22). Furthermore, CT scan is intrinsically associated with several limitations such as high costs and radiation exposures, especially relevant when dealing with pediatric patients (23,24). Moreover, its optimal acquisition can be altered by an incorrect patient positioning as wells as the incorrect positioning of the plane of the CT cuts and the reference lines (21,25-29). To overcome at least some of the aforementioned limitations, research has been conducted in order to refine the safety and efficacy of CT: several studies compared the different measuring methods for CT scans and low-dose protocols for CT scans have been developed and validated for the assessment of lower limb torsional deformities. Furthermore, alternative radiological techniques have been proposed when assessing lower limb torsional abnormalities: specifically, magnetic resonance imaging (MRI) and biplanar X-rays (BP-XR) have been proposed as alternatives to CT with specifical advantages for each of those technique. Moreover, such techniques could be used in combination to CT scans or to other non-radiological measurement methods, such as clinical assessment, ultrasonography, gait analysis and sensor-based measurements, to increase the precision and reliability of the measurement of lower limb torsional deformities.

Rationale and objective

Several radiological techniques have been proposed to determine femoral and tibial torsional deformities. Previous studies failed to comprehensively include the available evidence on the topic reporting strengths and limitations of each specific technique. Aim of this review is to collect the relevant evidence regarding the different radiological techniques available to determine lower limb torsional abnormalities and to compare, when possible, their different advantages and limitations as well as their best field of application. We present this article in accordance with the Narrative Review reporting checklist (available at https://aoj.amegroups.com/article/view/10.21037/aoj-24-42/rc).

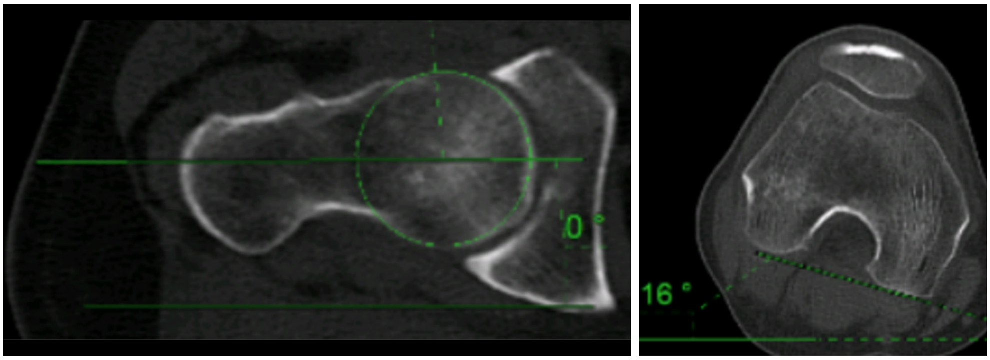

Figure 1 CT measurements of femoral torsion using the center of the femoral neck and the posterior condylar line as references. CT, computed tomography.

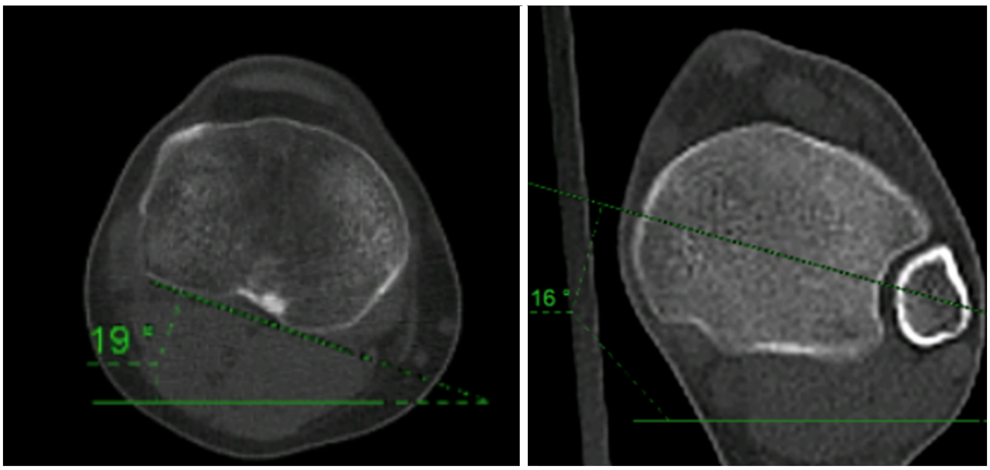

Figure 2 CT measurements of external tibial torsion using the posterior condylar line and bimalleolar line as references. CT, computed tomography.

Methods

Literature research was performed on PubMed, Embase, and Google Scholar databases on the 23rd May 2024, utilizing the following search string: "torsion" AND ("lower limb" OR "femur" OR "tibia"). The screening process was performed by two independent reviewers (P.C. and G.A.). The first step was the initial screening based on titles and abstracts, considering the following inclusion criteria: (I) clinical and preclinical studies on both prospective and retrospective human cohorts; (II) English language; (III) published in indexed journals; and (IV) evaluating different radiological techniques (CT, MRI and X-rays) to assess lower limb torsional deformities. Articles reporting preclinical evidence on animal models, non-radiological methods such as ultrasonography, gait analysis, clinical assessment and sensor-based measurements or that were not written in English language were discarded. Furthermore, giving that the radiological assessment was the main focus of this study, manuscripts reporting data on ultrasonography, sensor-based evaluations and clinical assessment were not included in the present review.

Upon concluding the initial abstract screening phase, full texts of included articles were evaluated, and the reference list of all the retrieved articles was further reviewed for identification of potentially relevant studies during the whole process. The selected studies were later reviewed together with N.P. and S.P. and finally included in the review analysis. Year of publication covered a 30-year time span from 1994 to 2024. Complete search criteria are presented in *Table 1*. A comparation of the strengths and limitations of each technique is reported in *Table 2*.

Table 1 The search strategy summary

Items	Specification
Date of search	23rd May 2024
Databases and other sources searched	PubMed, Embase, and Google Scholar
Search terms used	"torsion" AND ("lower limb" OR "femur" OR "tibia")
Timeframe	1994–2024
Inclusion criteria	Clinical and preclinical studies on humans, English language, indexed journals, evaluating different radiological techniques (CT, MRI and X-rays) to assess lower limb torsional deformities
Selection process	Independent selection of potentially relevant manuscripts and later review with the senior authors

CT, computed tomography; MRI, magnetic resonance imaging.

Table 2 Main strengths and limitations of CT, MRI and LD-BR

Technique	Strengths	Limitations
CT	Still considered the gold standard	Exposure to ionizing radiations
	High inter- and intra-observer accuracy	Dependent on patient positioning
	Quick acquisition	Dependent on correct reference positioning
	Conducted in a supine position, standing is not necessary	
	Ultra-low-dose protocols are now available	
MRI	Non-ionizing	Long acquisition times
	Applicable to the pediatric population of any age	Dependent of ability of the patient to remain still
	Good correlation with CT measurements	Dependent on patient positioning
		Dependent on correct reference positioning
		Interference of metal implants
		High costs
LD-BR	Good correlation with CT measurements	Not applicable <6 years of age
	Based on semi-automatic 3D reconstruction	Skeletal immaturity (<15 years of age) could interfere with the correct reference positioning
	Low dose of ionizing radiations	Potential post processing user errors
	Less dependent on patient positioning	Dependent on patient ability to remain still in a standing position
	Less dependent of references positioning	High capital expense and costs
		Not applicable to severe deformities
		Reconstruction is based on surface anatomy and doesn't consider inner structure

CT, computed tomography; MRI, magnetic resonance imaging; LD-BR, low-dose biplanar radiography; 3D, three-dimensional.

Radiological techniques to assess lower limb torsional abnormalities

CT

CT is generally considered the gold standard to detect and quantify lower limb torsional deformities because of its cost effectiveness, acquisition times and accuracy in placing bony landmarks in the axial plane (1). However, there is still no consensus on which of those landmarks are the most accurate and standardizable meaning that there is

Table 3 Most common reference methods to measure femoral and tibia torsional profiles, adapted from Schock *et al.* (30) and Liodakis *et al.* (31)

Reference methods	Descriptions of measure
Proximal femur	
Weiner (32)	The line passing through the middle of the neck parallel to the ventral and dorsal cortices. The CT axial slice is the one distal to the femoral head, where the ventral and dorsal cortices are approximately parallel to each other
Hernandez (33)	The line passing through the center of the femoral head and the midpoint of the femoral neck. The CT axial slice is the one where the femoral head, isthmus of the femoral neck, and the superior border of the greater trochanter are evident
Reikeras (34)	The line connecting the femoral head center and the femoral neck axis on a superimposed image. The CT axial slice is the one where the anterior and posterior cortices run parallel
Murphy (35)	The line connecting the center of a circle on the femoral head and another circle centered in the femoral shaft below the lesser trochanter
Distal femur	
Posterior condylar (34)	The line tangent to the most posterior points of the medial and lateral femoral condyles. The CT axial slice is the one where the largest diameter of the femoral condyles is obtained
Transcondylar (33)	The line representing the bisector of the angle formed by two lines tangent to the anterior and posterior aspects of the femoral condyles
Proximal tibia	
Posterior condylar (34)	The line tangent to the most posterior points of the medial and lateral tibial condyles. The CT axial slice is the one just cranial to the fibular head
Distal tibia	
Ulm/Waidelich/ Elipses (36)	The line between the centers of an ellipse from the surface of the medial malleolus and another ellipse formed by the incisura fibularis
Jend (37)	The line intersecting the middle of the line connecting the end points of the incisura fibularis of the tibia with the center of a circle created from the junction of the tibial pilon and incisura fibularis
Bimalleolar (34)	The line connecting the centers of the medial and lateral malleolus
Jakob (38)	The line through the lower end of the tibia which bisects the anteroposterior diameter and passes through the anterior half of the lateral malleolus

CT, computed tomography.

no consistency in current measurements (21,25). Accurate measurement of FAV is crucial to diagnosing, correct surgical decision-making and the preoperative planning of a derotational femoral osteotomy (i.e., the amount of correction needed). Scorcelletti *et al.* reported that more than 20 different methods to measure FAV with CT scans have been proposed and that it is still impossible to draw conclusions on which is the most accurate in terms of reproducibility (22). Kaiser *et al.* (21) have shown significant differences between different measurement techniques of up to 11°. The most frequently used reference methods are summarized in *Table 3*.

Historically, the single-slice CT method just distal to the femoral head was thought to be the most accurate in assessing FAV (39) while, for tibial torsion, CT cuts within 2 cm of the proximal tibial joint line were considered reliable regardless of the selected reference axis (posterior condylar, transcondylar, or anterior condylar) (40). More recently, Liodakis *et al.* compared the methods most frequently used to define the femoral neck axis [Hernandez (33) and Weiner (32) methods] and the distal tibial axis [Jend (37), Ulm/ Waidelich/Elipses (36), and bimalleolar methods (34)]. The authors concluded that the Hernandez and bimalleolar methods for measuring femoral and tibial torsion respectively, had the greatest inter- and intra-observer reliabilities (31).

Finally, Murphy *et al.* described a more complex method of measurement based on two planes that are not affected

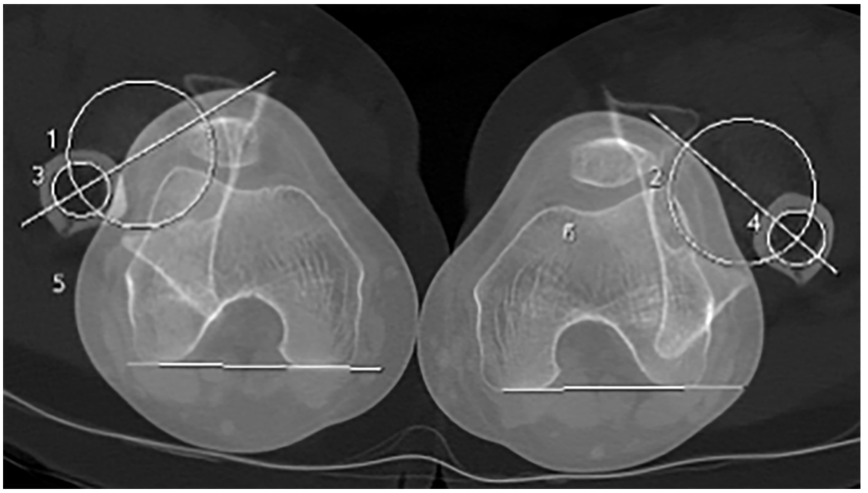

Figure 3 CT measurement of femoral anteversion using the Murphy's method. 1, circle that marks the femoral head; 2, patello-femoral joint; 3, circle that marks the femoral shaft below the lesser trochanter; 4, line that connects the center of the two circles; 5, posterior condylar line; 6, distal epipysis of the femur. CT, computed tomography.

by anatomical anomalies of the neck like "cam deformity", the femoral head and the base of the neck (35). The method is based on Billing definition of femoral torsion (41) described as the angle between a knee axis located in the distal femur and the proximal or neck axis defined by two points. One of the two points is in the center of the femur, which locates the longitudinal axis of the femur, and the other one is in the center of the femoral head (*Figure 3*). Some authors described as this method comes closest to defining anatomical reality claiming that common method of running a line along the femoral neck on a CT image underestimated the actual anteversion by a mean 13° (35) and that the differences between the FAV measurements obtained with Murphy's method and the classic method are greater in patients with pathological FAV than in the normal population (42).

Nonetheless, significant inter-observer variability and bias could be still found between different experts when manually measuring torsional profiles even if a unique reference method was chosen (28). For this reason, Stephen *et al.* proposed and validated on cadavers specimens a computer-based method to automatically calculate tibial torsion either with CT or MRI acquisitions (43). In their study, this automated method outperformed the current manual methods of Jakob (38) and Reikerås (34) in reliability with no significant differences obtained with either MRI or CT scans acquisitions (43). The advantage of an automated software-based system is that it ensures consistency, time efficiency, validity, and accuracy that are not feasible with manual measurements, which are dependent on assessor experience (28,43). A similar software-based measurement method was recently assessed by Leonard *et al.* comparing its reliability and validity to manual measurements in patients with post-traumatic deformities and patellofemoral issues: the group found high intra- and inter-rater reliability for both techniques thus concluding that the software-based measurement might improve confidence in reliable medical decisions in diagnostics and treatment, especially for inexperienced surgeons (44).

However, agreeing on a standardized measuring method and adopting it correctly may not be sufficient to truly assess lower limb torsional abnormalities. Indeed, those measurements can differ from the real anatomical deformity because of bony abnormalities such as CAM lesions (45), valgus and short neck, severe joint contracture (25) and can even depend on patient positioning: Morvan *et al.* evaluated the impact of different femoral positions during acquisition on CT and stereographic measurement of femoral torsion. The authors found that hip flexion and extension statistically significantly affected CT measurement of femoral torsion: specifically, hip flexion led to underestimated femoral torsion values (up to 8.5°) while hip extension led to overestimated values (up to 12.6°) (29). It is worth mentioning that abnormal femoral positioning is generally found in flexion, especially in osteoarthritic and symptomatic patients holding a hip antalgic position: in those patients femoral torsion values could be underestimated with CT scans and this should be kept in mind when planning a surgical procedure. Conversely, in the aforementioned study, stereoradiography measurement were not influenced by hip flexion and extension and hip abduction and adduction had no impact on neither of the two radiological techniques (29). Similar influences of joint positioning have been seen also for reciprocal bony rotational measurements such as the TT-TG distance: several studies demonstrated that progressive knee flexion leads to lower TT-TG distances compared to full extension and rest position (46-49). Similar alterations can also be produced in the coronal plane given that a different patient positioning, with the leg resting in a varus or valgus position compared to rest, can modify the TT-TG measurement: Egund *et al.* reported that a decrease of TT-TG values is produced by knee abduction (valgus position) whether knee adduction (varus position) seems to increase the measured TT-TG (50). Furthermore, TT-TG distance measurements are also influenced by internal and external knee rotation during acquisition: each degree of rotation from the neutral plane changes of 0.52 mm the true TT-TG distance with internal rotation reducing its value and external rotation increasing it (51).

While knee flexion/extension malpositioning can be easily detected on sagittal images while reviewing lower limb CT scans, detecting an incorrect positioning can be more challenging for the hip joint. Indeed, a unique method to assess hip flexion positioning in pelvis CT scans is not available and, in lower limb CT scans, the acquisition of the pelvic bone is frequently limited thus preventing a complete evaluation of the femoral-acetabular positioning. For this reason, the importance of patients' positioning for its impact of torsional analysis, should be strongly transmitted and reported to the professional figures performing the CT acquisitions in order to provide radiologists and surgeon with correct and reliable images.

Lastly, a representative determination of FAV could be not sufficient to assess the clinically relevant overall femoral rotation. Indeed, Seitlinger *et al.* established that the angular torsions measured at the neck, midshaft and distal part of the femur, all contribute to the total femoral torsion (27). This was later confirmed also by Archibald *et al.* (26) demonstrating that the exclusive assessment of femoral neck anteversion could produce misleading results determining torsional abnormalities in a normal or pathological femur.

Apart from the aforementioned issues limiting the correct measurement of torsional profiles with CT scan, this technique holds the major limitation of the inherent radiation exposure, especially relevant when dealing with the pediatric population (52). In the aim of pursuing the As Low As Reasonably Achievable (ALARA) principle, radiation dose reduction has recently been pursued (24): Keller *et al.* where among the first to prove that radiation dose reduction down to 1% of original CT dose levels may be achieved in CT torsion measurements of the lower limb without compromising diagnostic accuracy (53). Those results were later confirmed by several other reports paving the way to a wider and less harmful use of CT scans. Indeed, the most recent ultra-low dose CT scan protocols produce an effective radiation exposure of 0.17 mSv, less than a single standard anteroposterior radiograph of the pelvis (54-56).

In conclusion, CT is still considered the gold standard to assess lower limb torsional deformities. Nonetheless, several precautions must be used to correctly perform the acquisition, correctly interpret those values as physiological or pathological and to reduce the radiation exposure.

MRI

Lower limb torsional deformities are common in several pediatric neurological conditions such as cerebral palsy (57,58). In such young patients, the need to avoid radiation exposure led to the increasing use of non-radiating methods such as MRI. Tomczak *et al.* were among the first to compare the accuracy, precision, and reliability of MRI and CT scan to measure FAV angle (59). Good correlation (correlation coefficient 0.77) and good inter and intra-observer agreement between the two techniques were reported but mean anteversion angles were found to be slightly higher with CT compared to MRI (34° *vs.* 23°, respectively) (59). Similar results were also reported by Botser *et al.* when evaluating FAV with MRI and CT scans on 129 patients with non-arthritic hip pathologies: while CT and MRI measurements showed high correlation with each other (r=0.80), in 96% of the cases the CT measurement was larger, with a mean difference of 8.9° (range, −37° to 1.5°) (60).

Torsional assessment with MRI generally adopts similar anatomical landmarks as those used with CT thus maintaining the same limitations highlighted above: indeed, also MRI measurements of femoral torsion angles were found to be dependent on patients' positioning and on the level and type of selected landmarks used to define the reference axis (25). In the aforementioned study by Stephen *et al.*, an automated software-based method, that could overcome the issues linked to incorrect manual positioning of the anatomical references, was proposed to quantify tibial torsion both with CT and MRI and the measurements were found to be comparable between the two techniques (43). Similarly, Schock *et al.* recently proposed and validated a deep learning-based method for the fully automatic measurement of femoral and tibial torsion on MRI: in the 93 included patients, the artificial intelligence (AI)-based method, compared to several manual methods, had excellent correlation and inter-reader agreement coefficients while resulting significantly faster than the manual method (30). The lowest inter-reader differences and highest inter-reader correlations and correlation coefficients were found between the AI-based algorithm and the Lee method for proximal femur (61) and Ulm/Waidelich/Elipses method (36) for the distal tibia (30).

Hence, MRI is now considered a reliable alternative to CT to determine both femoral and tibial torsional deformities (20,30,43,62,63). Grünwald *et al.* recently published the results of a prospective study comparing the concurrent assessment of both femoral and tibial torsion with CT and MRI (62). The two techniques were found to be comparable for the assessment of such lower limb deformities thus supporting the use of MRI to reduce the exposure to radiations (62). Similarly, Beebe *et al.* to tried to determine the accuracy and consistency of MRI and CT femur rotational studies based on four described protocols (CT-axial, CT-oblique, MRI-axial, MRI-oblique) on 12 cadaveric samples to compare the measurements to the true torsion angles (20). Even though CT-axial was both most accurate and reproducible when compared with true torsion of the femur, both magnetic resonance (MR)-axial and CT-oblique reach a so high accuracy level that is likely less than clinical significance. Therefore, it suggests that MR-axial images should be used in clinical situations where radiation exposure needs to be limited (20). Interestingly, MRI-oblique images were found to overestimate the true FAV especially when those values increased (20) and this comes in contrast with the above-mentioned studies that reported higher FAV values found in CT scans compared to MRI (59,60).

Nonetheless, it is worth mentioning that MRI generally requires longer scanning times compared to CT scan (43). This could represent a major limitation when considering efficiency, mainly in a large-scale model, but is also relevant when dealing with patients that struggle to remain still, such as neurological pediatric patients, thus altering the precision of the acquisition.

Lastly, MRI is generally not recommended in the presence of metal implants given the signal disturbance that can be produced. Conversely, ultra-low dose CT protocols have been proven to be feasible for torsion measurement of the lower limb even in patients with metal implants (54).

Three-dimensional (3D) reconstructions based on low-dose biplanar radiography (LD-BR)

LD-BR has been developed to provide a precise, accurate, quick method to evaluate bony anatomy while significantly reducing the radiation dose. Specifically, EOS Imaging® (Paris, France) is a LD-BR system initially proposed for pediatric hip and spine diseases and later applied to detect femoral and tibial torsional abnormalities (64,65). Indeed, with the EOS system®, a 3D model of the lower limb anatomy useful to assess tibial and femoral torsions is reconstructed from low-dose biplanar (coronal and sagittal) radiographies acquired in a standing position. The 3D reconstruction process is a software-based protocol that recreates bony contours by identifying osseous landmarks such as the femoral head, the greater and lesser trochanters, the femoral condyles, tibial plateau and medial and lateral malleoli and then automatically calculates axial parameters including FAV, femorotibial rotation and tibial torsion. Several studies have assessed the accuracy and interobserver agreement of LD-BR and CT scans generally reporting promising results and thus proposing LD-BR as a valid alternative to CT scans in the assessment of lower limb torsional deformities (29,66-74).

Rosskopf *et al.* conducted two separate studies to compare the tibial and femoral torsion measurements obtained with 3D models produced from biplanar radiographies to the ones obtained with CT scans and MRI. In the first, 50 children and adolescents (age 4.7–14.8 years) underwent both LD-BR and CT scans: the two techniques were found to be comparable with good inter-method agreement for both femoral torsion [intraclass correlation coefficient (ICC) =0.90; 95% confidence interval (CI): 0.87–0.92] and tibial torsion (ICC =0.75; 95% CI: 0.68–0.80) (67). Furthermore, despite skeletal immaturity that could interfere with the correct identification of the bony landmarks, torsion measurements in children on biplanar radiography seemed to be as reliable as those on CT images with no detected trend for larger differences with decreasing age of the children (67). Similar results were also found when comparing LD-BR and MRI in 60 children and adolescents (mean age 10.1 years; range, 6.2–16.2 years) (66).

3D models based on LD-BR and CT scans have also been compared in older patients: Buck *et al.* performed the comparison in 35 osteoarthritic patients scheduled for total knee replacement surgery and found average differences between the two techniques of 0.1° (range, 0°–9°) and 0.8° (range, 0°–10°) for the femur and tibia respectively (69).

Even if several other studies reported excellent reliability for 3D models based on LD-BR, it is worth mentioning a study from Brooks *et al.*, despite reporting strong correlations between torsional values of the femur and tibia measured with LD-BR and CT/MRI, also found significantly higher femoral torsional with LD-BR when compared to CT/MRI measurements with some notable outliers (75).

The most relevant benefit of the use of biplanar radiographies is the drastic reduction of ionizing radiation when compared to CT scans. Delin *et al.* compared the two doses during measurements of lower limb torsion and anteversion on an anthropomorphic phantom capable of measuring the absorbed dose for specific organs: the EOS® sterioradiography system, compared to CT scans, delivered substantially lower doses of ionizing radiation to the ovaries (4.1 times), the testicles (24 times), and the knees and ankles (13–30 times) (76). Further research is now needed to compare the radiation exposure of LD-BR and ultra-low dose CT scans.

Furthermore, LD-BR seems be less dependent on patient positioning compared to CT. Morvan *et al.* published the results of *in vitro* (30 dry femurs) and *in vivo* (18 patients) studies conducted to evaluate the stereoradiographic measurements of femoral torsion with different femoral positions, in comparison with CT measurements (29). Their results demonstrated that flexion and extension statistically significantly affected CT measurement of femoral torsion ($P<0.01$) but not stereoradiography measurement ($P>0.21$) and that the differences between the two techniques became higher when hip flexion increased (29).

On the other hand, several limitations of 3D models based on LD-BR must be acknowledged. Patients' positioning could interfere with the correct images acquisition when bony landmarks are superimposed or when motion artifacts are produced in patients not capable of remaining still in a standing position (77). This means that the technique could have limited applicability to patients with underlying neurologic or neuromuscular disorders. Furthermore, post-processing errors could be produced during the software-based 3D reconstruction and the EOS® technique could only be applicable on a limited cohort of patients. Indeed, the EOS® imaging is not recommended below 6 years of age (because incomplete ossification could interfere with landmarks positioning) and is not applicable to severe deformities since the statistical model, on which the software was built, is based on "normal" anatomy (77).

Lastly, the capital expenses linked to the acquisition and maintenance of an EOS® machine with its corresponding software can be relevant and cost-effectiveness analysis evaluating the benefit of radiation exposure reduction compared to CT scans are still lacking.

Conclusions

The correct assessment of lower limb torsional deformities remains a challenge for the orthopedic surgeon. Although CT appears as the gold standard, there is still no agreement on how to correctly and uniquely measure both tibial and femoral torsion and several confounding factors must be acknowledged and have been reported in this review. Furthermore, CT involves radiation exposure thus limiting its use in the pediatric population. As a results both MRI and LD-BR have been proposed and demonstrated to be valid alternatives to CT when assessing lower limb torsional deformities. Nonetheless, considering that the introduction of MRI and LD-BR is recent, at the moment CT scans still provide a more standardized and reliable analysis of torsional abnormalities consolidated in the years that can be easily interpreted by different specialists. In this narrative review, the most relevant evidence regarding the refinement of CT protocols and the validation of radiological alternatives such as MRI and LD-BR have been gathered and discussed to better understand the radiological evaluation of femoral and tibial torsional profiles. Future research should also focus on non-radiological solutions not discussed in this review such as ultra-sonography, gait analysis, clinical and sensor-based assessments. Such solutions could be seen both as possible alternatives to the radiological techniques described in this review but also as combination strategies [e.g., CT + ultrasound (US), LD-BR + clinical assessment, MRI + gait analysis] that could improve the precision and reliability of the measurement of lower limb torsional deformities.

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Footnote

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