■ SYSTEMATIC REVIEW

The importance of axial rotation of the lower limb

A SYSTEMATIC REVIEW OF MEASUREMENT METHODS

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Aims

Assessment of lower limb alignment is a cornerstone of orthopaedics. Few studies look at rotational alignment in the axial plane as measured by femoral version (FV) and tibial torsion (TT), both of which have implications for hip, knee, and ankle pathology. This review provides an overview of the axial rotation and evaluates CT-based measurement methods for FV and TT to identify the most reliable and reproducible techniques for use in clinical practice.

Methods

A systematic PRISMA-guided review assessed original CT-based methods, examining inter- and intraobserver reliability (intraclass correlation coefficient (ICC)), frequency of use, and validation.

Results

Seven FV and nine TT CT-based techniques were identified. FV had a weighted mean of 17.8° anteversion (-9° to 60°). TT had a weighted mean of 30.8° (2° to 82°). ICCs ranged from good to excellent. The Murphy method (FV) and Goutallier method (TT) had the highest reliability and clinical utility.

Conclusion

Lower limb axial rotational profile plays an important role in the management of hip, knee, and ankle arthroplasty surgery as well as many other orthopaedic pathologies. The Murphy and Goutallier methods should be adopted as standard for measuring FV and TT. Their high reproducibility and validation make them ideal for consistent clinical and research use.

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Introduction

Assessing lower limb deformity has been a cornerstone of orthopaedics since its inception. While most studies have focused on lower limb alignment in the coronal and sagittal plane, much less research has looked at rotational alignment in the axial plane as measured using a combination of femoral version (FV) and tibial torsion (TT),[1,2] even though this is of critical importance when assessing and correcting deformity.

Measurement can be clinical, using cadavers, or by imaging studies. Clinical assessment is the least reliable, and cadaveric measurements lack clinical data to ensure generalizability.[3,4] Imaging studies traditionally rely on conventional radiographs, but assessment in the axial plane is difficult and unreliable.[5,6] MRI has the advantage of lower radiation doses, but the long capture times increases the chances of patients moving between scans of different ends of the bones, making it less practicable and thus leaving CT as the gold standard to date.[7]

FV refers to the twist between the femoral neck and distal condyles. FV varies within a normal population and changes during growth, from approximately +30° anteversion at birth to +15° anteversion by skeletal maturity.[4] FV has been associated with developmental dysplasia of the hip, and increased FV in early childhood is a common cause for intoeing gait, and pes planus, due to the increased range of internal rotation of the hip.[4,8] Abnormal FV has also been associated with femoroacetabular impingement (FAI),[9] and osteoarthritis of the hip due to an abnormal relationship between proximal femur and acetabulum,[4] leading to altered joint loading. Increased FV has also

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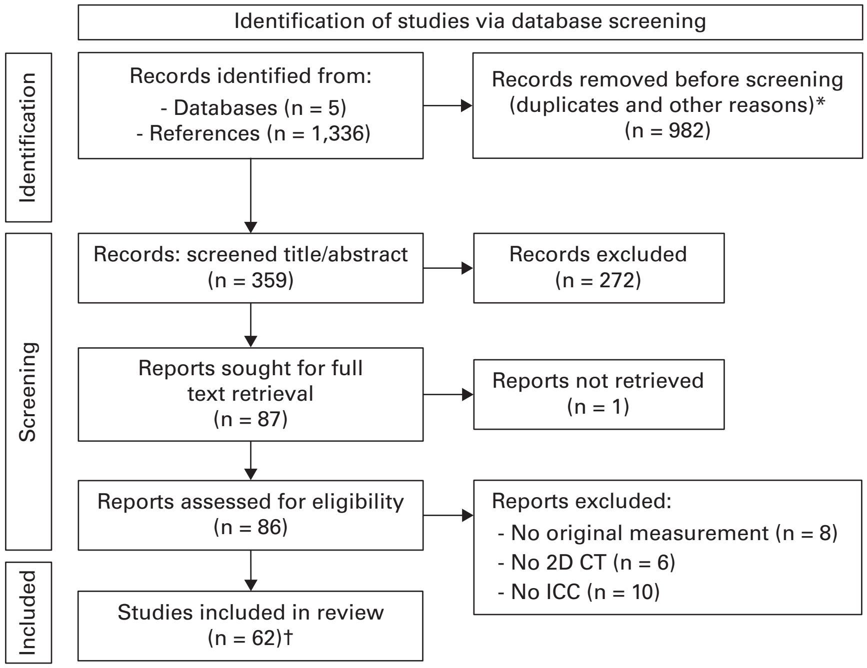

Fig. 1

PRISMA flowchart. *Other reasons include: no full text availability. †Of which 16 original measurements for rotation tibia and femur. ICC, intraclass correlation coefficient.

been associated with patellofemoral maltracking and osteoarthritis of the knee.[10,11]

TT relates to the axial plane twist of the tibia in its longitudinal axis that leads to a change in the alignment of the planes of motion of the proximal and distal articulations.[12] When the distal tibia is more externally rotated in comparison with the proximal tibia this is referred to as external tibial torsion (ETT). The tibia also undergoes structural remodelling during growth, starting at approximately 5° of ETT at birth to approximately 15° to 20° of ETT at skeletal maturity.[10] Altered TT has been shown to be associated with patellofemoral issues, meniscal and ligament injuries, patellofemoral pain, and knee osteoarthritis.[3,13–16] High ETT is associated with a cavus foot morphology;[17] however, some patients with a high ETT can still present with pes planus. A high ETT in patients with pes planus means there is less medial rotation of the talus, which has been shown to result in a more complex flat foot deformity.[18]

Combined deformities of FV and TT, termed torsional malalignment,[19] can worsen clinical symptoms, particularly in hip and knee pathology. Indices such as the Index of Cumulative Torsion (ICT) have demonstrated this additive effect.[20-22] Both FV and TT show wide individual, geographical, and developmental variability.[23,24]

This systematic review identifies, compares, and ranks CT-based measurement techniques for FV and TT based on validation, reproducibility, and clinical usability, to propose standardization in practice. Our primary outcome is research impact as determined by its clinical validation. We hypothesize that one measurement method will have the highest research impact and should become the gold standard for use in clinical practice.

Methods

A systematic review was conducted according to PRISMA guidelines and registered on PROSPERO (CRD42023482723). Electronic databases (PubMed, EMBASE, Cochrane, Web of Science) were searched for articles published up to December 2024 using terms related to 'rotation', 'version', 'torsion', 'tibia', 'femur', and 'CT'. Duplicate removal and screening were performed independently by two reviewers (BF, AA).

Inclusion criteria included: original CT-based techniques for FV and TT measurement; reported intra- and/or interobserver reliability using intraclass correlation coefficient (ICC); and studies in humans, with full-text access. Case reports, editorials, animal studies, or studies focused solely on prosthetic positioning or software-based measurements were excluded.

All included articles underwent quality appraisal using the MINORS score (Supplementary Material).[25] A diagram of the study selection is seen in Figure 1. References of selected articles and forward citation tracking were also performed to ensure completeness.

Data extraction and statistical analysis. Key data extracted included: anatomical landmarks used in each technique; intra- and interobserver ICCs; number of subjects and citation frequency; and reported normative values.

A novel "research impact" score was created, which facilitated comparison of reliability and validation strength across methods:

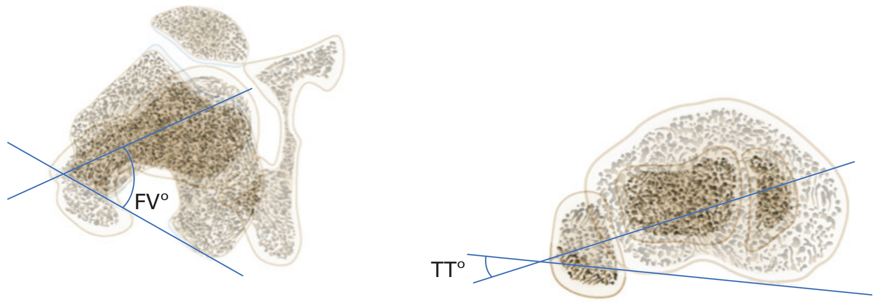

Fig. 2

Overlay technique for a) femoral version (FV) and b) tibial torsion (TT).

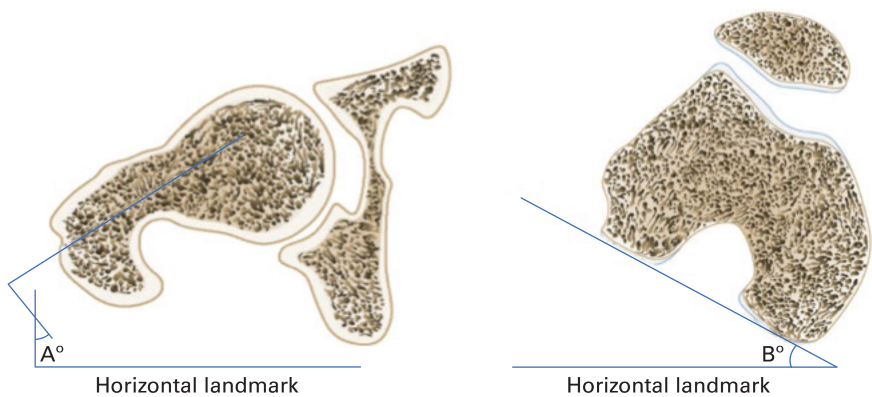

Fig. 3

Alternative horizontal landmark technique; femoral version angle (FV°) = A°+ B°.

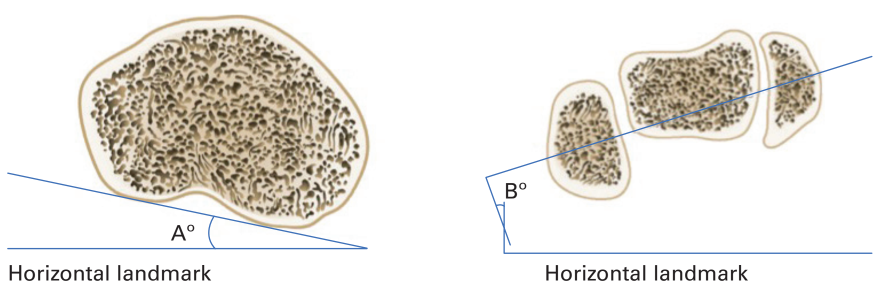

Fig. 4

Alternative horizontal landmark technique; tibial torsion angle (TT°) = A°+ B°.

Research impact *= number of citations × number of validation studies measuring intraobserver reliability × number of validation studies measuring interobserver reliability × median ICC for intraobserver reliability × median ICC for interobserver reliability.*

Results

A total of 1,341 papers were retrieved in the initial search, of which 16 original measurement techniques were included (seven FV and nine TT; Supplementary Tables i and ii). All methods used axial 2D CT slices; most employed an overlay technique or referenced a fixed horizontal axis to calculate angular differences (Figure 2). An alternate method incorporates a summation of two separate angles (Figures 3 and 4).

Femoral version. Seven techniques were identified. Most used the posterior condylar axis (PCA) for the distal femur, while proximal landmarks varied. FV values of all included studies with original techniques had a weighted mean of 17.79° (-9° to 60°). The Murphy method, using two non-coplanar CT slices to define the femoral neck axis and the PCA, showed the highest research impact score and high intra- and interobserver ICCs and frequent clinical validation.

Table I. The different measurement techniques, number of citations in literature, and mean or range of femoral version (in cohorts of healthy patients).

Method	Year	Citations, n	Measurement plane	Mean / range femoral version	Cohort
Weiner et al[26]	1978	153	Axial	Original: not stated	36 patients
				Muhamad et al:[27] not stated	32 patients
Hernandez et al[28]	1981	176	Axial	Original: not stated	10 patients (20 limbs)
				Kuo et al:[29] 12.4° (SD 3.8°)	10 femora (cadaver)
Reikerås et al[30]	1983	172	Axial	Original: 13° (SD 7°)	86 patients
				Schmaranzer et al:[31] 15° (SD 11°)	46 patients (52 limbs)
				Folinais et al:[32] 13.7° (SD 9.1°)	30 patients (43 limbs)
				Cho et al:[33] 15.9° (SD 10.2°)	11 patients
Jeanmart et al[34]	1983	N/A (book)	Axial	Original: 5° to 15°	Not stated
				Ferràs-Tarragó et al:[35] 12.84° (SD 8.6°)	30 patients
Murphy et al[36]	1987	407	Axial	Original: 31.0° (SD 4.2°)	12 patients
				Kaiser et al:[37] 17.5° (SD 7.0°)	26 patients (52 limbs)
				Ferràs-Tarragó et al:[35] 15.87° (SD 10.68)	30 patients
				Lerch et al:[22] 16° (SD 11°)	384 patients
				Schmaranzer et al:[31] 28° (SD 13°)	46 patients (52 limbs)
Waidelich et al[38]	1992	175	Axial	Original: 20.4° (SD 9°)	50 patients
				Kaiser et al:[37] 22.4° (SD 6.8°)	26 patients (52 limbs)
				Grünwald et al:[39] 24.23° (SD 11.9°)	58 patients (115 limbs)
Jarrett et al[40]	2011	45	Oblique	Kaiser et al:[37] 14.9° (SD 7.5°)	26 patients (52 limbs)
				Schmaranzer et al:[31] 19° (SD 13°)	46 patients (52 limbs)

Table II. The different measurement techniques for femoral version and included validation studies with reported intraclass correlation coefficients (ICCs).

Article	Method	ICC	
		Interobserver	Intraobserver
Muhamad et al[27]	Weiner et al[26]	0.897 to 0.977	0.932 to 0.959
Liodakis et al[41]*	Weiner et al[26]	0.91	0.96
Kuo et al[29]	Hernandez et al[28]	0.873 to 0.959	0.981 to 0.992
Schmaranzer et al[31]	Reikerås et al[30]	0.939	0.948 to 0.962
Folinais et al[32]	Reikerås et al[30]	0.90	None
Cho et al[33]	Reikerås et al[30]	0.845 to 0.882	0.912
Ferràs-Tarragó et al[35]	Jeanmart et al[34]	0.87 to 0.88	0.92 to 0.97
Kaiser et al[37]	Jeanmart et al[34]	0.93	0.95 to 0.98
Ferràs-Tarragó et al[35]	Murphy et al[36]	0.96	0.97 to 0.98
Lerch et al[22]	Murphy et al[36]	0.96	0.87 to 0.98
Schmaranzer et al[31]	Murphy et al[36]	0.964	0.958 to 0.962
Kaiser et al[37]	Waidelich et al[38]	0.91 to 0.92	0.88 to 0.98
Grünwald et al[39]	Waidelich et al[38]	Software measurement†	0.786 to 0.979 (manual)
Kaiser et al[37]	Jarrett et al[40]	0.92 to 0.94	0.94 to 0.98
Schmaranzer et al[31]	Jarrett et al[40]	0.938	0.905 to 0.928

*Different distal landmark as described in original article: posterior aspect of femoral condyles instead of original diacondylar axis.
†Only manual measurements are included.
ICC, intraclass correlation coefficient.

Table III. Research impact original methods of femoral torsion measurement techniques.

Method	Research impact
Weiner et al[26]	540
Hernandez et al[28]	153
Reikerås et al[30]	864
Jeanmart et al[34]	N/A
Murphy et al[36]	3,357
Waidelich et al[38]	290
Jarrett et al[40]	158

N/A, not available.

Differences in slice level, landmark definition, and measurement plane accounted for variability in reported FV. Methods using single-slice measurements were more prone to inaccuracy. Supplementary Table i shows all the included original measurement techniques with their original description, as well as comments by the authors on pitfalls and strengths of each technique. In Tables I and II we present the validation of the original measurement techniques.

Table III shows the research impact as calculated by number of citations × number of validation studies × median ICC of validation studies.

Table IV. The different measurement techniques, number of citations in literature, and mean or range of tibial torsion.

Method	Year	Citations, n	Mean / range tibial torsion	Cohort
Jakob et al[42]	1980	170	Original: 30.3° (2° to 76°; 79° to 82°)	45 patients (cadavers)
			Hoch et al:[43] 30.1°	82 patients
			Madadi et al:[44] 30.4° (SD 8.6°)	60 patients
			Stephen et al:[45] 28° (SD 12°)	56 patients
Jend et al[46]	1981	89	Original: 40° (SD 9°)	70 patients
			Volkmar et al:[47] 35.8°	229 patients
Widjaja et al[48]	1985	23	Original: not stated	Not stated
			Zheng et al:[49] 22.1° (SD 6.1°)	50 patients
			Kwon et al:[50] 32.7° (SD 6.15°)	31 patients
Reikerås et al[51]	1989	57	Original: 32.3° (SD 8.5°)	26 patients
			Stephen et al:[45] 28° (SD 12°)	56 tibiae
Waidelich et al[38]	1992	172	Original: 33.1° (SD 8°)	50 patients
			Grünwald et al:[39] 36.3° (SD 9.4°)	58 patients (115 limbs)
Goutallier et al[52]	2006	59	Original: 23.1° (SD 9.85°)	68 patients
			Nejima et al:[53] 18.0° (SD 7.4°)	75 tibiae
			Cho et al:[33] 23.0° (SD 9.8°)	11 patients
			Hoch et al:[43] 24.1°	82 tibiae
Madadi et al[44]	2016	11	Original: 35.2° (SD 9.1°)	60 patients
Keller et al[54]	2021	10	Original: 40.4° (SD 11.1°)	30 patients
Ramprasath et al[55]	2021	1	Original: 29.25° (SD 5.41°)	106 patients

Tibial torsion. Nine techniques were included (Supplementary Table ii). Most used the posterior tibial condyles proximally and bimalleolar or talar dome landmarks distally. Tibial torsion from all the original publications had a weighted mean of 30.81° (2° to 82°). The Goutallier method had the highest research impact and clear anatomical definitions, ease of use, and robust ICC validation.

In Tables IV and V, all original measurement techniques are described. Some methods excluded the fibula from measurement, leading to systematic variation of up to 5°, although clinical significance was unclear. The validation data for each technique is in Supplementary Table ii and Table VI shows the research impact.

Discussion

This review identified seven techniques for FV and nine for TT using CT imaging. Variability in anatomical landmarks, slice level, and technique contributes to inconsistent values across studies.

FV ranged from -9° to 60°, with a weighted mean of 17.8°. Approximately 5% to 10% of patients were reported in the studies as having retroversion of the femur (FV < 0°).[56,57] Any patients in whom the FV is less than the mean might be considered as relative retroversion, even if their absolute FV when measured is greater than 0°. In clinical practice, patients with relative (or true) retroversion might present not only with out-toeing, but also with restricted internal rotation of the hip, and find certain movements and sitting postures difficult. Key sources of variation include landmark choice (landmarks which are most distal on the femoral neck tend to yield higher FV values), distal landmark (most used the posterior condylar axis (PCA), which differs by 1° to 5° from other axes like the transcondylar or diacondylar), and patient positioning (hip flexion and neck-shaft angle influence the orientation of axial slices, biasing measurements).

The Murphy technique scored highest in research impact and offers practical advantages,[36] especially capturing proximal landmarks on different CT slices, which better reflects the true femoral neck axis. Although slightly more demanding to calculate using conventional medical imaging software, it consistently shows high reliability and validation. It is important to note that despite a high ICC the validation papers included for the Murphy method still had a range for FV of 16° to 31°, which is likely to reflect the heterogeneity of patients included in the different studies.

TT values ranged from 2° to 82° (weighted mean: 30.8°). No studies reported true internal torsion (TT < 0°), suggesting that 'internal' TT is likely relative rather than absolute in contrast to FV where values below zero have been recorded. The reason that relative internal tibial torsion is clinically relevant in our opinion is that it can lead to internal rotation of the talus and a propensity to pes planus and hallux valgus. That said, in clinical practice, the most important metric is likely to be the sum of FV and TT as the key driver of biomechanical issues in the lower limb. Measurement variability stems from slice selection (as proximal slices at the fibular head level may include the growth plate or be non-parallel to the knee axis) and distal landmarks, as techniques vary between including or excluding the fibula, influencing angle measurements. The Goutallier technique ranks highest in reproducibility and usability.[52] It uses consistent, articular-based landmarks, avoids fibular positional variability, and has strong validation. It is also simple to execute and widely cited. It is important to note that despite a high ICC, the validation papers included for the Goutallier method still had a range for TT of 18° to 24°, which again is likely to reflect the heterogeneity of patients included in the different studies.

There are clinical implications in orthopaedic procedures. In hip arthroplasty, accurate FV measurement is crucial for component positioning and joint stability.[58,59] Errors may lead to altered biomechanics or dislocation.[60,61] Rotational stability

Table V. The different measurement techniques for tibial torsion and included validation studies with reported intraclass correlation coefficients (ICCs).

Article	Method	ICC	
		Interobserver	Intraobserver
Stephen et al[45]	Jakob et al[42]	0.84	Not stated
Hoch et al[43]	Jakob et al[42]	0.917	Not stated
Madadi et al[44]	Jakob et al[42]	0.861	0.868
Liodakis et al[41]	Jend et al[46]	0.956	0.916
Volkmar et al[47]	Jend et al[46]	0.92	Not stated
Zheng et al[49]	Widjaja et al[48]	> 0.9	> 0.9
Kwon et al[50]	Widjaja et al[48]	Not stated	0.98
Reikerås et al[51]	Reikerås et al[51]	0.78	Not stated
Stephen et al[45]	Reikerås et al[51]	0.78	Not stated
Liodakis et al[41]	Waidelich et al[38]	0.984	0.918
Grünwald et al[39]	Waidelich et al[38]	Software measurement*	0.920 to 0.982 (manual)
Liodakis et al[41]	Goutallier et al[52]	0.997	0.92
Nejima et al[53]	Goutallier et al[52]	0.91	0.92
Hoch et al[43]	Goutallier et al[52]	0.938	Not stated
Cho et al[33]	Goutallier[52]	0.805 to 0.871	0.957
Madadi et al[44]	Madadi[44]	0.863	0.868
Keller et al[54]	Keller[54]	0.99	Not stated
Ramprasath et al[55]	Ramprasath[55]	0.96	Not stated

*Only manual measurements are included.

Table VI. Research impact original methods of tibial torsion measurement techniques.

Method	Research impact
Jakob et al[42]	394
Jend et al at el[46]	153
Widjaja et al[48]	39
Reikerås et al[51]	0
Waidelich et al[38]	318
Goutallier et al[52]	597
Madadi et al[44]	8
Keller et al[54]	0
Ramprasath et al[55]	0

of the hip can be related to sum of the FV and the acetabular anteversion.[26,30,62] Because correction of FV is difficult in uncemented hip arthroplasty, consideration might need to be given to careful implant selection where gross FV needs to be addressed. In knee arthroplasty, excessive TT, particularly external TT, cannot be corrected intra-articularly, and may result in pain, patellofemoral malalignment, or early implant failure.[63] In foot and ankle surgery, torsional malalignment can influence ankle arthroplasty outcomes,[64] and deformity correction,[18,65] although more research is needed.

Combined torsional malalignment (FV + TT) contributes to knee and hip pathology and is captured by indices like the ICT. Acetabular version also contributes to hip instability and impingement. This concept reinforces the importance of evaluating acetabular, femoral, and tibial components together. It is also important to acknowledge that even in healthy individuals there is often asymmetry in femoral and tibial rotation between sides.[57] The reasons for this asymmetry may be developmental or post-traumatic.[66]

All included studies used 2D CT slices. However, new automated 3D measurement tools may provide improved accuracy by avoiding slice-dependent errors.[45,67] Van Fraeyenhove et al[68] showed that using 2D slices might underestimate true femoral torsion, with a difference between 2D and 3D measurements up to 5°, and Yang et al[69] also showed superiority for 3D measurements of femoral version. In clinical practice, most companies in current workflows still use 2D measurements that are subsequently reconstructed into 3D visualizations, which are then sent to the surgeon giving the impression that these have been calculated in 3D. A move to 3D measurements will only evolve as universal measurement tools mature in quality and accuracy. Additionally, biplanar imaging and weightbearing CT may also add further insight into functional alignment under load, particularly for deformity correction and arthroplasty planning.[70–73]

Children present additional challenges due to evolving bone morphology and the presence of growth plates near key landmarks. Normative values also shift with age: FV decreases while TT increases throughout development,[74,75] necessitating age-specific reference ranges.

As with all systematic reviews, there is a risk of selection bias, in that some articles may not have been identified, although additional screening of the references was performed to reduce this risk. There is also a risk of reporting bias, in that negative studies may not have been published. We used ICC as a measurement of inter- and intraobserver reliability which might overestimate accuracy.[76] Additionally, the techniques used in clinical practice may not always correlate with the published methods we assessed. Finally, although an attempt was made for a meta-analysis, this was not possible due to heterogeneity of the data.

In conclusion, lower limb axial rotation is central to understanding and managing hip, knee, and foot/ankle pathology.

Among available CT-based methods, the Murphy technique for FV and the Goutallier technique for TT are the most reliable, validated, and clinically applicable. We recommend their routine adoption to standardize assessment and improve surgical planning. Future work should focus on the clinical impact of malrotation, and integration of weightbearing and 3D imaging technologies into practice.

Take home message

- This systematic review identifies, compares, and ranks CT-based measurement techniques for femoral version and tibial torsion based on validation, reproducibility, and clinical usability, to propose standardization in practice.

Social media

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Supplementary material

Appraisal of the techniques for measuring femoral version and tibial torsion.

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