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3D alignment analysis principles: an international Delphi consensus study

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***3D Leg Alignment Consensus Expert Group**

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Abstract

Introduction 3D bone models are increasingly adopted for leg alignment analysis, but there is substantial variability in the methods and underlying principles used to derive axes and joint orientations from 3D bone models. Therefore, the purpose was to reach consensus on a structured framework for standardized 3D leg alignment analysis based on 3D bone models.

Methodology A Delphi study was performed in four rounds. Rounds 1 and 2 involved a steering and rating group that developed 31 statements based on principles preserving the complexity of 3D anatomical structures, identified through a systematic review. These statements encompassed deriving joint centres and joint orientations, and defining coordinate systems using 3D bone models. In Rounds 3 and 4, an international panel of experts, evaluated these statements. Consensus was defined as ≥80% agreement.

Results Of the 31 statements, 26 achieved consensus in Round 3. Five statements were refined and subsequently all achieved consensus in Round 4. Experts agreed on utilising all available relevant surface data to define joint centres, joint orientations, and individual femoral and tibial coordinate systems alongside a combined leg coordinate system, and adopting central 3D axes for femoral version and tibial torsion.

Conclusion This international Delphi consensus study provides a structured framework for a standardized 3D leg alignment analysis based on 3D bone models. By utilizing all relevant surface data, this framework provides a more accurate representation of joint geometries compared to traditional landmark-based methods. Future research should focus on validating the methods adhering to these principles in diverse clinical settings.

1 Introduction

3D bone models are increasingly adopted for leg alignment analysis [1, 2, 6]. Unlike traditional 2D radiographs and CT slices, the use of 3D bone models enables a more accurate assessment of multiplanar deformities without oversimplifying the complexity of reality. This advancement has laid the foundation of several proposed clinical workflows [4, 5].

The transition from 2D to 3D, and the resulting increase of data, necessitates a fundamental shift in how alignment analysis is approached. However, a recent systematic review identified substantial variability in the methods and underlying principles used to derive axes and joint orientations from 3D bone models [8]. Such variability may result in considerable differences in alignment parameter values across studies, complicating the comparison of outcomes across studies.

Despite these inconsistencies, several underlying principles for deriving axes and joint orientations from 3D bone models have been identified that better preserve the complexity of anatomical structures in 3D bone models [8]. These include using centroids of marked articular surface data to determine joint centers, geometrical shape-fitting to determine joint centers and joint orientations of articular surfaces that are more round, and plane-fitting to determine joint centers and joint orientations of articular surfaces that are more flat (Figure 1). Establishing consensus on these principles may be an important step towards developing a unified 3D framework for leg alignment analysis.

Therefore, the purpose of this study was to reach consensus on a structured framework for standardized 3D leg alignment analysis based on 3D bone models, with the potential to standardize clinical workflows and enhance surgical planning.

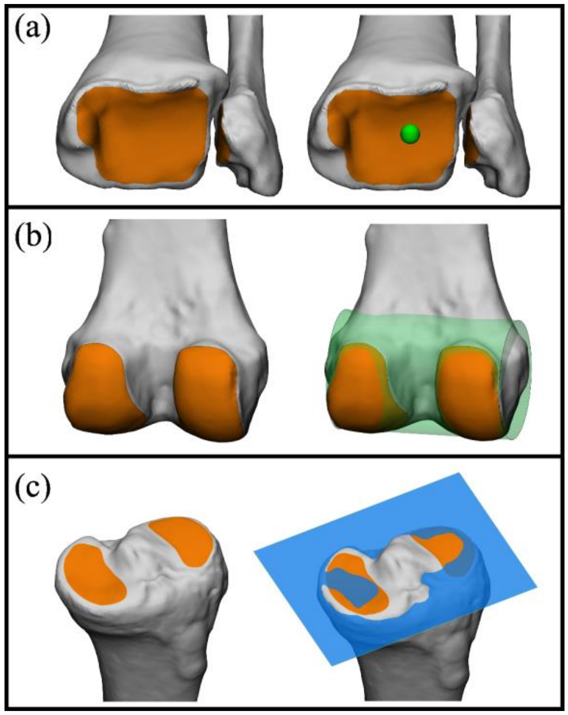

Figure 1 Illustrative examples of possible methods that adhere to the underlying principle to use all available relevant surface data from 3D bone models and could be used to define joint centers and joint orientations. (a) centroid calculation for joint centers. (b) geometrical-shape fitting for joint orientations of articular surfaces that are more round. (c) plane-fitting for joint orientations of articular surfaces that are more flat.

2 Methodology

A Delphi method was employed with two preparatory rounds (Rounds 1 and 2) to develop statements within a steering and rating group, followed by two rounds (Rounds 3 and 4) aimed to validate these statements through consensus among a panel of international experts.

2.1 Rounds 1 and 2: statement development

A steering group drafted the initial set of statements (Round 1), based on principles which reflect the preserved complexity of anatomical structures in 3D bone models [8]. The statements were structured into five key categories: 1) joint centers; 2) joint orientations; 3) individual femoral and tibial/fibular coordinate systems; 4) combined femoral and tibial/fibular (leg) coordinate system; 5) femoral version and tibial torsion. Each statement was accompanied by an illustrative example of a potential method based on the supporting principles (Figure 1). These examples were provided to clarify the principle, not to prescribe a specific method.

In Round 2, the statement were refined with input of an extended rating group of international experts recruited from the steering groups' professional network.

2.2 Rounds 3 and 4: Delphi consensus process

International experts were invited to join a peer review group if they were: 1) surgeons and engineers recognized in the field of 3D-planned osteotomies around the knee; 2) authors who had made significant contributions to the literature on 3D leg alignment analysis [8]; 3) referrals by the already-invited experts. Members of the steering group were excluded from participation in the surveys.

The expert panel received an online survey and were asked to agree or disagree with each statement (Round 3). Defined a priori, statements were considered to have reached consensus if they received at least 80% agreement in a round.

Statements that did not meet the predefined threshold were either revised or supplemented with additional context or clarification and re-evaluated in Round 4. Free-text comments were encouraged to capture additional feedback or suggested refinements.

3 Results

35 participants took part in the survey. The majority of participants were from Europe (28/35; 80%). 19 participants (54%) had a clinical background, while 16 (46%) had an engineering background.

Of the 31 statements presented in Round 3, 26 (84%) reached consensus, while the remaining five were refined based on feedback and all reached consensus in Round 4.

The expert panel reached consensus that joint centers and joint orientations in 3D should be derived from all available articular surface data of the 3D bone models. The expert panel also agreed on definitions for both individual femoral and tibial/fibular coordinate systems, and a combined femoral and tibial/fibular (leg) coordinate system. Furthermore, the expert panel agreed that joint alignment and distal femoral and proximal tibial coronal joint orientation angles should be calculated in the coronal plane of the leg coordinate system, provided that the knee is extended. Finally, consensus was reached that 3D femoral version and tibial torsion should be determined from the central medial-lateral axes of both the proximal and distal joints.

4 Discussion

The most important finding of this study is that consensus was reached on a structured framework for standardized 3D leg alignment analysis using 3D bone models. By defining foundational principles, it addresses substantial methodological variability in existing literature, potentially enhancing clinical applicability and improving cross-study comparability.

Despite advances in 3D technology, many methods for determining joint centers continue to rely on traditional 2D, landmark-based approaches. While reproducible [3, 8], such methods fail to fully capture the joint's complex 3D geometry. In contrast, the consensus approach leverages the complexity of 3D bony anatomy more, potentially reducing subjectivity and increasing reproducibility in alignment assessment.

Furthermore, this consensus elevates the 3D framework to a comparable level of agreement as the 2D framework by providing agreed-upon principles that ensure standardization while allowing flexibility in method application. Similar to 2D analyses – where multiple methods exist to determine key parameters [7] – the 3D framework accommodates various methods to adhere to its principles, ensuring consistency despite methodological variability. These principles can be directly integrated into clinical workflows, enabling clinicians to optimize correction osteotomies based on patient-specific anatomy.

References

1. Amirtharaj MJ, Hardy BM, Kent RN, 3rd, Nawabi DH, Wickiewicz TL, Pearle AD, et al. (2018) Automated, accurate, and three-dimensional method for calculating sagittal slope of the tibial plateau. J Biomech 79:212-217; https://doi.org/10.1016/j.jbiomech.2018.07.047
2. Degen N, Sass J, Jalali J, Kovacs L, Euler E, Prall WC, et al. (2020) Three-dimensional assessment of lower limb alignment: Reference values and sex-related differences. Knee 27:428-435; https://doi.org/10.1016/j.knee.2019.11.009
3. Furmetz J, Sass J, Ferreira T, Jalali J, Kovacs L, Muck F, et al. (2019) Three-dimensional assessment of lower limb alignment: Accuracy and reliability. Knee 26:185-193; https://doi.org/10.1016/j.knee.2018.10.011
4. Hodel S, Hasler J, Roth TA, Flury A, Sutter C, Fucentese SF, et al. (2024) Validation of a Three-Dimensional Weight-Bearing Measurement Protocol for Medial Open-Wedge High Tibial Osteotomy. J Clin Med 13; https://doi.org/10.3390/jcm13051280
5. Jorgens M, Keppler AM, Ahrens P, Prall WC, Bergstraesser M, Bachmeier AT, et al. (2024) 3D osteotomies-improved accuracy with patient-specific instruments (PSI). Eur J Trauma Emerg Surg 50:3-10; https://doi.org/10.1007/s00068-022-02060-4
6. Kuiper RJA, Seevinck PR, Viergever MA, Weinans H, Sakkers RJB (2023) Automatic Assessment of Lower-Limb Alignment from Computed Tomography. J Bone Joint Surg Am 105:700-712; https://doi.org/10.2106/JBJS.22.00890
7. Paley D. *Principles of Deformity Correction.* Springer Berlin; 2002.
8. Veerman Q, ten Heggeler R, Tuijthof G, de Graff F, Fluit R, Hoogeslag R (2024) High Variability Exists In 3D Leg Alignment Analysis, But Underlying Principles That Might Lead To Agreement On A Universal Framework Could Be Identified: A Systematic Review. Knee Surgery Sports Traumatology Arthroscopy; https://doi.org/10.1002/ksa.12512