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Development and Reliability of a Standardized Ultrasound Protocol for Adult Femoral Trochlear Morphology Assessment

Yi Zhen Lim

limyz@um.edu.my

Universiti Malaya

Mohd Noorazmi

Universiti Malaya

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Abstract

Objective

To develop a standardized ultrasound protocol for measuring osseous-based femoral trochlear sulcus angle and trochlear depth in adults and determine its intra-rater and inter-rater reliability and measurement error.

Methods

In this prospective methodological study, 35 adults contributed 70 knees. A proximal axial ultrasound protocol was developed iteratively from published methods and pilot scanning. Two examiners—an experienced sports medicine specialist and a sports medicine trainee—independently acquired three images per knee in two sessions. Session means were analyzed. Reliability was quantified using 2-way random-effects, absolute-agreement, single-measure intraclass correlation coefficients (ICC[A,1]); 95% confidence intervals were estimated using participant-cluster bootstrap resampling. Standard error of measurement (SEM), minimal detectable change at 95% confidence (MDC95), and Bland–Altman agreement was calculated.

Results

Intra-rater reliability was excellent for sulcus angle (ICC, 0.928 and 0.921) and trochlear depth (ICC, 0.936 and 0.925). Primary inter-rater reliability was good for sulcus angle (ICC, 0.887; 95% confidence interval, 0.798–0.938) and trochlear depth (ICC, 0.852; 95% confidence interval, 0.708–0.930). The inter-rater MDC95 was 6.65° for sulcus angle and 1.06 mm for trochlear depth. Small fixed inter-rater differences were observed (0.99° and − 0.20 mm, respectively), without proportional bias.

Conclusion

The standardized proximal axial protocol produced good-to-excellent reliability for adult femoral trochlear morphology assessment across examiners with different ultrasound experience. The accompanying SEM and MDC95 values provide practical thresholds for interpreting repeat measurements.

Key points

A reproducible proximal axial ultrasound protocol was developed for osseous-based femoral trochlear measurements.

Intra-rater reliability was excellent, and inter-rater reliability was good across a specialist and trainee.

Inter-rater changes should exceed 6.65° for sulcus angle or 1.06 mm for trochlear depth to surpass measurement error.

Introduction

Trochlear dysplasia is a three-dimensional morphologic abnormality of femoral trochlea and an important structural contributor to patellofemoral instability. A shallow or flattened groove provides less osseous restraint during early patellar engagement, and abnormal trochlear morphology has also been associated with patellofemoral pain and premature degenerative change. Cross-sectional evaluation commonly uses the sulcus angle and trochlear depth, although measured values depend on the selected axial level and whether cartilaginous or osseous landmarks are used. [1–4]

Radiography, computed tomography (CT), and magnetic resonance imaging (MRI) remain established modalities for evaluating trochlear morphology. However, MRI and CT scans are less suited to rapid bilateral assessment or repeated point-of-care measurements because of cost, accessibility, scanning time, and ionizing radiation for CT scan. Ultrasound can display the trochlear cartilage and subchondral contour in real time, is portable, and permits immediate contralateral comparison. [4–7]

Previous ultrasound studies have shown that the femoral trochlea can be visualized and that sulcus angle and trochlear depth can be measured reproducibly. Nevertheless, published techniques vary in participant age, knee position, acquisition level, landmark definitions, examiner experience, and whether reliability reflects image acquisition, image measurement, or both. [5–9] Because trochlear morphology changes along its proximo-distal course, small differences in transducer position may introduce clinically important variation. A protocol intended for clinical translation therefore requires an operational definition of the acquisition level, explicit image-quality criteria, and measurement-error indices in addition to an ICC.

The primary objective of this study was to develop a standardized proximal axial ultrasound protocol for measuring osseous-based trochlear sulcus angle and trochlear depth in adults. The secondary objective was to determine intra-rater and inter-rater reliability, absolute agreement, SEM, and MDC95 when the protocol was applied by examiners with different levels of musculoskeletal ultrasound experience. We hypothesized that both measurements would demonstrate at least good reliability.

Materials and Methods

Study Design and Ethics

This methodological reliability study formed the ultrasound-development phase of a broader ultrasound–MRI imaging-validation study. Reporting was guided by the Guidelines for Reporting Reliability and Agreement Studies.[10]

The study was approved by the institutional medical research ethics committee. All participants provided written informed consent before study procedures.

Participants were recruited between March and June 2026 at Universiti Malaya Medical Centre.

Participants

Adults aged 18–45 years who could provide informed consent were eligible. Participants were recruited by convenience sampling among healthcare workers at Universiti Malaya Medical Centre. Individuals with systemic musculoskeletal disorders, congenital musculoskeletal deformity, a history of femoral or tibial fracture, or previous knee surgery were excluded. For the broader imaging-validation study, MRI contraindications—including pacemakers and ferromagnetic implants—were also exclusion criteria.

Sample Size

Sample size planning used the framework of Walter et al. [11] Assuming an expected ICC of 0.80, a minimum acceptable ICC of 0.60, 2 raters, and a 95% confidence level, at least 50 knees were required. Recruitment was increased to 35 participants (70 knees) to allow for unusable examinations and to improve precision while retaining both knees for the planned imaging-validation study.

Protocol Development

The protocol was developed iteratively from published ultrasound methods, established cross-sectional trochlear measurements, and pilot scanning. [4–9] Before reliability testing, the development team specified the acquisition plane, image-quality criteria, and landmark definitions. The final protocol used the most proximal axial level at which the medial and lateral trochlear cartilage, trochlear groove and respective subchondral bones were completely visible. This level was selected to reduce variability related to more distal morphology and to represent the region involved in early patellofemoral engagement. The operational protocol is summarized in Table 1 and Figs. 1.1 and 1.2.

Table 1
Standardized Ultrasound Acquisition and Measurement Protocol

Component	Operational specification	Acceptance criterion
Participant position	Seated; feet supported in 90–100° flexion; quadriceps relaxed	No active quadriceps contraction
Transducer	8–12-MHz linear array; transverse orientation	Trochlea centered with no facet truncation
Acquisition level	First proximal axial level showing complete medial and lateral cartilage, subchondral bones and groove	Cartilage, osseous peaks and deepest groove visible in 1 frame
Image optimization	Depth 3–4 cm; focus at groove; gain optimized; tilt corrected	Clear cartilage-bone interface without anisotropy that obscures landmarks
Replicates	3 stored images per knee, examiner, and session	Each image independently meets quality criteria
Sulcus angle	Angle between lines from each osseous peak to the deepest groove point	Recorded in degrees
Trochlear depth	Perpendicular distance from osseous peak-to-peak reference line to deepest groove point	Recorded in millimeters
The protocol uses osseous-based landmarks at a reproducible proximal axial level.		

Ultrasound Equipment and Examiner Training

All examinations were performed using LOGIQ P9 R3 ultrasound system (GE HealthCare, Chicago, IL, USA) with an 8–12-MHz linear-array transducer and a musculoskeletal knee preset. Imaging depth was 3–4 cm and was adjusted to include both cartilage surfaces and the subchondral bone; gain and a single focal zone were optimized for the cartilage–bone interface. Images were stored in DICOM format.

The examiner team comprised a sports medicine specialist with 7 years of musculoskeletal ultrasound experience and a sports medicine trainee. Both examiners completed protocol familiarization and pilot scanning before data collection. During formal testing, examiners were blinded to each other's measurements.

Image Acquisition

Participants were seated with the examined knees exposed and supported in 90–100° flexion; the quadriceps remained relaxed. Generous coupling gel was applied. The transducer was placed transversely over the proximal patella, then translated proximally to identify the distal femur and trochlear groove. A true axial orientation perpendicular to the femoral shaft was maintained. The probe was moved proximally until the first level showing complete medial and lateral trochlear cartilages.

trochlear groove and subchondral bone in one frame were identified. Probe tilt was adjusted to minimize anisotropy while preserving the axial plane.

A technically acceptable image required simultaneous visualization of the medial cartilage peak, lateral cartilage peak, deepest point of the groove, and subchondral bone line, without truncation of either facet. Each examiner acquired 3 images of each knee during each session. Examinations were repeated after 30 minutes for intra-rater reliability measurements.

Measurements

For the sulcus angle, straight lines were drawn from the highest point of the medial and lateral trochlear subchondral bone surface to the deepest point of the trochlear groove; the included angle was recorded in degrees (Fig. 1.1). For trochlear depth, a reference line connected the medial and lateral osseous peaks, and the perpendicular distance from this line to the deepest point of the groove was recorded in millimeters (Fig. 1.2). The mean of 3 images represented the knee-level value for each examiner and session.

Statistical Analysis

Continuous participant characteristics were summarized as mean ± standard deviation (SD) and range; categorical variables were summarized as counts and percentages. The knee was the measurement unit. Because both knees were included, uncertainty for ICC estimates was calculated by resampling participants rather than individual knees, thereby preserving the bilateral cluster.

Reliability was estimated using the 2-way random-effects, absolute-agreement, single-measure ICC, denoted ICC(A,1). [12, 13] Intra-rater analyses compared Sessions 1 and 2 separately for each examiner. The prespecified primary inter-rater analysis compared the 2 examiners' first-session values. A sensitivity analysis compared each examiner's mean across both sessions. Ninety-five percent confidence intervals (CIs) were obtained from 3000 participant-cluster bootstrap samples. ICCs were interpreted as poor (< 0.50), moderate (0.50–0.74), good (0.75–0.89), or excellent (≥ 0.90).[13]

Absolute measurement error was summarized using SEM = pooled SD × √(1 − ICC) and MDC95 = 1.96 × √2 × SEM.[14] Bland–Altman analysis used the second measurement minus the first for intra-rater comparisons and the trainee minus the specialist for inter-rater comparisons; 95% limits of agreement were calculated as mean difference ± 1.96 SD of the differences.[15] Paired tests assessed fixed bias, and linear regression of pairwise differences on pair means assessed proportional bias. Statistical significance was defined as 2-sided $P < .05$. Statistical analyses were performed using Python version 3.12.13 (Python Software Foundation, Wilmington, DE, USA), with pandas version 2.2.3, NumPy version 2.3.5, and SciPy version 1.17.0. Bland–Altman plots were generated using Matplotlib version 3.10.8.

Declaration of Generative AI Use

OpenAI was used for the development of Python code for statistical analysis. The authors independently verified the data, analytical methods, code outputs, and manuscript content and take full responsibility for the accuracy and integrity of the work.

Results

Participants and Data Completeness

All 35 enrolled participants contributed both knees, yielding 70 knees and 560 knee–examiner–session–outcome observations. The mean participant age was 34.6 ± 3.2 years; 24 participants (68.6%) were male. Anthropometric characteristics are shown in Table 2. No knee-level session means were missing.

Table 2
Participant Demographic and Anthropometric Characteristics (N = 35)

Characteristic	Value
Age, y	34.6 ± 3.2 (29–42)
Male sex	24 (68.6)
Female sex	11 (31.4)
Height, cm	168.1 ± 7.1 (155.0–183.0)
Weight, kg	70.2 ± 12.5 (50.0–106.0)
Body mass index, kg/m²	24.8 ± 3.5 (18.4–32.7)
Knees analyzed	70

Values are mean ± SD (range) or number (percentage).

Intra-rater Reliability

Intra-rater reliability was excellent for both measurements and both examiners (Table 3). For sulcus angle, ICCs were 0.928 (95% CI, 0.864–0.962) for the specialist and 0.921 (95% CI, 0.841–0.961) for the trainee. Corresponding ICCs for trochlear depth were 0.936 (95% CI, 0.892–0.958) and 0.925 (95% CI, 0.854–0.961). The intra-rater MDC95 ranged from 5.10° to 5.75° for sulcus angle and from 0.70 to 0.73 mm for trochlear depth. No significant fixed or proportional intra-rater bias was identified.

Table 3
Reliability and Measurement Error for Sulcus Angle and Trochlear Depth (70 Knees)

Measurement and comparison	Measurement 1, mean ± SD	Measurement 2, mean ± SD	ICC(A,1) (95% CI)	SEM	MDC95
Sulcus angle: specialist S1 vs S2	140.07 ± 6.84°	140.20 ± 6.87°	0.928 (0.864–0.962)	1.84°	5.10°
Sulcus angle: trainee S1 vs S2	141.07 ± 7.43°	141.33 ± 7.36°	0.921 (0.841–0.961)	2.08°	5.75°
Sulcus angle: inter-rater S1	140.07 ± 6.84°	141.07 ± 7.43°	0.887 (0.798–0.938)	2.40°	6.65°
Trochlear depth: specialist S1 vs S2	6.01 ± 1.02 mm	5.96 ± 0.98 mm	0.936 (0.892–0.958)	0.25 mm	0.70 mm
Trochlear depth: trainee S1 vs S2	5.81 ± 0.97 mm	5.78 ± 0.95 mm	0.925 (0.854–0.961)	0.26 mm	0.73 mm
Trochlear depth: inter-rater S1	6.01 ± 1.02 mm	5.81 ± 0.97 mm	0.852 (0.708–0.930)	0.38 mm	1.06 mm

CI, confidence interval; ICC(A,1), 2-way random-effects absolute-agreement single-measure intraclass correlation coefficient; MDC95, minimal detectable change at 95% confidence; S1, Session 1; S2, Session 2; SEM, standard error of measurement. ICC CIs were obtained from 3000 participant-cluster bootstrap samples. In inter-rater rows, Measurement 1 is the specialist and Measurement 2 is the trainee.

Inter-rater Reliability and Agreement

Primary inter-rater reliability was good for sulcus angle (ICC, 0.887; 95% CI, 0.798–0.938) and trochlear depth (ICC, 0.852; 95% CI, 0.708–0.930). The corresponding SEM and MDC95 were 2.40° and 6.65° for sulcus angle and 0.38 and 1.06 mm for trochlear depth. The trainee measured sulcus angle an average of 0.99° higher than the specialist (P = .013) and trochlear depth 0.20 mm lower (P = .002). These fixed differences were smaller than their respective MDC95 values. Bland–Altman limits of agreement were −5.44° to 7.43° for sulcus angle and − 1.20 to 0.80 mm for trochlear depth (Table 4 and Fig. 2). No proportional bias was detected (P = .125 and .392, respectively).

Table 4
Bland–Altman Agreement and Inter-rater Sensitivity Analysis (70 Knees)

Measurement and comparison	Mean bias	95% limits of agreement	P for fixed bias	P for proportional bias	ICC(A,1) (95% CI)
Sulcus angle: specialist S2 − S1	0.13°	−5.00° to 5.25°	.679	.913	0.928 (0.864–0.962)
Sulcus angle: trainee S2 − S1	0.26°	−5.50° to 6.03°	.455	.836	0.921 (0.841–0.961)
Sulcus angle: trainee − specialist, S1	0.99°	−5.44° to 7.43°	.013	.125	0.887 (0.798–0.938)
Sulcus angle: trainee − specialist, session means	1.06°	−3.71° to 5.83°	< .001	.073	0.929 (0.874–0.959)
Trochlear depth: specialist S2 − S1	−0.06 mm	−0.75 to 0.64 mm	.185	.320	0.936 (0.892–0.958)
Trochlear depth: trainee S2 − S1	−0.03 mm	−0.77 to 0.70 mm	.438	.687	0.925 (0.854–0.961)
Trochlear depth: trainee − specialist, S1	−0.20 mm	−1.20 to 0.80 mm	.002	.392	0.852 (0.708–0.930)
Trochlear depth: trainee − specialist, session means	−0.19 mm	−0.99 to 0.61 mm	< .001	.388	0.894 (0.811–0.942)

S1, Session 1; S2, Session 2. Positive inter-rater bias indicates a larger trainee measurement. Session-means comparisons average Sessions 1 and 2 within each examiner.

When each examiner's 2-session mean was used, inter-rater reliability increased to excellent for sulcus angle (ICC, 0.929; 95% CI, 0.874–0.959) and remained good for trochlear depth (ICC, 0.894; 95% CI, 0.811–0.942).

Discussion

This study developed an operational proximal axial ultrasound protocol for adult femoral trochlear morphology and demonstrated good-to-excellent reliability when the complete acquisition-and-measurement process was repeated by examiners with different experience levels. All intra-rater ICCs exceeded 0.92. Primary inter-rater ICCs were 0.887 for sulcus angle and 0.852 for trochlear depth and averaging 2 sessions improved agreement. The study additionally provides SEM, MDC95, and Bland–

Altman limits, allowing clinicians and researchers to distinguish likely measurement variation from change.

The findings are consistent with the expanding literature on ultrasound assessment of the trochlea. Schlüter et al.[5] reported moderate-to-excellent reliability for a newly developed ultrasound sulcus-angle protocol in 12 healthy adults and noted better performance for the experienced examiner. Roberts et al.[7] demonstrated high reliability and measurement precision for suprapatellar transverse sonographic assessment of trochlear cartilage thickness in healthy adults. More recently, Djordjevic et al.[6] found that sulcus angle and trochlear depth were among the most reliable cartilaginous and osseous ultrasound measurements in 35 healthy adolescents. Our study extends these observations to bilateral adult assessment using a predefined proximal cartilage-based level and quantifies error across repeated acquisition by a specialist and trainee.

The acquisition level is central to reproducibility. The trochlea changes from a relatively shallow proximal entry zone to a deeper distal groove, and cross-sectional measurements depend on slice selection and landmark convention. [3, 4] The present protocol therefore defines the target as the first proximal axial level showing complete medial and lateral bone-cartilage and the groove in a single frame. This rule is intended to be easier to reproduce than selecting an apparently deepest or visually optimal slice, which may shift distally between examinations.

Although statistically significant, the inter-rater fixed differences were small: approximately 1° for sulcus angle and 0.20 mm for trochlear depth. Both were substantially below their MDC95 values, suggesting limited clinical importance for isolated measurements. The wider limits of agreement and higher MDC95 for inter-rater than intra-rater comparisons nevertheless indicate that serial examinations should preferably be performed by the same trained examiner and with the same protocol. If examiners change, differences smaller than approximately 6.7° or 1.1 mm should be interpreted cautiously.

Averaging repeated sessions improved the sulcus-angle ICC from 0.887 to 0.929 and the trochlear-depth ICC from 0.852 to 0.894. This finding supports averaging repeated acquisitions in research or borderline cases, but the additional time may be unnecessary for routine screening.

This study has limitations. Convenience sampling from a single center and the predominance of male participants may limit generalizability. Healthy adults were studied; abnormal trochlear morphology, pain, effusion, body habitus, or previous instability may make landmark visualization more difficult. Both knees were analyzed, although participant-cluster bootstrap resampling was used to preserve within-participant dependence for ICC confidence intervals. The examiner team participated in protocol training, so performance may be lower among untrained users. Finally, no MRI comparisons are presented here because cross-modality validity is the subject of the prespecified second study.

Future work should complete MRI validation at matched proximal cartilage landmarks, evaluate diagnostic thresholds in participants with patellofemoral instability or pain, and test reproducibility across centers and ultrasound systems.

Conclusions

A standardized proximal axial ultrasound protocol produced good-to-excellent intra-rater and inter-rater reliability for adult trochlear sulcus angle and trochlear depth. The protocol was reproducible across a sports medicine specialist and trainee, and the reported SEM and MDC95 values provide practical benchmarks for interpreting repeat measurements. These findings support further MRI validation and clinical evaluation but do not yet justify ultrasound-only diagnosis of trochlear dysplasia.

Abbreviations

USG Ultrasound

TD Trochlear dysplasia

MRI Magnetic resonance imaging

ICC Intraclass correlation coefficient

CI Confidence interval

SEM Standard error of measurement

MDC Minimal detectable change

BA Bland–Altman

SD Standard deviation

BMI Body mass index

Declarations

Ethics Approval and Consent to Participate

The study was approved by the Medical Research Ethics Committee, University Malaya Medical Centre (ID NO: 2025528-15113) and was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants before study participation.

Consent for Publication

Not applicable

Conflicts of Interest

The authors declare no conflicts of interest.

Clinical Trial Number

Not applicable

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Author Contribution

Conceptualization: [YZL], Methodology: [YZL]; Investigation: [YZL], [MNS]; Data curation: [YZL]; Formal analysis: [YZL], [MNS]; Validation: [YZL], [MNS]; Visualization: [YZL]; Writing—original draft preparation: [YZL]; Writing—review and editing: [YZL]; Supervision: [YZL]; Project administration: [YZL], [MNS]; Funding acquisition: [YZL].

Acknowledgments

None

Data Availability

The datasets generated and analysed during the current study are not publicly available due to restrictions related to participant privacy and the conditions of the institutional ethics approval. An anonymised dataset containing the measurements supporting the findings of this study may be available from the corresponding author upon reasonable request and subject to approval by the relevant institutional authorities. The original ultrasound images are retained on the institutional ultrasound imaging system and are not publicly available because they are derived from human participants and may contain potentially identifiable clinical information. Access to the underlying ultrasound images may be considered upon reasonable request, subject to institutional and ethical requirements.

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Figures



Figure 1

Fig 1.1. Ultrasound measurement of the osseous sulcus angle. Axial ultrasound image of the femoral trochlea showing the osseous landmarks used for measurement. The osseous sulcus angle (cyan) was defined by two lines extending from the highest points of the medial and lateral trochlear subchondral bone surfaces to the deepest osseous point of the trochlear groove.



Figure 2

Fig 1.2. Ultrasound measurement of the trochlear depth. For trochlear depth (orange), a reference line connected the medial and lateral osseous peaks, and the perpendicular distance from this line to the deepest osseous point of the groove was measured in millimetres.

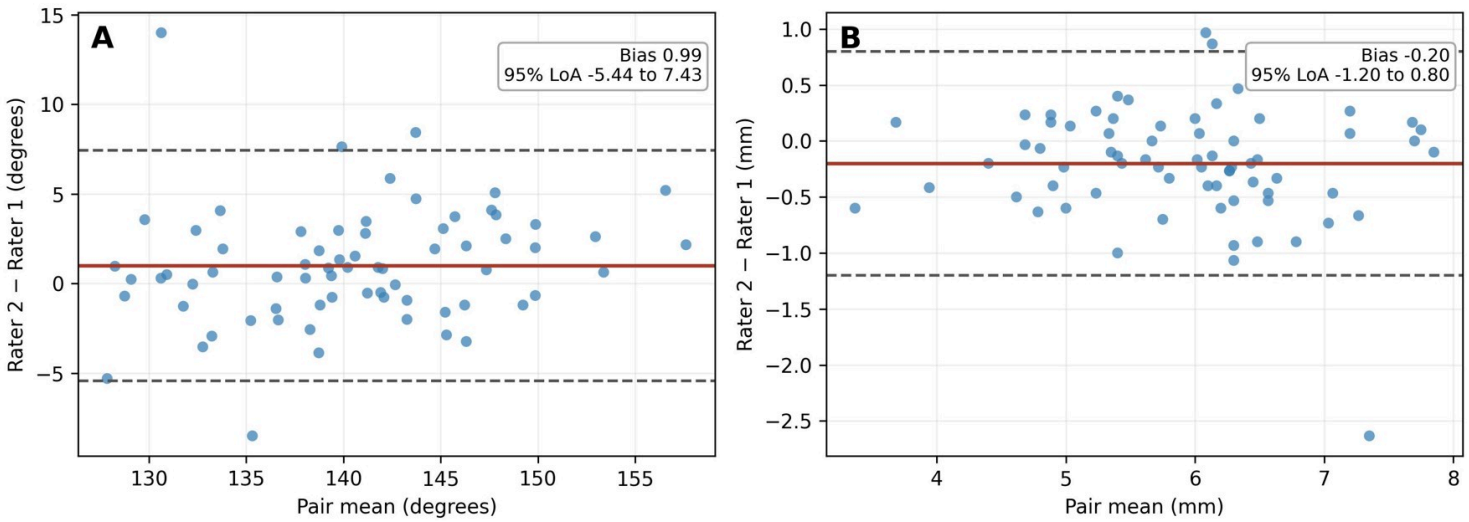


Figure 3

Fig 2. Bland–Altman plots for primary inter-rater agreement during Session 1. Differences were calculated as trainee (Rater 2) minus specialist (Rater 1). A, Sulcus angle. B, Trochlear depth. Solid red lines indicate mean bias; dashed lines indicate 95% limits of agreement. LoA indicates limits of agreement.