

Original paper

Reliability of anterior cruciate ligament (ACL) graft signal intensity measurement on MRI: a novel method with intra- and interrater analysis over a 1-week interval

Wojciech Szewczyk^{1,B,D,E,F}, Michał Marek^{1,B,D,E,F}, Florian Forelli^{2,3,A,D,E,F}, Maciej Biały^{4,A,C,D,E,F}

¹Helimed Diagnostic Imaging, Żory, Poland

²Haute-Ecole Arc Santé, HES-SO University of Applied Sciences and Arts Western Switzerland, Delémont, Switzerland

³Orthopaedic Surgery Department, OrthoLab, Clinic of Domont, Domont, France

⁴Institute of Physiotherapy and Health Sciences, Academy of Physical Education, Katowice, Poland

Abstract

Purpose: To determine the intra- and interrater reliability of the anterior cruciate ligament (ACL) graft signal-to-noise quotient (SNQ) assessed on magnetic resonance imaging (MRI) using a standardized coronal-oblique plane and region-of-interest (ROI) measurement protocol.

Material and methods: Twelve adults following ACL reconstruction underwent MRI graft assessment. Five ROIs were placed along the intra-articular portion of the ACL graft. Posterior cruciate ligament (PCL) and background ROIs were used for SNQ normalization ($SNQ = [ACL\ signal - PCL\ signal] / background\ signal$). Two radiologists independently performed two blinded measurement sessions, 1 week apart. Reliability included intraclass correlation coefficients (ICCs), 95% confidence intervals (CIs), standard error of measurement (SEM), and smallest detectable difference (SDD).

Results: Intrarater ICCs for individual ROIs ranged from 0.67 to 0.90, with the highest reliability at R2 (ICC = 0.90; 95% CI: 0.70-0.97) and the lowest at R5 (ICC = 0.67; 95% CI: 0.20-0.89). Corresponding SEM values ranged from 0.31 to 1.01 and SDD from 0.87 to 2.79. Interrater ICCs ranged from 0.52 to 0.83, again highest at R2 (ICC = 0.83; 95% CI: 0.65-0.92) and lowest at R5 (ICC = 0.52; 95% CI: 0.15-0.76). Interrater SEM values ranged from 0.51 to 1.23 and SDD from 1.43 to 3.43. Averaging SNQ across all five ROIs improved reliability, yielding excellent intrarater agreement (ICC = 0.90; 95% CI: 0.67-0.97; SEM = 0.28; SDD = 0.76) and good interrater agreement (ICC = 0.85; 95% CI: 0.67-0.93; SEM = 0.34; SDD = 0.96).

Conclusions: The proposed MRI-based SNQ protocol demonstrates excellent intrarater and good interrater reliability over a 1-week interval. ROI averaging meaningfully enhances reproducibility and provides actionable SDD thresholds for detecting ACL graft signal change.

Key words: magnetic resonance imaging, anterior cruciate ligament reconstruction, measurement reliability, graft signal intensity, signal-to-noise quotient.

Introduction

An anterior cruciate ligament (ACL) tear is a common and significant knee joint injury, with an annual incidence of

approximately 8 cases per 10 000 individuals aged 10 to 64 years [1]. For most patients, ACL reconstruction (ACLR) is required, and both reconstruction rates and hospitalization costs have risen globally in recent decades, parti-

Correspondence address:

Maciej Biały, Institute of Physiotherapy and Health Sciences, Academy of Physical Education, 72A Mikołowska St., 40-065 Katowice, Poland,
e-mail: mbfizjoterapia@gmail.com

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A Study design · B Data collection · C Statistical analysis · D Data interpretation · E Manuscript preparation · F Literature search · G Funds collection

cularly among female and pediatric populations [2-6]. The process of ACL graft healing in the human knee following ACLR is not yet fully understood [7], and it remains unclear how much postoperative time is required for an ACL graft to fully mature in humans [8]. Typically, three stages of graft maturation are recognized: the initial inflammatory phase, the revascularization phase, and the final remodeling phase [8]. To date, no study has definitively determined the optimal time for returning to activity after ACLR, while considering both the patient's functional recovery and the ACL graft maturation phase to ensure the highest level of safety. Numerous tests have been established for functional evaluation, including movement and biomechanical assessments [9,10], hop tests [11], balance tests [12], and evaluations of quadriceps and hamstring strength [13,14]. However, the correlation between functional performance and graft healing remains a topic of debate [15,16]. Van Eck *et al.* [17] reported that most ACL graft failures occurred between 6 and 9 months following ACLR, which coincides with the period when most patients are allowed and clinically or functionally cleared to return to sports activities. This finding not only highlights the importance of assessing functional readiness but also emphasizes the need for ACL graft evaluation to ensure a safe return to sport and reduce the risk of graft failure.

Magnetic resonance imaging (MRI) has been extensively studied as a tool for predicting the biomechanical and histological properties of ACL grafts following ACLR, both in animal models [18] and in humans [19]. The signal intensity (SI) of the ACL graft has been shown to reflect the progressive remodeling process of the graft [20]. Higher SI, indicative of increased vascularity or cellularity, is commonly observed during the early postoperative phase and gradually diminishes, with significant reductions occurring between the first and second years after ACLR, reflecting the graft's ongoing remodeling process [21]. Abnormal SI, inconsistent with the expected healing phase, has also been associated with ACL graft damage caused by factors such as iterative injury or surgical com-

plications, including improper tunnel positioning [22]. Stöckle *et al.* [23] first proposed the use of the signal-to-noise quotient (SNQ) to normalize graft SI grayscale values, a method that has since been widely used in studies assessing graft maturity via MRI. Despite normalization using the SNQ, SI variations remain influenced by technical and biological factors, highlighting the limited sensitivity of current clinical outcome measures in accurately evaluating ACL graft recovery following ACLR.

Therefore, this study was performed to evaluate the reliability of measuring ACL graft SI using a standardized assessment protocol that could serve as an additional metric in ACL graft evaluation following ACLR. Specifically, we analyzed both intrarater and interrater reliability of ACL graft SNQ measurements in the coronal-oblique plane over a 1-week interval.

Material and methods

Participants

This study was a prospective analysis of retrospectively collected data from patients who underwent anatomic single-bundle ACLR using autologous grafts (hamstring: $n = 10$; patellar tendon: $n = 2$) followed by postoperative MRI using a 1.5-T MRI magnet. All images were acquired between December 2023 and March 2024. The research was conducted in accordance with the Declaration of Helsinki and received approval from the local research ethics committee (Approval No. 2017/3). Patients with evidence of ACL graft rupture, concurrent posterior cruciate ligament (PCL) injury, or imaging artifacts were excluded. The final cohort comprised 12 participants (6 males), with a mean age of 30.7 ± 9.7 years, height of 173.8 ± 10 cm, body mass of 86.8 ± 23.9 kg, body mass index of 28.4 ± 5.3 kg/m², and time from ACLR to MRI evaluation of 31.1 ± 25 months (Table 1).

Raters

Two raters, each with more than 10 years of experience in musculoskeletal radiology, were responsible for ACL graft SI data collection. Prior to the measurements, both raters received detailed instructions on the procedure for assessing ACL graft SI and were given sufficient time to practice the protocol. To evaluate intra- and interrater reliability, each rater measured the ACL graft SI twice, with a 1-week interval between measurement sessions. The images were randomized and blinded to the raters to ensure unbiased assessment across all evaluations. The measurement protocol is illustrated in Figure 1.

MRI scans and ACL graft SI measurement

All MRI images were acquired using a 1.5-T scanner (GE Signa; GE Healthcare, USA) equipped with an eight-

Table 1. Demographic characteristics of the study group

Characteristic	Value
Total patients	12
Male sex	6 (50)
Age (years)	30.7 ± 9.7 (20-51)
Body mass (kg)	86.8 ± 23.9 (53-150)
Body height (cm)	173.8 ± 10 (160-191)
Body mass index (kg/m ²)	28.4 ± 5.3 (23.5-41.1)
ACLR to measurement (months)	31.1 ± 25 (8-84)

Data are presented as n , n (%), or mean \pm standard deviation (range).
ACLR – anterior cruciate ligament reconstruction

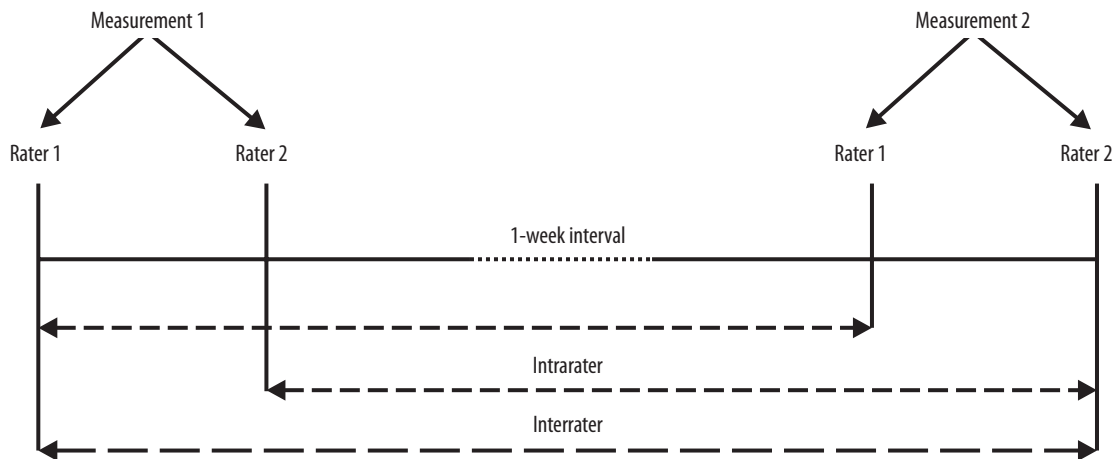


Figure 1. Schematic representation of anterior cruciate ligament graft signal intensity measurements conducted by each rater for each participant

channel knee coil. A T2-weighted turbo spin echo sequence acquired without fat suppression was applied in the standard oblique-coronal plane, optimized for visualization of the ACL graft. Sequence parameters included a slice thickness of 2 mm, repetition time of 4000 ms, and echo time of 98 ms. These acquisition parameters were identical for all participants, and registered images were analyzed using Syngo.via software (Siemens Healthineers, Germany). SI of the graft was manually measured using the region-of-interest (ROI) tool. ROI placement was performed according to a predefined protocol to ensure precision. In the first step, the slice with the best visualization of the intra-articular portion of the ACL graft was selected (Figure 2A). Line A was drawn connecting the bony surfaces at the entry points of the femoral bone tunnel. Line B

was then identified in the femoral region, perpendicular to Line A, and drawn from the lower edge of the femoral bone tunnel entry point to the medial edge of the graft. In the tibial region, Line C was drawn from the lateral to the medial edge of the bone tunnel entry point, parallel to Line B. The centers of Lines B and C were connected by Line D, indicating the longitudinal center of the ACL graft. In the second step, circular ROIs (3-mm diameter, area = 7.07 mm²) [24] were defined and positioned as follows: R1 and R5 were tangent to the lower edge of Line B and the upper edge of Line C, respectively, and centered on the ACL graft, with Line D dividing each ROI into two equal halves. R3 was positioned at the midpoint between Lines B and C, centered on the ACL graft. R2 and R4 were placed midway between adjacent ROIs (R1-R3 and R3-R5,

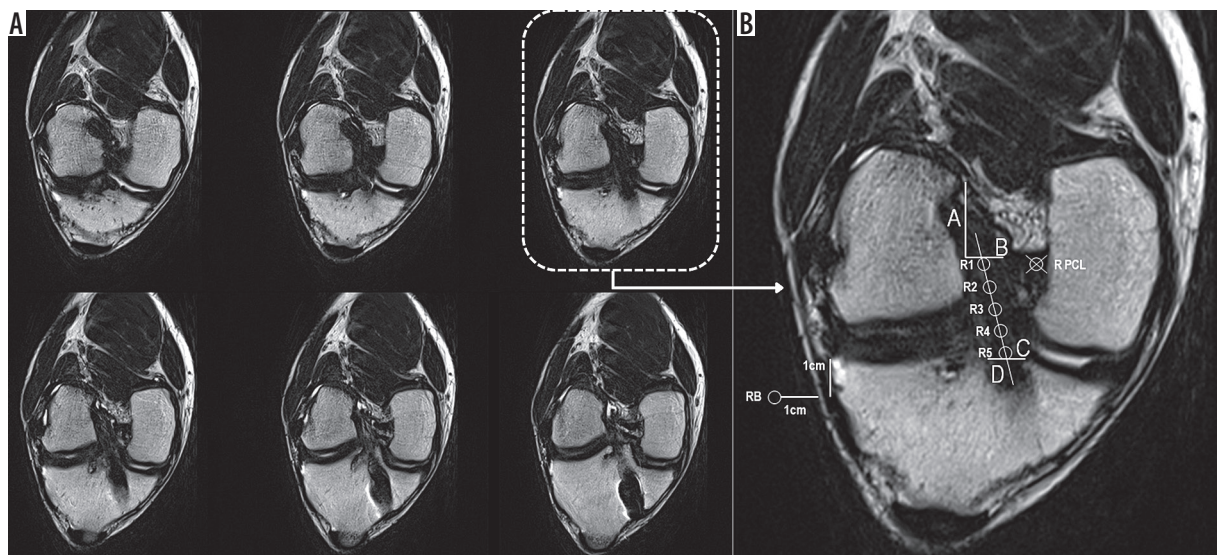


Figure 2. A) First step of the measurement protocol, showing selection of the slice with the best visualization of the intra-articular portion of the anterior cruciate ligament (ACL) graft. (B) Measurement protocol for ACL graft signal intensity in the standard oblique-coronal plane. Line A connects the femoral bone tunnel entry points. Line B (femoral region) and Line C (tibial region) are drawn perpendicular and parallel, respectively, to Line A. Line D connects the centers of Lines B and C, indicating the longitudinal center of the graft. Circular region of interests (ROIs) (3-mm diameter) are positioned as follows: R1 and R5 are tangent to Lines B and C, respectively; R3 is located midway between them; and R2 and R4 are positioned midway between adjacent ROIs. All ROIs are centered on the ACL graft and bisected by Line D. The ROI is placed at the center of the posterior cruciate ligament, and the background region is positioned near the skin margin

respectively), also centered on the ACL graft and bisected by Line D. An ROI at the center of the PCL cross-sectional area (RPCL) was defined, and a background ROI (RB) was placed in the air background outside the body contour on the lateral side, using a standardized offset (Figure 1B). This configuration facilitated accurate assessment of the ACL graft area while minimizing measurement error. SI of the ACL graft was calculated using the SNQ ($SNQ = [ACL \text{ graft signal} - PCL \text{ signal}] / RB$) [25] for each ACL graft ROI (R1-R5) (Figure 2A, B).

Statistical analysis

Reliability of the SNQ was assessed for each individual ROI within the ACL graft, as well as for the average SNQ value across all graft ROIs. Reliability, expressed as intraclass correlation coefficient (ICC) values, was calculated using a mixed-model analysis of variance, with consecutive measurements as the repeated factor and participants as the independent factor. Intrarater reliability, incorporating error associated with repeated ROI placement within the ACL graft (R1-R5), RPCL, and RB by a single rater, was assessed using the ICC_(3,k) model. Interrater reliability, incorporating error associated with ROI placement by two independent raters, was assessed using the ICC_(2,k) model. All reliability analyses were performed with a 1-week interval between measurements. Reliability was classified as poor (< 0.50), moderate (0.50-0.75), good (0.75-0.90), or

excellent (> 0.90) [26]. In addition, 95% confidence intervals (CIs), standard error of measurement ($SEM = SD \times (1 - ICC)^{1/2}$) and the smallest detectable difference ($SDD = SEM \times 1.96 \times 2^{1/2}$) were calculated using Statistica Version 13 (TIBCO Software Inc., Palo Alto, CA, USA) and SPSS (IBM Corp., Armonk, NY, USA). The present analyses quantify analytical (rater-dependent) reproducibility on a fixed image dataset and do not include variability attributable to repeated MRI acquisitions (inter-scan/test-retest variability).

Results

Intrarater reliability for SNQ measurements of the ACL graft was evaluated using the ICC_(3,k) model, which captures the consistency of ROI placement within the ACL graft by the same rater across repeated measurements. ICC values for individual ROIs ranged from 0.67 to 0.90, indicating moderate to excellent reliability. The highest intrarater reliability was observed for R2 (ICC = 0.90, 95% CI: 0.70-0.97), while the lowest was found for R5 (ICC = 0.67, 95% CI: 0.20-0.89). The SEM for individual ROIs ranged from 0.31 to 1.01, and SDD values ranged from 0.87 to 2.79. Intrarater reliability for SNQ calculated as the average across all ROIs (R1-R5) was classified as excellent, with an ICC of 0.90 (95% CI: 0.67-0.97), SEM of 0.28, and SDD of 0.76 (Table 2).

Interrater reliability for SNQ measurements of the ACL graft was evaluated using the ICC_(2,k) model, which accounts for variability introduced by two raters independently defining ROIs within the ACL graft. Reliability between raters varied across individual ROIs, with ICC values ranging from 0.52 to 0.83. The highest interrater reliability was observed for R2 (ICC = 0.83, 95% CI: 0.65-0.92), corresponding to good reliability. The lowest interrater reliability was recorded for R5 (ICC = 0.52, 95% CI: 0.15-0.76), indicating moderate agreement between raters. The SEM for individual ROIs ranged from 0.51 to 1.23, while SDD values ranged from 1.43 to 3.43. Interrater reliability for SNQ calculated as the average across all ROIs (R1-R5) was classified as good, with an ICC of 0.85 (95% CI: 0.67-0.93), SEM of 0.34, and SDD of 0.96 (Table 3).

Table 2. Intrarater reliability of signal-to-noise quotient (SNQ) measurements of the anterior cruciate ligament graft

SNQ	ICC	95% CI	SEM	SDD
R1	0.83	0.52-0.94	0.38	1.05
R2	0.90	0.70-0.97	0.44	1.21
R3	0.80	0.45-0.93	0.72	1.98
R4	0.86	0.58-0.95	0.31	0.87
R5	0.67	0.20-0.89	1.01	2.79
Mean (R1-R5)	0.90	0.67-0.97	0.28	0.76

CI – confidence interval, ICC – intraclass correlation coefficient, R1-R5 – regions of interest 1-5, SDD – smallest detectable difference, SEM – standard error of measurement

Table 3. Interrater reliability of signal-to-noise quotient (SNQ) measurements of the anterior cruciate ligament graft

SNQ	ICC	95% CI	SEM	SDD
R1	0.71	0.43-0.86	0.55	1.53
R2	0.83	0.65-0.92	0.51	1.43
R3	0.75	0.50-0.88	0.78	2.16
R4	0.70	0.43-0.85	0.55	1.54
R5	0.52	0.15-0.76	1.23	3.43
Mean (R1-R5)	0.85	0.67-0.93	0.34	0.96

CI – confidence interval, ICC – intraclass correlation coefficient, R1-R5 – regions of interest 1-5, SDD – smallest detectable difference, SEM – standard error of measurement

Discussion

The aim of this study was to evaluate the reliability of measuring ACL graft SI using a refined and standardized assessment protocol. To the authors' knowledge, this is the first study to provide reliability data demonstrating that ACL graft SNQ measurements obtained on coronal-oblique MRI are reproducible over a 1-week interval. Intrarater reliability for individual ROIs ranged from ICC_(3,k) = 0.67 to 0.90, with the highest agreement observed at R2 (ICC = 0.90, 95% CI: 0.70-0.97) and the lowest at R5 (ICC = 0.67, 95% CI: 0.20-0.89). Interrater reliability

for individual ROIs ranged from $ICC_{(2,k)} = 0.52$ to 0.83 , peaking at R2 ($ICC = 0.83$, 95% CI: $0.65-0.92$) and lowest at R5 ($ICC = 0.52$, 95% CI: $0.15-0.76$). Precision metrics mirrored these patterns: intrarater SEM ranged from 0.31 to 1.01 with SDD from 0.87 to 2.79 , whereas interrater SEM ranged from 0.51 to 1.23 with SDD from 1.43 to 3.43 . Notably, averaging SNQ across all five graft ROIs (R1-R5) improved reproducibility to excellent intrarater agreement ($ICC = 0.90$; 95% CI: $0.67-0.97$; $SEM = 0.28$; $SDD = 0.76$) and good interrater agreement ($ICC = 0.85$; 95% CI: $0.67-0.93$; $SEM = 0.34$; $SDD = 0.96$). Taken together, these data indicate that the method is robust within raters and acceptably consistent between raters, particularly when the multi-ROI average is used. Importantly, the present analysis quantifies rater-dependent reliability of ROI placement and SNQ computation on a fixed set of postoperative MRI examinations. It does not capture test-retest variability attributable to repeated MRI acquisitions (inter-scan variability), scanner drift, or sequence-parameter changes. Accordingly, the reported ICC, SEM, and SDD values reflect analytical reproducibility rather than full clinical workflow repeatability.

Our findings are concordant with prior work reporting excellent intraobserver and good interobserver agreement for MRI-based ACL graft signal metrics obtained in the sagittal plane, including SNQ (intraobserver $ICC = 0.83$; interobserver $ICC = 0.67$), and align with systematic syntheses that judged interrater reliability to be generally good while emphasizing substantial methodological heterogeneity across studies [27-29]. Clinically, several studies have associated lower ACL graft signal (or lower SNQ) with more advanced graft maturation and elements of return-to-sport readiness. For example, Zhou *et al.* [30] observed lower mean, proximal, and middle SNQ values in athletes who returned to sport at 9 months following ACLR, while Kim *et al.* [31] associated lower SNQ with better synovialization on second-look knee arthroscopy. Conversely, other investigations have reported that MRI signal metrics do not consistently correlate with instrumented knee laxity or patient-reported outcomes, despite associations with return-to-sport rates. These discrepancies underscore that reliability and biological plausibility, while necessary, are not sufficient for establishing clinical validity [32]. Recent systematic reviews echo this uncertainty, calling for standardized imaging and analysis protocols and outcome-anchored validation before signal-based metrics are used to guide individual clearance decisions [19,33]. Methodologically, this study employed a standardized protocol applied to a routinely acquired coronal-oblique plane, enabling measurements to be performed directly in the plane of the ACL graft and thereby enhancing generalizability to everyday clinical workflows. The measurement procedure incorporates SNQ normalization and predefined ROI templates distributed along the graft, features intended to be sequence-agnostic and portable across scanner types. Averaging SNQ across

multiple graft ROIs clearly enhanced reproducibility, plausibly by mitigating local signal heterogeneity; this aggregation step is straightforward to implement and does not require additional scan time or complex post-processing.

From a clinical perspective, SEM and SDD values provide actionable thresholds for interpreting longitudinal change. For the averaged SNQ, week-to-week changes of ≥ 0.76 (intrarater) or ≥ 0.96 (interrater) exceeded measurement error in the present setting and can therefore be considered detectable. These characteristics support the potential use of the SNQ for serial monitoring of postoperative ACL graft remodeling. Because the SNQ is intrinsically normalized and based on commonly acquired imaging planes, it may be applied consistently across patients and independently of concomitant procedures (e.g., anterolateral ligament reconstruction), facilitating comparisons between surgical strategies and rehabilitation protocols. Nevertheless, the SNQ should be interpreted alongside complementary imaging biomarkers and clinical assessments rather than as a standalone determinant of clinical decision-making, in line with conclusions from recent systematic reviews [33].

This study has several strengths, including the use of ICC models matched to the study design ($ICC_{(3,k)}$ for intrarater and $ICC_{(2,k)}$ for interrater reliability), explicit reporting of SEM and SDD to enable practical thresholds for change, and demonstration that multi-ROI averaging improves measurement stability. However, several limitations should be acknowledged. Concurrent clinical or arthroscopic reference standards were not available in this cohort, precluding assessment of criterion or predictive validity. In addition, the sample size was largely pragmatic, based on available imaging, rather than derived from an a priori, precision-based sample size calculation for reliability. The small cohort contributes to wider ICC CIs for some ROIs and warrants cautious interpretation, particularly for ROI-specific estimates. Moreover, the postoperative interval ranged widely (8-84 months), introducing biological heterogeneity that may influence ICC magnitude because ICC is a variance-ratio measure driven in part by between-subject variability. Importantly, repeated measurements were performed within a 1-week interval on the same MRI examinations; therefore, true biological changes in graft signal over the test-retest period are unlikely to account for within-subject differences, and the present results primarily reflect rater-dependent analytical reproducibility. Nevertheless, future studies should evaluate reliability within narrower postoperative windows and in larger samples to further confirm generalizability. We also did not assess test-retest repeatability across repeated MRI acquisitions; thus, inter-scan variability and scanner drift were not quantified. Future studies should therefore predefine reliability targets and perform formal sample size calculations accordingly, evaluate workflow-level repeatability across sessions (and ideally across scanners/protocols), and critically assess

longitudinal SNQ trajectories against clinical outcomes such as return to sport, knee laxity, and patient-reported measures, as well as structural benchmarks from second-look arthroscopy. Further work should also explore semi-automated or fully automated ROI strategies to reduce rater dependence. Subgroup analyses (e.g., with and without anterolateral augmentation or across different graft types) may further clarify generalizability across surgical techniques and rehabilitation pathways [34].

Conclusions

A standardized, ROI-based SNQ method for MRI assessment of the ACL graft in the coronal-oblique plane demonstrates excellent intrarater and good interrater reliability over a 1-week interval, with multi-ROI averaging materially improving reproducibility. The derived SDD

thresholds (0.76 intrarater and 0.96 interrater for averaged SNQ) provide pragmatic benchmarks for detecting ACL graft signal change over time. These properties support the use of the SNQ for serial postoperative monitoring, although confirmatory studies linking the SNQ to functional and structural outcomes and evaluating inter-scan repeatability are required to establish its prognostic utility.

Disclosures

1. Institutional review board statement: The study was approved by the Bioethics Committee for Scientific Research at The Jerzy Kukuczka Academy of Physical Education in Katowice (approval number 2017/3).
2. Assistance with the article: None.
3. Financial support and sponsorship: None.
4. Conflicts of interest: None.

References

1. Frobell RB, Lohmander LS, Roos HP. Acute rotational trauma to the knee: poor agreement between clinical assessment and magnetic resonance imaging findings. *Scand J Med Sci Sports* 2007; 17: 109-114.
2. Longo UG, Nagai K, Salvatore G, Cella, E, Candela V, Cappelli, F, et al. Epidemiology of anterior cruciate ligament reconstruction surgery in Italy: a 15-year nationwide registry study. *J Clin Med* 2021; 10: 223. DOI: 10.3390/jcm10020223.
3. Zhang Y, McCammon J, Martin RK, Prior HJ, Leiter J, MacDonald PB. Epidemiological trends of anterior cruciate ligament reconstruction in a Canadian province. *Clin J Sport Med* 2020; 30: e207-e213. DOI: 10.1097/JSM.0000000000000676.
4. Lopes TA, Simic M, Pappas E. Epidemiology of anterior cruciate ligament reconstruction in Brazil's public health system. *Rev Bras Med Esporte* 2016; 22: 297-301.
5. Chung KS, Kim JH, Kong DH, Park I, Kim JG, Ha JK. An increasing trend in the number of anterior cruciate ligament reconstruction in Korea: a nationwide epidemiologic study. *Clin Orthop Surg* 2022; 14: 220-226.
6. Janssen KW, Orchard JW, Driscoll TR, van Mechelen W. High incidence and costs for anterior cruciate ligament reconstructions performed in Australia from 2003-2004 to 2007-2008: time for an anterior cruciate ligament register by Scandinavian model? *Scand J Med Sci Sports* 2012; 22: 495-501.
7. Dong S, Xie G, Zhang Y, Shen P, Huangfu X, Zhao J. Ligamentization of autogenous hamstring grafts after anterior cruciate ligament reconstruction: midterm versus long-term results. *Am J Sports Med* 2015; 43: 1908-1917.
8. Claes S, Verdonk P, Forsyth R, Bellemans J. The ligamentization process in anterior cruciate ligament reconstruction: what happens to the human graft? A systematic review of the literature. *Am J Sports Med* 2011; 39: 2476-2483.
9. Biały M, Kublin K, Brzuszkiewicz-Kuźmicka G, Gnat R. Myofascial and movement tests after anterior cruciate ligament reconstruction. *J Hum Kinet* 2022; 83: 67-75.
10. Bortone I, Moretti L, Bizzoca D, Caringella N, Delmedico M, Piazzolla A, Moretti B. The importance of biomechanical assessment after return to play in athletes with ACL reconstruction. *Gait Posture* 2021; 88: 240-246.
11. Ebert JR, Du Preez L, Furzer B, Edwards P, Joss B. Which hop tests can best identify functional limb asymmetry in patients 9-12 months after anterior cruciate ligament reconstruction employing a hamstrings tendon autograft? *Int J Sports Phys Ther* 2021; 16: 393-403.
12. Biały M, Kublin K, Wilczyński B, Forelli F, Gnat R. Does concomitant meniscectomy or meniscus repair affect muscle strength, lower extremity balance, and functional tests after anterior cruciate ligament reconstruction? *J Clin Med* 2024; 13: 3310. DOI: 10.3390/jcm13113310.
13. Chatzilamprinos K, Semaltianou E, Hatzimanouil D, Lytras D, Sykaras E. Evaluation of strength and functional ability of soccer players two years after anterior cruciate ligament reconstruction: a cross-sectional study. *J Musculoskelet Neuronal Interact* 2024; 24: 55-66.
14. Biały M, Wilczyński B, Forelli F, Hewett TE, Gnat R. Functional deficits in non-elite soccer (football) players: a strength, balance, and movement quality assessment after anterior cruciate ligament reconstruction. *Cureus* 2024; 16: e75846. DOI: 10.7759/cureus.75846.
15. Li H, Chen J, Li H, Wu Z, Chen S. MRI-based ACL graft maturity does not predict clinical and functional outcomes during the first year after ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2017; 25: 3171-3178.
16. Biercevicz AM, Akelman MR, Fadale PD, Hulstyn MJ, Shalvoy RM, Badger GJ, et al. MRI volume and signal intensity of ACL graft predict clinical, functional, and patient-oriented outcome measures after ACL reconstruction. *Am J Sports Med* 2015; 43: 693-699.
17. Van Eck CF, Schkrohowsky JG, Working ZM, Irrgang JJ, Fu FH. Prospective analysis of failure rate and predictors of failure after anatomic anterior cruciate ligament reconstruction with allograft. *Am J Sports Med* 2012; 40: 800-807.

18. Biercevicz AM, Murray MM, Walsh EG, Miranda DL, Machan JT, Fleming BC. T2* MR relaxometry and ligament volume are associated with the structural properties of the healing ACL. *J Orthop Res* 2014; 32: 492-499.
19. Grassi A, Bailey JR, Signorelli C, Carbone G, Tchonang Wakam A, Lucidi GA, Zaffagnini S. Magnetic resonance imaging after anterior cruciate ligament reconstruction: a practical guide. *World J Orthop* 2016; 7: 638-649.
20. Ntoulia A, Papadopoulou F, Zampeli F, Ristanis S, Argyropoulou M, Georgoulis A. Evaluation with contrast-enhanced magnetic resonance imaging of the anterior cruciate ligament graft during its healing process: a two-year prospective study. *Skeletal Radiol* 2013; 42: 541-552.
21. Weiler A, Peters G, Mäurer J, Unterhauser FN, Südkamp NP. Biomechanical properties and vascularity of an anterior cruciate ligament graft can be predicted by contrast-enhanced magnetic resonance imaging: a two-year study in sheep. *Am J Sports Med* 2001; 29: 751-761.
22. Lee SM, Yoon KH, Lee SH, Hur D. The relationship between ACL femoral tunnel position and postoperative MRI signal intensity. *J Bone Joint Surg Am* 2017; 99: 379-387.
23. Stöckle U, Hoffmann R, Schwedke J, Lubrich J, Vogl T, Südkamp NP, Haas N. Anterior cruciate ligament reconstruction: the diagnostic value of MRI. *Int Orthop* 1998; 22: 288-292.
24. Zdanowicz U, Ciszowska-Lysoń B, Paśnik M, Drwiegga M, Ratajczak K, Fulawka K, et al. Evaluation of ACL graft remodeling and prediction of graft insufficiency in sequenced MRI: two-year follow-up. *Appl Sci* 2021; 11: 5278. DOI: 10.3390/app11115278.
25. Cavaignac E, Marot V, Faruch M, Reina N, Murgier J, Accadbled F, et al. Hamstring graft incorporation according to the length of the graft inside tunnels. *Am J Sports Med* 2018; 46: 348-356.
26. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med* 2016; 15: 155-163.
27. Yau WP, Lin W. Evaluation of graft maturation by MRI in anterior cruciate ligament reconstruction with and without concomitant anterolateral ligament reconstruction. *Orthop J Sports Med* 2024; 31: 23259671231223976. DOI: 10.1177/23259671231223976.
28. Van Dyck P, Zazulia K, Smekens C, Heusdens CHW, Janssens T, Sijbers J. Assessment of anterior cruciate ligament graft maturity with conventional magnetic resonance imaging: a systematic literature review. *Orthop J Sports Med* 2019; 7: 2325967119849012. DOI: 10.1177/2325967119849012.
29. Van Groningen B, van der Steen MC, Janssen DM, van Rhijn LW, van der Linden AN, Janssen RPA. Assessment of graft maturity after anterior cruciate ligament reconstruction using autografts: a systematic review of biopsy and magnetic resonance imaging studies. *Arthrosc Sports Med Rehabil* 2020; 2: e377-e388. DOI: 10.1016/j.asmr.2020.02.008.
30. Zhou T, Xu Y, Zhang A, Zhang X, Deng K, Wu H, Xu W. Association of graft maturity on MRI with return to sports at 9 months after primary single-bundle ACL reconstruction with autologous hamstring graft. *Orthop J Sports Med*. 2024; 12: 23259671241248202. DOI: 10.1177/23259671241248202.
31. Kim JH, Oh E, Yoon YC, Lee DK, Lee SS, Song SY, Wang JH. The relationship between graft synovialization and graft revascularization after ACL reconstruction: assessment using dynamic contrast-enhanced MRI and second-look arthroscopy. *Eur J Radiol* 2020; 133: 109346. DOI: 10.1016/j.ejrad.2020.109346.
32. Lutz PM, Achtnich A, Schütte V, Woertler K, Imhoff AB, Willinger L. Anterior cruciate ligament autograft maturation on sequential postoperative MRI is not correlated with clinical outcome and anterior knee stability. *Knee Surg Sports Traumatol Arthrosc* 2022; 30: 3258-3267.
33. D'Ambrosi R, Sconfienza LM, Albano D, Meena A, Abermann E, Fink C. Can MRI predict return to sport after anterior cruciate ligament reconstruction? A systematic review of the literature. *Radiol Med* 2025; 130: 638-649.
34. Wang X, Xu Z, Song S, Mao Z, Huang X, Luo M, et al. Which technique provides more benefits in return to sports and clinical outcomes after anterior cruciate ligament reconstruction: double-bundle or single-bundle? A randomized controlled study. *Chin Med J (Engl)* 2025; 138: 2283-2292.