

Psychological and Knee Function Measures at 1 Month Predict High Kinesiophobia at 6 Months After Anterior Cruciate Ligament Reconstruction: Development and Internal Validation of a Prognostic Model

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Article

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Abstract

Background

To develop and internally validate a prognostic model based on psychological and knee-function measures obtained 1 month after surgery to identify patients with high kinesiophobia 6 months after anterior cruciate ligament reconstruction (ACLR).

Methods

Data from a single-center prospective cohort were used, with postoperative month 1 defined as the prediction landmark. High kinesiophobia was defined as a 17-item Tampa Scale for Kinesiophobia (TSK-17) score ≥ 37 at postoperative month 6. Based on prior evidence, clinical relevance, construct representation, and sample-size constraints, seven predictor parameters were prespecified: age, sex, TSK-17, ACL-RSI, K-SES, HADS-A, and IKDC. A demographic model, a model adding TSK-17, and a multidimensional full model were fitted sequentially. All three models underwent 2,000 paired bootstrap resamples for internal validation, and the optimism-corrected incremental performance of the full model over the TSK model was estimated. Flexible calibration curves, inverse-probability-weighted sensitivity analysis for attrition, post hoc sample-size precision assessment under the Riley framework, and checks for nonlinear effects of continuous predictors were performed.

Results

Of 209 patients who met the age criterion, 177 entered the primary analysis; 84 (47.5%) had high kinesiophobia. Apparent AUCs for the three models were 0.600, 0.821, and 0.874, respectively, and optimism-corrected AUCs were 0.578, 0.812, and 0.852. For the full model versus the TSK model, the corrected Δ AUC was 0.040 (bootstrap 95% interval, -0.015 to 0.074) and the corrected Δ Brier was -0.017 (-0.036 to 0.013), suggesting possible incremental value but limited precision. The optimism-corrected Brier score of the full model was 0.162, and the calibration slope was 0.853. Coefficients and performance changed little after inverse probability weighting.

Conclusion

TSK-17 at postoperative month 1 provided the core predictive information for high kinesiophobia at month 6. Multidimensional measures such as ACL-RSI may provide additional information, but the interval estimates for incremental performance included no improvement. The current sample is insufficient for precise individual risk estimation; the full model should be regarded as a preliminary development model and externally validated in a larger independent cohort.

1. Introduction

Anterior cruciate ligament reconstruction (ACLR) can restore knee stability, but structural repair and objective functional improvement do not necessarily translate into adequate psychological recovery. Systematic reviews indicate that kinesiophobia, fear of reinjury, and low knee self-efficacy are common after anterior cruciate ligament (ACL) injury and ACLR and are associated with worse patient-reported outcomes, lower activity levels, and failure to return to sport[1–3]. Recovery assessed only by time from surgery, strength, or limb symmetry may therefore miss important psychological barriers that limit rehabilitation participation and return to sport. Kinesiophobia generally manifests as excessive avoidance of activity because of anticipated pain, injury, or reinjury. Classic work showed that patients who did not regain their preinjury sport level tended to have greater fear of reinjury[4]; greater fear may also coexist with poorer functional performance and a higher risk of second ACL injury[5]. Preoperative and early postoperative psychological states show some temporal stability, and preoperative kinesiophobia, pain, and psychological readiness have been associated with subsequent kinesiophobia or return to sport[6, 7]. These findings suggest that early rehabilitation may provide an important window for identifying persistent psychological barriers.

The 1-month postoperative time point has particular clinical relevance. By then, patients have experienced surgery and early rehabilitation, so psychological and knee-function measures can reflect their actual recovery experience while still leaving sufficient time to modify the subsequent rehabilitation plan. Chmielewski and George found that fear avoidance and self-efficacy at 4 weeks after ACLR were associated with early impairment resolution and readiness for advanced rehabilitation[8]. Longitudinal studies have also shown interrelated changes in kinesiophobia, psychological readiness, and subjective knee function from preoperatively through 6 months after surgery[9]. However, previous studies have largely focused on individual psychological measures, associations, or return-to-sport outcomes. Few have integrated kinesiophobia, psychological readiness, self-efficacy, emotional symptoms, and knee function at postoperative month 1 into an internally validated model for predicting high kinesiophobia at month 6.

Accordingly, we defined postoperative month 1 as the prediction landmark and developed and internally validated a prognostic model for high kinesiophobia at 6 months after ACLR. The primary focus was to determine whether multidimensional psychological and functional measures provide incremental predictive information beyond age, sex, and early kinesiophobia, rather than to identify causal effects of individual factors. We hypothesized that adding an early kinesiophobia measure at postoperative month 1 would substantially improve prediction over a demographic model and that further addition of psychological readiness, knee self-efficacy, anxiety symptoms, and subjective knee function would improve discrimination and overall model fit.

2. Methods

2.1 Study Design and Ethics

This study was a secondary prediction-model analysis of a prospective follow-up cohort at Sichuan Orthopaedic Hospital. The parent prospective cohort recruited patients at Sichuan Orthopaedic Hospital from August 24, 2024, to July 7, 2025. Postoperative month 1 was defined as the landmark prediction time, and high kinesiphobia at postoperative month 6 was the outcome. Reporting was organized according to the Transparent Reporting of a multivariable prediction model for Individual Prognosis Or Diagnosis + Artificial Intelligence (TRIPOD + AI) guidance applicable to regression-based prediction models[10]. The institutional ethics committee of Sichuan Orthopaedic Hospital approved the protocol (KY2024-037-01). All participants provided written informed consent, and the study was conducted in accordance with the Declaration of Helsinki and the approved protocol.

2.2 Participants, Surgery, Rehabilitation, and Follow-up

Participants were drawn from the institution's prospective ACL injury follow-up cohort. Eligibility for the parent follow-up cohort had already been assessed according to predefined clinical criteria. For this secondary prediction-model analysis, the additional requirements were: (1) age 18–55 years at surgery; (2) clinically and radiographically confirmed unilateral ACL injury treated with primary unilateral ACLR; and (3) ability to complete the relevant patient-reported measures independently and provision of written informed consent. Patients with bilateral or revision ACLR, meniscal repair requiring more than one suture or severe lower-limb injury likely to materially affect knee-function assessment or rehabilitation, or cognitive or language impairment preventing questionnaire completion were not included in this analysis. Completion of postoperative follow-up was not a baseline eligibility requirement; patients without subsequent outcomes were treated as having missing outcomes rather than being redefined as baseline exclusions. Patients with an available 6-month TSK-17 outcome and complete core predictors at postoperative month 1 entered the primary analysis. Patients with missing outcomes were retained for attrition comparisons and in the observation-probability model used for inverse probability weighting. The source database included 234 patients. After excluding 25 patients outside the 18-55-year age range, 209 were age eligible; 208 had complete core predictors at postoperative month 1, and 177 also had a postoperative month 6 TSK-17 outcome and entered the primary analysis.

All patients underwent arthroscopic anatomic single-bundle ACLR. Most received hamstring autografts; a small number received autografts incorporating the peroneus longus tendon or contralateral hamstring tendon depending on graft harvest. Some patients underwent concomitant lateral extra-articular tenodesis according to intraoperative rotational stability, age, and sporting demands. All patients followed a staged, standardized perioperative rehabilitation program. Before surgery, a physical therapist assessed lower-limb strength and function and prescribed targeted training. After anesthesia had subsided, ankle pumps and quadriceps isometric contractions were initiated, followed progressively by straight-leg raises, knee flexion, weight shifting, terminal knee extension, balance training, and segmented gait practice. Progressive weight bearing began as early as permitted by the surgeon and tolerated by the patient. Training was modified to avoid sharp pain, increased swelling, or abnormal joint instability. The postoperative month 1 predictors and month 6 outcome were collected within the

prespecified 7-day allowable window for each scheduled follow-up time point. Postoperative questionnaires used the same versions and scoring rules as the preoperative assessments.

2.3 Outcome Definition

The primary outcome was high kinesiophobia at postoperative month 6. The 17-item Tampa Scale for Kinesiophobia (TSK-17) contains 17 items scored from 1 to 4, with items 4, 8, 12, and 16 reverse scored, yielding a total score from 17 to 68; higher scores indicate greater fear of movement or reinjury. The TSK-17 has shown good internal consistency and test-retest reliability in patients with ACL injury[11]. We used $TSK-17 \geq 37$ as a research-oriented threshold for high kinesiophobia. Previous ACLR studies have dichotomized TSK-17 around 37 points, but operational definitions have not been fully consistent and the cutoff was not originally derived in an ACLR population[7, 12]. We therefore did not interpret it as a diagnostic threshold or a direct treatment cutoff. Because dichotomization can lose information and create threshold dependence, the continuous TSK-17 total score at postoperative month 6 was also analyzed as a secondary outcome. Recent work further suggests that the TSK-17 total score may reflect both pain-related avoidance and reinjury concerns, so its construct interpretation in ACLR populations warrants caution[12].

2.4 Candidate Predictors

Candidate predictors were all measured at postoperative month 1 and included TSK-17; the Anterior Cruciate Ligament–Return to Sport after Injury (ACL-RSI) scale, scored from 0 to 100, with higher scores indicating greater psychological readiness to return to sport[13]; the Knee Self-Efficacy Scale (K-SES), oriented to a 0-100 scale in this database, with higher scores indicating greater knee-related self-efficacy[14]; the anxiety subscale of the Hospital Anxiety and Depression Scale (HADS-A), with higher scores indicating greater anxiety symptoms[15]; and the International Knee Documentation Committee Subjective Knee Form (IKDC), scored from 0 to 100, with higher scores indicating better subjective knee function and with demonstrated reliability and validity in its Chinese version[16]. Age and sex were included as basic demographic predictors. Candidate predictors were determined according to prior evidence, clinical relevance, availability at postoperative month 1, and a prespecified multidimensional psychological-functional framework. Consistent with recommendations for clinical prediction-model development, we used a full-model strategy and did not screen predictors according to univariable P values[17–19]. All prespecified candidate predictors entered the multivariable logistic regression model simultaneously. Between-group comparisons were descriptive only and did not determine variable entry or removal. This approach was intended to avoid excluding predictors that may contribute only in a multivariable context and to reduce instability and selection bias from data-driven screening[20].

2.5 Statistical Analysis

To limit model dimensionality and reduce construct redundancy, the primary model selected one representative measure from each prespecified domain: TSK-17 for kinesiophobia, ACL-RSI for psychological readiness to return to sport, K-SES for knee self-efficacy, HADS-A for anxiety symptoms, and IKDC for overall subjective knee function. Knee injury and Osteoarthritis Outcome Score (KOOS)

subscales and IKDC both represent patient-reported symptom or knee-function domains, while the Photographic Series of Sports Activities for Anterior Cruciate Ligament Reconstruction measures perceived harmfulness of movement and overlaps conceptually with kinesiophobia; therefore, all available measures were not entered into the primary model simply because they were present in the database. Replacing IKDC with the KOOS Quality of Life subscale (KOOS-QoL) and other domain substitutions were reserved for sensitivity or exploratory analyses and were not used to modify the prespecified primary model post hoc. Continuous variables are presented as mean $\pm$ standard deviation and categorical variables as number (%). Standardized mean differences (SMDs) for postoperative month 1 measures were calculated according to 6-month kinesiophobia status, but between-group P values were not used to select predictors. Pearson correlation coefficients and variance inflation factors (VIFs) were used to assess correlations and multicollinearity among candidate predictors. Three sequential binary logistic regression models were fitted: model 0 (M0) included age and sex; model 1 (M1) added postoperative month 1 TSK-17 to M0; and model 2 (M2), the multidimensional full model, added ACL-RSI, K-SES, HADS-A, and IKDC to M1. Continuous predictors were retained as continuous variables and z-standardized for effect-size reporting in the full model, so odds ratios represent the relative change in odds per 1-standard-deviation increase. Regression coefficients on the original measurement scales were also retained to construct the prediction equation. Nested models were compared using likelihood-ratio tests. Discrimination was assessed with the area under the receiver operating characteristic curve (AUC), overall prediction error with the Brier score, and Nagelkerke R^2 , calibration intercept, and calibration slope were also reported. Sensitivity and specificity at a predicted-probability threshold of 0.50 were calculated only as descriptive measures of apparent classification performance. M0, M1, and M2 underwent 2,000 paired bootstrap resamples. In each resample, all models were refitted and evaluated in the original dataset to estimate mean optimism in AUC and Brier score and derive optimism-corrected values. The 95% sampling intervals for apparent AUC and Brier score were obtained from the distribution of the fixed original model in bootstrap samples and were not interpreted as confidence intervals (CIs) for optimism-corrected estimates. Corrected Δ AUC and Δ Brier for M2 versus M1 were based on paired differences in optimism within the same resamples and are reported with bootstrap percentile intervals. A loess flexible calibration curve was fitted to individual predicted probabilities, with curve optimism estimated in each resample to obtain an optimism-corrected curve and pointwise bootstrap intervals[17]. Post hoc sample-size precision assessment followed the Riley framework for binary prediction models. Because prior ACLR studies did not provide a Cox–Snell or Nagelkerke R^2 directly corresponding to this prediction time point and binary outcome that could be used to prespecify model performance, we did not use the R^2 observed in the development data to retrospectively justify sample-size adequacy. We focused on precision of the overall outcome-risk estimate and considered the bootstrap calibration slope and optimism-corrected performance when judging model stability. With an observed outcome proportion of 47.5%, approximately 384 patients would be required for a 95% CI half-width no greater than 0.05 around the overall risk estimate. The conventional events-per-parameter ratio was reported descriptively only[21]. Sensitivity analyses included: (1) replacing postoperative month 1 HADS-A with the depression subscale of the Hospital Anxiety and Depression Scale (HADS-D); (2) replacing IKDC with the KOOS Quality of Life subscale; (3)

further adjusting for body mass index (BMI), ln(injury-to-surgery days), and preinjury Tegner activity level; and (4) modeling postoperative month 6 TSK-17 as a continuous outcome using multiple linear regression with heteroscedasticity-consistent type 3 (HC3) robust standard errors for 95% CIs. We also compared postoperative month 1 characteristics between patients with and without an observed 6-month outcome. Among patients with complete core predictors at postoperative month 1, an observation-probability model was fitted with 6-month outcome availability as the dependent variable, and M2 was refitted using stabilized inverse probability weighting (IPW), with weights truncated at the 1st and 99th percentiles. Nonlinearity of each continuous predictor was examined separately using restricted cubic splines with 3 knots, adding one nonlinear degree of freedom for each predictor. Because of sample-size limitations, spline models were sensitivity analyses only. All tests were two-sided with $P < 0.05$ considered statistically significant. Analyses were performed in R version 4.5.1.

3. Results

3.1 Patient Flow and Outcome Incidence

The source database included 234 patients. After excluding 25 patients outside the 18-55-year age range, 209 were age eligible. One patient lacked the core postoperative month 1 predictors, leaving 208 with complete core predictors. Among these 208 patients, 31 lacked the postoperative month 6 TSK-17 outcome, and 177 had both complete month 1 core predictors and a month 6 TSK-17 outcome and entered the primary analysis. Postoperative month 1 characteristics of patients with and without an observed outcome are compared in Supplementary Table S1. In the final analysis sample, 84 patients had high kinesophobia and 93 did not, corresponding to an incidence of 47.5% (95% confidence interval [CI], 40.2%-54.8%). Patient flow is shown in Fig. 1.

3.2 Postoperative Month 1 Characteristics

The analysis sample had a mean age of 30.00 ± 7.51 years, and 122 patients (68.9%) were male. Compared with patients without high kinesophobia at month 6, those with high kinesophobia had higher postoperative month 1 TSK-17 and HADS-A scores and lower ACL-RSI, K-SES, and IKDC scores. The largest standardized between-group differences were observed for TSK-17 and ACL-RSI, with absolute SMDs of 1.310 and 1.151, respectively (Table 1). The five postoperative month 1 psychological and functional measures showed moderate correlations. Absolute correlation coefficients ranged from 0.292 to 0.708, with the strongest correlation between ACL-RSI and K-SES ($r = 0.708$). VIFs for all predictors ranged from 1.086 to 2.474, with no evidence of marked multicollinearity (Supplementary Table S2).

Table 1
Postoperative Month 1 Characteristics by Kinesiophobia Status at Month 6

Measure	Overall (n = 177)	No high kinesiophobia (n = 93)	High kinesiophobia (n = 84)	SMD
Age, years	30.00 ± 7.51	30.42 ± 7.30	29.54 ± 7.76	-0.117
Male, n (%)	122(68.9)	70(75.3)	52(61.9)	-0.291
TSK-17, points	36.88 ± 7.01	33.23 ± 6.13	40.92 ± 5.57	1.310
ACL-RSI, points	60.34 ± 18.46	69.09 ± 16.08	50.64 ± 15.97	-1.151
K-SES, points	52.35 ± 24.09	61.44 ± 22.95	42.29 ± 21.25	-0.864
HADS-A, points	5.59 ± 3.07	4.34 ± 2.68	6.98 ± 2.89	0.947
IKDC, points	51.80 ± 15.90	57.63 ± 15.07	45.33 ± 14.29	-0.836
Note: Continuous variables are presented as mean ± standard deviation and categorical variables as number (%). SMD represents the standardized mean difference for the high-kinesiophobia group relative to the no-high-kinesiophobia group. These comparisons are descriptive only and were not used for predictor selection.				

3.3 Predictive Performance of Sequential Models

M0, which included only age and sex, had an apparent AUC of 0.600 and a Brier score of 0.243. After adding postoperative month 1 TSK-17, the apparent AUC of M1 increased to 0.821 and the Brier score decreased to 0.170. After further adding ACL-RSI, K-SES, HADS-A, and IKDC, M2 had an apparent AUC of 0.874, a Brier score of 0.144, and a Nagelkerke R² of 0.521. After 2,000 paired bootstrap resamples, optimism-corrected AUCs for M0, M1, and M2 were 0.578, 0.812, and 0.852, respectively, and corrected Brier scores were 0.251, 0.179, and 0.162. The apparent Δ AUC for M2 versus M1 was 0.053, and the corrected Δ AUC was 0.040 (bootstrap 95% interval, -0.015 to 0.074); the corrected Δ Brier was -0.017 (-0.036 to 0.013). The likelihood-ratio test supported better fit for M2 than M1 ($P < 0.001$), but the intervals for optimism-corrected incremental performance included no improvement (Table 2).

Table 2
Apparent and Optimism-Corrected Performance of Sequential Prediction Models

Model	Parameters	Apparent AUC	Corrected AUC	Apparent Brier	Corrected Brier	Nagelkerke R ²	P vs previous model
M0	2	0.600	0.578	0.243	0.251	0.036	—
M1	3	0.821	0.812	0.170	0.179	0.406	< 0.001
M2	7	0.874	0.852	0.144	0.162	0.521	< 0.001
Note: M0 included age and sex; M1 added postoperative month 1 TSK-17 to M0; M2 added postoperative month 1 ACL-RSI, K-SES, HADS-A, and IKDC to M1. Corrected values were obtained from 2,000 paired bootstrap resamples. P values are from likelihood-ratio tests comparing adjacent nested models.							

3.4 Predictors in the Full Model

After simultaneous adjustment for the other predictors, each 1-standard-deviation increase in postoperative month 1 TSK-17 was associated with an odds ratio (OR) of 3.051 for high kinesiphobia at month 6 (95% CI, 1.712–5.438; $P < 0.001$). Each 1-standard-deviation increase in ACL-RSI was associated with an OR of 0.398 (95% CI, 0.212–0.745; $P = 0.004$). HADS-A showed a trend toward higher risk (OR = 1.578; 95% CI, 0.973–2.557; $P = 0.064$). Adjusted coefficients for age, sex, K-SES, and IKDC were not statistically significant (Table 3). The apparent model on the original measurement scales was: $\text{logit}(P) = -2.5999 - 0.0231 \times \text{age} + 0.3270 \times \text{male sex} + 0.1591 \times \text{TSK-17} - 0.0500 \times \text{ACL-RSI} + 0.0095 \times \text{K-SES} + 0.1485 \times \text{HADS-A} - 0.0249 \times \text{IKDC}$, where male sex was coded as 1 and female sex as 0, and P denotes the probability of high kinesiphobia at postoperative month 6.

Table 3
Predictors in the Multidimensional Full Model

Predictor	Adjusted OR	95% CI	P value
Age	0.841	0.562–1.257	0.397
Male	1.387	0.551–3.489	0.487
Month 1 TSK-17	3.051	1.712–5.438	< 0.001
Month 1 ACL-RSI	0.398	0.212–0.745	0.004
Month 1 K-SES	1.258	0.697–2.271	0.446
Month 1 HADS-A	1.578	0.973–2.557	0.064
Month 1 IKDC	0.673	0.399–1.135	0.138
Note: ORs for continuous predictors represent the change in odds per 1-standard-deviation increase. All predictors were entered simultaneously.			

3.5 Internal Validation and Classification Performance

After 2,000 bootstrap resamples for internal validation, the AUC of the original M2 was corrected from 0.874 to 0.852 and the Brier score from 0.144 to 0.162. The calibration slope was 0.853 and the calibration intercept was 0.003, indicating some overfitting and calibration uncertainty in the original model (Table 4). The AUC, Brier score, and calibration metrics reported in Tables 2–4 and Figs. 2–3 correspond to the unshrunk original M2 and its bootstrap optimism-corrected results. To provide a candidate model for subsequent validation, 0.853 was used as a uniform shrinkage factor for all non-intercept coefficients of the original M2, followed by re-estimation of the intercept. The resulting equation was: $\text{logit}(P) = -2.2236 - 0.0197 \times \text{age} + 0.2788 \times \text{male sex} + 0.1357 \times \text{TSK-17} - 0.0426 \times \text{ACL-RSI} + 0.0081 \times \text{K-SES} + 0.1266 \times \text{HADS-A} - 0.0212 \times \text{IKDC}$. This shrinkage equation has not been evaluated in an independent sample; therefore, its performance in the development data is not interpreted as validation performance. At a predicted-probability threshold of 0.50 using the original M2, apparent sensitivity was 76.2%, specificity 76.3%, positive predictive value 74.4%, and negative predictive value 78.0%. Classification performance across probability thresholds is shown in Supplementary Table S3. Because no clinical decision threshold was prespecified and decision-curve analysis was not performed, no threshold is interpreted as an optimal clinical cutoff. Receiver operating characteristic curves and the bootstrap-corrected flexible calibration curve based on individual predicted probabilities are shown in Figs. 2 and 3, respectively.

Table 4
Bootstrap Internal Validation of the Full Model

Measure	Apparent estimate (95% sampling interval)	Mean optimism	Optimism-corrected estimate
AUC	0.874(0.819–0.919)	0.022	0.852
Brier score	0.144(0.117–0.176)	0.018	0.162
Calibration slope	1.000	—	0.853
Calibration intercept	0.000	—	0.003
Note: Internal validation used 2,000 bootstrap resamples. Intervals shown in parentheses for AUC and Brier score are distributions of apparent performance for the fixed original model across bootstrap samples; they reflect sampling uncertainty in the apparent estimates and are not 95% CIs for the optimism-corrected estimates. Calibration intercept and slope are reported as bootstrap-corrected point estimates.			

3.6 Sensitivity Analyses

Replacing HADS-A with HADS-D yielded an AUC of 0.874 and a Brier score of 0.145; replacing IKDC with KOOS-QoL yielded an AUC of 0.875 and a Brier score of 0.144. Further adjustment for BMI, injury-to-surgery interval, and preinjury Tegner score yielded an AUC of 0.876 and a Brier score of 0.145 in 176

patients, suggesting that primary-model performance was relatively robust to measure selection and adjustment for conventional clinical covariates (Table 5). When postoperative month 6 TSK-17 was analyzed as a continuous outcome, model R^2 was 0.507, adjusted R^2 was 0.486, and root mean square error (RMSE) was 5.324 points. Postoperative month 1 TSK-17 ($B = 0.386$; 95% CI, 0.210–0.562; $P < 0.001$), HADS-A ($B = 0.534$; 95% CI, 0.141–0.928; $P = 0.008$), and IKDC ($B = -0.078$; 95% CI, -0.153 to -0.002; $P = 0.044$) retained independent associations, supporting that the primary finding was not entirely driven by the 37-point cutoff (Supplementary Table S5). Among the 209 age-eligible patients, the 177 with a 6-month outcome and the 32 without one differed little in age, postoperative month 1 TSK-17, HADS-A, and IKDC. Patients with missing outcomes had relatively higher ACL-RSI and K-SES scores, with absolute SMDs of 0.257 and 0.315, respectively, so selective attrition could not be completely excluded.

Among the 208 patients with complete core predictors at postoperative month 1, 177 had an observed 6-month outcome and 31 had a missing outcome. Stabilized weights from the IPW analysis, truncated at the 1st and 99th percentiles, ranged from 0.912 to 1.148, with an effective sample size of 176.3. After weighting, the estimated high-kinesiophobia rate was 46.8%; weighted AUC for M2 was 0.877 and the Brier score was 0.143. Changes in standardized predictor coefficients relative to the unweighted model were all below 8%. The ORs for TSK-17 and ACL-RSI changed from 3.051 and 0.398 to 3.138 and 0.389, respectively, supporting robustness of the main results to selective attrition explained by observed characteristics (Supplementary Table S6).

Post hoc sample-size precision assessment showed that, with an outcome proportion of 47.5%, approximately 384 patients would be required if the 95% CI half-width for the overall risk estimate were constrained to no more than 0.05, substantially more than the current 177 patients. The current model included 7 predictor parameters and 84 outcome events, corresponding to approximately 12.0 events per parameter; this ratio is descriptive only and was not used to judge sample-size adequacy. Together with the bootstrap calibration slope of 0.853 and uncertainty in the calibration curve, these findings indicate that the current data are more appropriate for preliminary model development and internal validation than for precise and stable individual risk estimation. The model should therefore remain classified as preliminary (Supplementary Table S7). In separate 3-knot spline checks, only ACL-RSI showed evidence of nonlinearity ($P = 0.029$), but the apparent AUC increased only from 0.874 to 0.875 and the Brier score decreased from 0.144 to 0.143. Given the additional parameter, limited sample size, and minimal performance gain, the prespecified linear primary model was retained and the spline result treated as a sensitivity analysis (Supplementary Table S8).

Table 5
Sensitivity Analyses

Model	Sample size	Events	AUC	Brier score
Primary model	177	84	0.874	0.144
Alternative model 1	177	84	0.874	0.145
Alternative model 2	177	84	0.875	0.144
Extended model	176	84	0.876	0.145
Note: The primary model included HADS-A and IKDC. Alternative model 1 replaced HADS-A with HADS-D; alternative model 2 replaced IKDC with KOOS-QoL. The extended model added BMI, injury-to-surgery interval, and preinjury Tegner score to the primary model.				

4. Discussion

We developed and internally validated a prognostic model using psychological and knee-function measures obtained at postoperative month 1 to predict high kinesiophobia at 6 months after ACLR. Three findings are most important. First, TSK-17 at postoperative month 1 provided most of the predictive information, with an optimism-corrected AUC of 0.812 for M1. Second, after ACL-RSI, K-SES, HADS-A, and IKDC were added, the apparent AUC of M2 increased to 0.874 and the corrected AUC to 0.852, but the intervals for corrected Δ AUC and Δ Brier versus M1 included no improvement, indicating substantial uncertainty in the additional value of the multidimensional measures. Third, the calibration slope was 0.853, and post hoc sample-size precision assessment also indicated that the current sample was insufficient for precise risk estimation. The model should therefore be regarded as a preliminary research model rather than an established clinical tool.

TSK-17 at postoperative month 1 was the strongest predictor in the full model, consistent with previous evidence that kinesiophobia shows temporal stability. Theunissen et al. found that preoperative pain and clinical factors predicted TSK-17 at 3 months after surgery[7]; Longo et al. observed associations between preoperative and postoperative kinesiophobia and functional outcomes[6]; and Ohji et al. further showed that TSK-17, ACL-RSI, and subjective knee function changed in parallel from preoperatively to 6 months after ACLR[9]. By moving the prediction landmark to postoperative month 1, our model incorporates patients' actual psychological and functional responses to surgery and early rehabilitation and may therefore more closely represent a subsequent, potentially modifiable rehabilitation state than preoperative risk markers alone. This longitudinal predictive relationship, however, should not be interpreted as a causal effect of kinesiophobia on later outcomes.

ACL-RSI remained independently associated with lower odds of high kinesiophobia at month 6 after adjustment for early TSK-17, suggesting that psychological readiness and kinesiophobia are related but not identical constructs. ACL-RSI captures emotions, confidence, and risk appraisal related to return to sport, whereas K-SES focuses more directly on patients' beliefs about their ability to perform knee-related tasks. Previous studies have associated greater psychological readiness and self-efficacy with

better return-to-sport and knee-function outcomes[3, 22]. In our study, K-SES showed a large between-group difference but was not independently significant after adjustment for the other psychological measures, possibly reflecting overlap with ACL-RSI and TSK-17. The correlation matrix and VIFs did not indicate severe multicollinearity, supporting its retention as a prespecified psychological-domain measure.

HADS-A and IKDC did not reach conventional statistical significance in the binary full model, but this does not imply an absence of predictive contribution. The primary goal of a prediction model is to estimate individual risk and evaluate overall model performance, not merely to identify variables with independently significant or causal effects. The Prediction model Risk Of Bias ASsessment Tool (PROBAST) specifically identifies avoidance of univariable predictor screening as an important consideration in the analysis domain[19], and clinical prediction-model guidance likewise discourages exclusion of candidate predictors solely on the basis of univariable P values[17, 18, 20]. Recent multidomain prediction research in ACLR has similarly retained psychological measures that were not significant in univariable comparisons and emphasized that univariable nonsignificance does not rule out multivariable predictive value[23]. In our study, the likelihood-ratio test suggested improved fit for the full model compared with the model containing TSK-17 alone, but the intervals for optimism-corrected incremental AUC and Brier score included no improvement. The multidimensional block can therefore only be considered potentially informative at present; these results do not establish that every added measure is indispensable or that incremental value has been robustly demonstrated.

The potential clinical relevance of this study is the identification of postoperative month 1 as an early risk-stratification window. For patients with higher predicted risk, the clinical team could further assess reinjury concerns, confidence in recovery, rehabilitation goals, emotional symptoms, and actual knee function and consider enhanced education, graded activity exposure, or psychological support. However, the model has undergone internal validation only. We did not evaluate whether use of the model improves rehabilitation decisions or patient outcomes, and decision-curve analysis was not performed to identify a probability range with net benefit. At this stage, the model is therefore better regarded as a research-oriented screening tool than as a diagnostic tool or a rule for directly determining treatment.

Strengths of this study include measurement of all predictors at a fixed postoperative month 1 time point before outcome assessment; coverage of multiple prespecified domains without univariable P-value screening; avoidance of random train-test splitting in a moderate-sized sample in favor of 2,000 paired bootstrap resamples for all three sequential models; direct quantification of optimism-corrected incremental performance of M2 over M1; and assessment of robustness using flexible calibration, alternative instruments, adjustment for conventional clinical covariates, a continuous outcome, IPW for attrition, and nonlinearity checks. Several limitations should also be considered. First, this was a single-center study without independent external validation. Second, post hoc sample-size precision assessment indicated that approximately 384 patients would be required for a 95% CI half-width no greater than 0.05 around the overall risk estimate, substantially more than the current 177 patients. In addition, the calibration slope of 0.853 and uncertainty in the calibration curve indicate some overfitting,

so individual predicted probabilities may be unstable. Third, 32 of the 209 age-eligible patients lacked a 6-month outcome, including one who also lacked the core postoperative month 1 predictors; the IPW analysis included the 31 outcome-missing patients among the 208 with complete core predictors. Although IPW results were similar to the primary analysis, this method assumes that missingness is explainable by observed variables and cannot exclude nonrandom attrition. Fourth, candidate predictors and the outcome were primarily patient-reported measures, which may introduce common-method bias. Fifth, the 37-point TSK-17 cutoff is not a diagnostic threshold derived in an ACLR population, and previous studies have not used completely consistent dichotomization around 37 points. Although analysis of the continuous outcome reduced dependence on a single threshold, construct interpretation still requires caution. Sixth, ACL-RSI showed some evidence of nonlinearity, but the sample was too small to support stable addition of spline parameters to the primary model. Seventh, rehabilitation exposure, complications, and treatment modifications between postoperative months 1 and 6 were not included. Finally, decision-curve analysis and fairness were not evaluated, and the model should not be extrapolated to patients outside the 18-55-year age range, revision ACLR, or more complex injuries.

5. Conclusion

Among patients aged 18–55 years undergoing ACLR, TSK-17 at postoperative month 1 provided the core predictive information for high kinesiophobia at postoperative month 6. Multidimensional psychological and functional measures such as ACL-RSI may provide additional information beyond early TSK-17, but the intervals for corrected incremental performance included no improvement, so incremental value cannot yet be considered firmly established. The full model retained good discrimination after internal validation but showed some overfitting and uncertainty related to sample size and selective attrition. Postoperative month 1 may serve as a research-oriented risk-stratification window. The model should not be used as a diagnostic or direct treatment-decision rule until it has undergone external validation in a larger sample and demonstrated clinical net benefit.

Abbreviations

Abbreviation	Definition
ACL	anterior cruciate ligament
ACLR	anterior cruciate ligament reconstruction
ACL-RSI	Anterior Cruciate Ligament–Return to Sport after Injury scale
AUC	area under the receiver operating characteristic curve
BMI	body mass index
CI	confidence interval
HADS-A	Hospital Anxiety and Depression Scale anxiety subscale
HADS-D	Hospital Anxiety and Depression Scale depression subscale
HC3	heteroscedasticity-consistent covariance matrix estimator, type 3
IKDC	International Knee Documentation Committee Subjective Knee Form
IPW	inverse probability weighting
K-SES	Knee Self-Efficacy Scale
KOOS	Knee injury and Osteoarthritis Outcome Score
KOOS-QoL	Knee injury and Osteoarthritis Outcome Score Quality of Life subscale
OR	odds ratio
PROBAST	Prediction model Risk Of Bias ASsessment Tool
RMSE	root mean square error
SMD	standardized mean difference
TRIPOD+AI	Transparent Reporting of a multivariable prediction model for Individual Prognosis Or Diagnosis + Artificial Intelligence
TSK-17	17-item Tampa Scale for Kinesiophobia
VIF	variance inflation factor

Declarations

Ethics approval and consent to participate

The study protocol was reviewed and approved by the Ethics Committee of Sichuan Provincial Orthopedics Hospital (approval No. KY2024-037-01). The study was conducted in accordance with the Declaration of Helsinki and applicable ethical principles. Written informed consent was obtained from all individual participants included in the study before enrollment.

Clinical trial number

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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No funding was received for this study.

Authors' contributions

JX contributed to conceptualization, methodology, data collection, formal analysis, and preparation of the original manuscript. MC contributed to participant follow-up and data collection. XL contributed to conceptualization, methodology, clinical supervision, interpretation of the findings, project administration, and supervision. All authors critically revised the manuscript and read and approved the final version.

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Figures

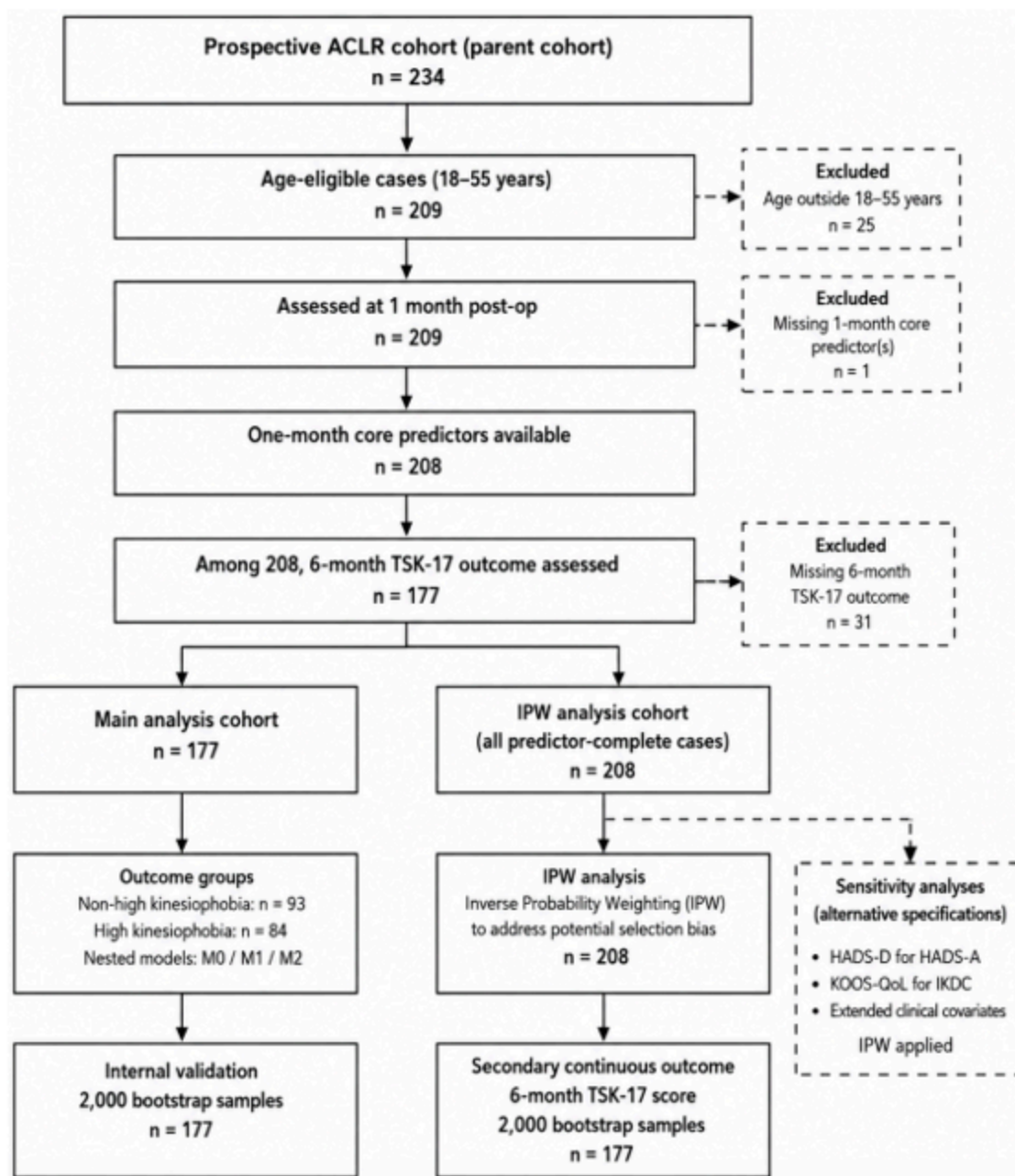


Figure 1

Participant inclusion and analysis flow. Internal validation used 2,000 bootstrap resamples.

Note: The main analysis included 177 participants with complete 1-month predictors and 6-month TSK-17 outcomes. IPW analyses included 208 participants with complete 1-month predictors. Internal validation was performed using 2,000 bootstrap samples.

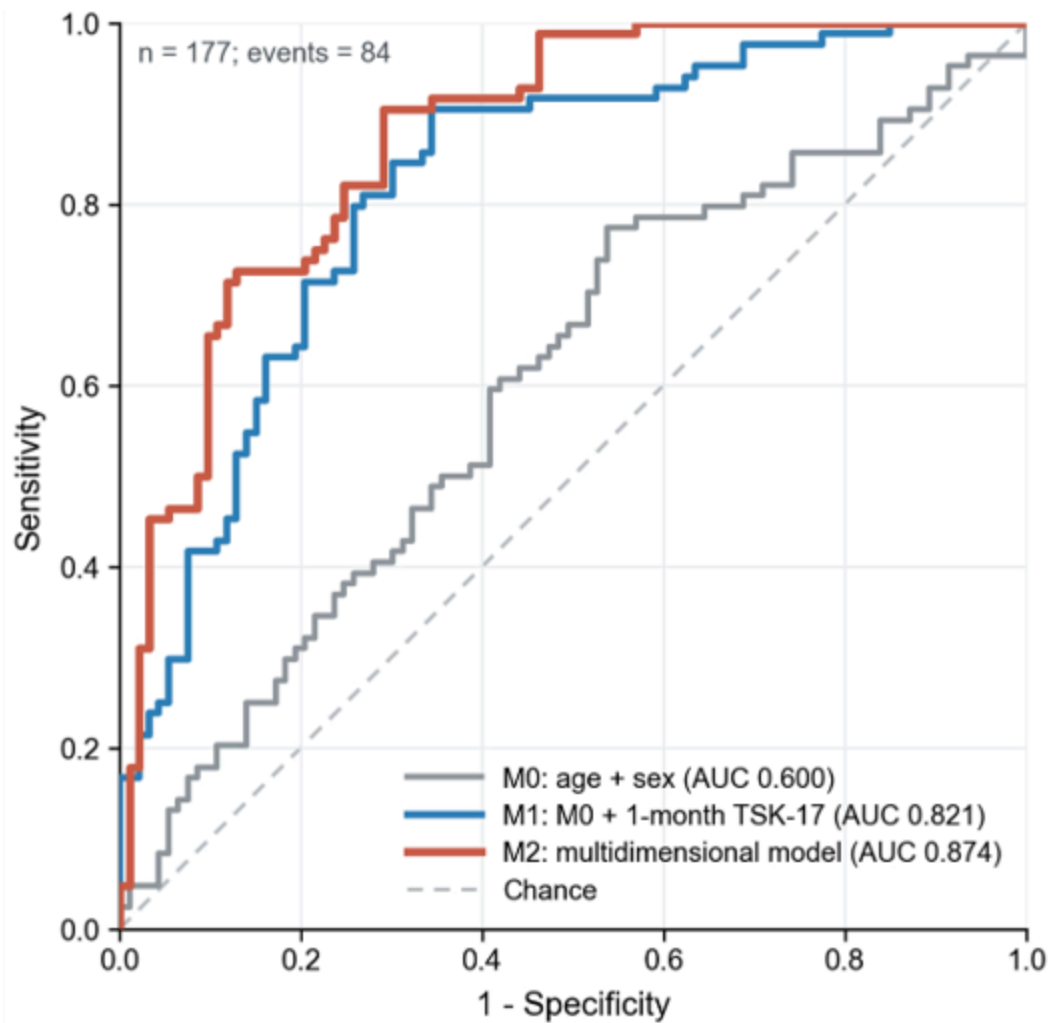


Figure 2

Receiver operating characteristic curves for the sequential prediction models.

Note: M0: age and sex; M1: M0 plus postoperative month 1 TSK-17; M2: multidimensional full model. AUC, area under the receiver operating characteristic curve. n=177; events=84.

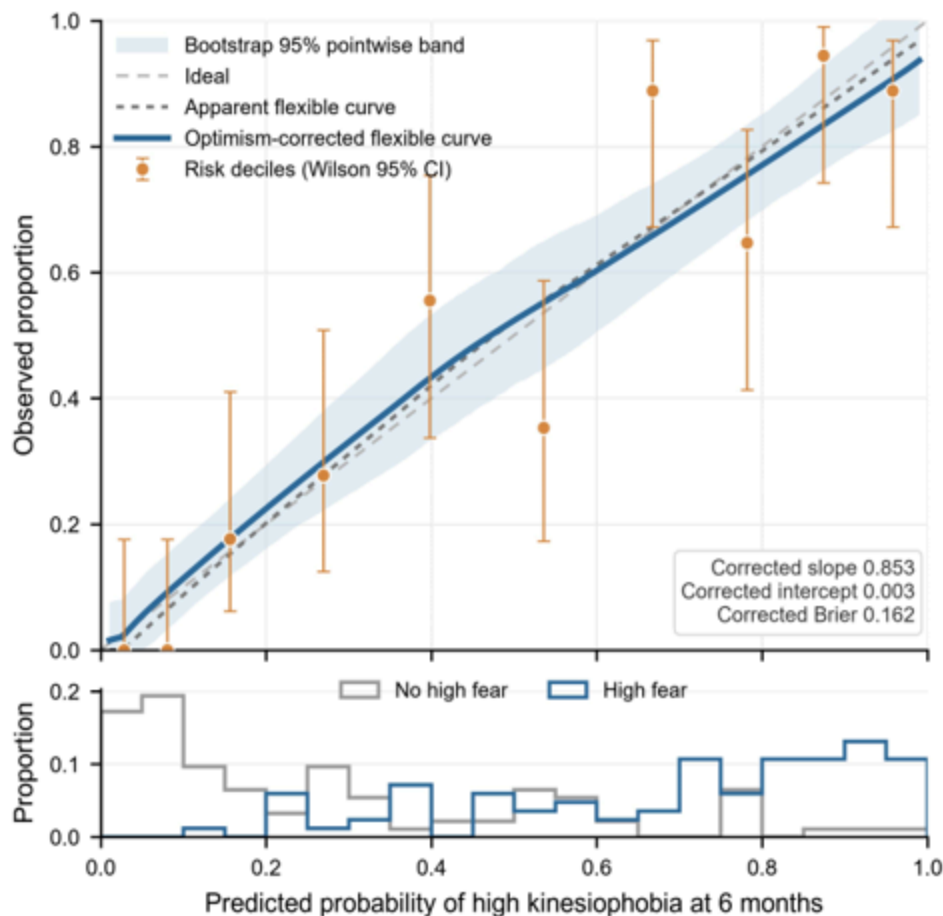


Figure 3

Bootstrap calibration performance of the full model.

Note: The blue solid line is the optimism-corrected flexible calibration curve based on individual predicted probabilities, the light-blue band is the pointwise bootstrap 95% interval, the gray dotted line is the apparent flexible curve, and the dashed line is ideal calibration. Orange circles and error bars show observed event rates and Wilson 95% CIs by decile of predicted risk. CI, confidence interval. The lower panel shows the distributions of predicted probabilities for patients with and without high kinesophobia.

Supplementary Files

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