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Original Article

Correlation between gait analysis parameters and joint function prognosis during rehabilitation after anterior cruciate ligament reconstruction: a retrospective study

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Abstract: Objective: To evaluate changes in gait parameters following autograft hamstring anterior cruciate ligament (ACL) reconstruction and their association with knee function recovery and to explore the predictive value of gait parameters in clinical assessment. Methods: A total of 186 patients who underwent ACL reconstruction between January 2020 and September 2023 were enrolled. Gait analysis and knee function assessments (Lysholm, International Knee Documentation Committee [IKDC], and Tegner scores) were performed pre- and postoperatively. Gait data were collected using the Sennotech Insole X 1.0 system. Multivariate linear regression and logistic regression models identified significant gait predictors, and function prediction models were constructed and evaluated using Receiver Operating Characteristic (ROC) curves and decision curve analysis (DCA). Results: Postoperative gait parameters significantly improved, particularly stride length, step height, and landing impact force (all $P < 0.05$). Knee function scores, including Lysholm and IKDC, significantly improved, while the Tegner score declined (all $P < 0.001$). Stride length was positively correlated with Lysholm and IKDC scores, while impact force was negatively correlated with IKDC. Multivariate regression analysis identified stride length and lift angle as significant predictors of Lysholm and IKDC scores, while flat phase and impact force were negatively associated with Tegner score. The predictive model demonstrated AUC values of 0.73 and 0.66 for the training and testing sets, respectively. DCA confirmed the clinical utility of the model. Conclusion: Gait improvements following ACL reconstruction are closely linked to knee function recovery. Key gait parameters serve as objective predictors and can guide personalized rehabilitation planning.

Keywords: Anterior cruciate ligament reconstruction, gait analysis, knee function, rehabilitation, predictive modeling

Introduction

Anterior cruciate ligament (ACL) injuries are among the most common knee joint traumas in athletes, often leading to knee instability. The global incidence is approximately 0.04%, with an increasing trend in recent years [1]. ACL reconstruction (ACLR) has evolved from open repair to arthroscopic techniques, with continuous refinements in surgical methods. Currently, autograft hamstring arthroscopic reconstruction is the most widely used and effective approach, restoring knee stability, improving knee function, and delaying the onset of osteoarthritis [2]. Postoperative rehabilitation following ACL anatomical reconstruction is crucial for restoring athletic function. Rehabilitation stabilizes the knee joint and promotes the recovery of surrounding muscle strength, joint range of motion, and proprioception. However, existing assessment systems for evaluating ACL reconstruction outcomes primarily rely on subjective patient-reported satisfaction [3, 4], which can be influenced by various factors, limiting the accuracy of results and making precise evaluation challenging. Consequently, effectively assessing and monitoring postoperative rehabilitation

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remains a significant challenge in ACL injury treatment.

Knee function is commonly assessed using self-reported questionnaires, such as the Lysholm score, the International Knee Documentation Committee (IKDC) subjective score, and the Tegner and Marx scales, which are frequently used to evaluate outcomes following ACLR [5]. The Tegner score reflects both the patient's pre-injury activity level and postoperative recovery, helping assess whether the patient has regained their pre-injury physical activity level [6]. While these scores provide valuable insights, they are subjective and do not fully capture the biomechanical recovery of the knee. In contrast, gait analysis is an objective, non-invasive tool increasingly employed to assess postoperative rehabilitation following ACLR [7]. Current clinical gait analysis techniques include computer vision, pressure-sensing, and wearable technologies [8, 9]. The Sennotech Insole X 1.0 foot posture evaluation system, a novel wearable gait analysis tool (Senno Gait), consists of three components: a sensor layer, control layer, and algorithm layer [10]. The system enables quantitative assessment of gait changes before and after ACL reconstruction, offering detailed insights into the biomechanical changes in the knee joint and facilitating the development of more effective and targeted treatment plans.

Although gait analysis has been incorporated into ACL rehabilitation assessments, most studies have focused on single gait parameters. Previous studies predominantly concentrated on isolated gait parameters, such as stride length and step height [11], neglecting a comprehensive, multi-parametric analysis that would clarify the relationships between gait characteristics and knee function scores. To address this gap, we conducted a retrospective analysis of gait characteristics and knee function in 186 patients following ACL reconstruction. We used the Sennotech Insole X 1.0 system to record gait parameters three months post-surgery and assessed knee function using the Lysholm, IKDC, and Tegner scores. Through multivariate regression analysis and correlation heatmaps, we systematically examined the influence of individual gait parameters on knee function and developed predictive models to evaluate the predictive power of gait parameters for knee function recovery.

Materials and methods

Clinical data

This retrospective cohort study included patients who underwent autograft hamstring ACL reconstruction at Anhui University of Traditional Chinese Medicine between January 2020 and September 2023. The inclusion criteria were as follows: age between 18 and 60 years; clinical diagnosis of ACL injury requiring primary arthroscopic ACL reconstruction; use of autograft hamstring single-bundle ACL reconstruction; and availability of complete gait analysis and knee function scores both pre- and postoperatively. Patients were excluded if they had other significant knee joint pathologies (e.g., knee osteoarthritis, severe meniscal injuries), experienced postoperative complications or required re-operation, or were unable to complete gait analysis or knee function assessments.

The primary outcome measure was the change in knee joint function scores postoperatively. Based on preliminary pilot data, the expected difference in postoperative IKDC scores was 8 points, with a standard deviation of 15 points. A two-tailed test with a significance level of $\alpha = 0.05$ and a test power ($1 - \beta$) of 0.80 was applied. Sample size calculations were performed using G*Power 3.1 software, which indicated that at least 85 patients per group were required. Considering the potential for missing data or patients not meeting inclusion or exclusion criteria in a retrospective study, the sample size was appropriately increased. Ultimately, 186 patients were included in the study, consisting of 95 males and 91 females. The average age at the time of ACL reconstruction was 35.68 ± 5.04 years, and the mean body mass index (BMI) was 25.16 ± 2.83. All patients received routine postoperative rehabilitation and participated in gait analysis, as well as the collection of Lysholm, IKDC, and Tegner scores. This study followed the ethical guidelines set forth in the Declaration of Helsinki and was approved by the ethics committee of Anhui University of Traditional Chinese Medicine. Written informed consent was provided by participants.

Treatment and rehabilitation

All patients underwent autograft hamstring ACL reconstruction with arthroscopic treatment of any concomitant meniscal injuries. The autograft hamstring tendon was harvested, prepared, and threaded through an Endobutton loop at both ends. The tibial tunnel was located at the junction of the tibial intercondylar midline and the front corner of the lateral meniscus. The femoral tunnel was positioned using a femoral locator via an anteromedial approach. Tibial fixation was achieved using absorbable interference screws and AO hollow nails, while femoral stabilization was secured with an Endobutton suspension device.

Postoperative rehabilitation began 6 hours after surgery with ankle plantarflexion and dorsiflexion exercises, performed as tolerated. From days 1 to 3, isometric quadriceps contractions (10-second holds) were initiated to prevent venous thrombosis and minimize muscle atrophy, provided they did not exacerbate pain. From days 4 to 7, heel slides with knee flexion limited to < 30 degrees were performed for 10 minutes per session, three times daily, to prevent periarticular soft tissue adhesions. Starting one week postoperatively, exercises to improve knee flexion and extension were introduced to maintain joint range of motion. The rehabilitation program was supervised by a team experienced in ACL reconstruction rehabilitation, ensuring the quality and safety of early rehabilitation.

Gait data collection

Gait data were collected using the Sennotech Insole X 1.0 system. Participants were fitted with appropriately sized insoles, and the device was linked via Bluetooth to a terminal where subject profiles and basic demographic information were entered. Participants then walked at a self-selected, comfortable pace along a straight line on a flat, hard surface for 60 seconds. The test was repeated to ensure data reliability. Following data acquisition, gait parameters were processed and stored in the cloud. The collected parameters included stride length, step height, landing impact force, and eight additional metrics automatically quantified by the system. While acknowledging the potential influence of factors such as terrain variations, individual gait patterns, and insole fit, data were acquired under standardized conditions to maximize consistency and reliability. The specific parameters assessed included:

(1) Stride length: The horizontal distance between the initial and subsequent ground contact of the same foot; excessively long strides can lead to changes in landing angle and increased impact force. (2) Step height: The vertical height from the highest point of foot push-off to the ground; excessively high or low step heights can affect balance and gait coordination. (3) Landing impact force: The maximum instantaneous pressure applied to the ground during the gait cycle; higher impact forces may place stress on the knee joint. (4) Support phase: The phase from heel contact with the ground until the toes begin to lift off the ground. (5) Ground contact phase: The period from forefoot contact with the ground to the initial heel contact. (6) Flat phase: The phase from forefoot contact to the point where the heel is about to leave the ground. (7) Push-off phase: The propulsion phase from heel rise to toe lift-off. (8) Swing phase: The period between toe lift-off and the subsequent re-contact of the same foot's toe with the ground. (9) Landing angle: The foot-ground angle at the moment of landing; excessive angles may increase knee impact. (10) Lift-off angle: The foot-ground angle at the moment of take-off; abnormal angles may indicate muscle tightness or insufficient joint mobility. (11) Maximum swing speed: The maximum speed reached by the foot during the swing phase of gait; significant differences in swing speed may reflect decreased balance and coordination.

Knee function assessment

Knee function was evaluated using the Lysholm score, the International Knee Documentation Committee (IKDC) subjective score, and the Tegner activity score. All assessments were conducted by experienced clinical evaluators under standardized conditions.

(1) Lysholm score: The Lysholm score consists of 8 evaluation criteria: limp, support, locking, pain, instability, swelling, stair climbing, and squatting. Each component is rated between 0 and 25 points, with a maximum total of 100 points. Higher scores suggest superior knee function. (2) IKDC subjective score: The IKDC score evaluates knee pain, instability, athletic

ability, and functional limitations, with a maximum total of 100 points. Higher scores suggest superior knee function. (3) Tegner score: The Tegner score assesses the patient's activity level, with ratings ranging from 0 to 10. Higher scores indicate a greater degree of physical activity.

Statistical analysis

Statistical analysis was conducted using SPSS 26.0 (IBM Corp., USA) and R software version 4.2.1 (Lucent Technologies Inc., Union, NJ, USA, https://www.r-project.org/). A two-tailed *p*-value < 0.05 was considered statistically significant. Normally distributed data with equal variances were expressed as means ± standard deviations ($\bar{x} \pm s$), and comparisons between groups were performed using paired t-tests. For data not following a normal distribution, paired rank-sum tests were applied.

Normality test and correlation analysis: Normality tests were conducted for all variables. For variables following a normal distribution, Pearson correlation analysis was used to assess the linear relationships between gait parameters and knee function scores (Lysholm, IKDC, and Tegner scores). The correlation coefficients (r) and associated *p*-values were calculated. If any variable did not meet the normality assumption, Spearman rank correlation was considered. However, all variables in this study met the assumptions required for Pearson analysis.

Multivariable linear regression analysis: To further evaluate the impact of gait parameters on knee function, multivariable linear regression analyses were performed. Each of the three functional scores (Lysholm, IKDC, and Tegner) was treated as a dependent variable, with gait parameters as independent variables. Regression coefficients (β), standard errors (SE), t-values, and *p*-values were reported for each predictor. Statistical significance for each coefficient was assessed using a two-tailed t-test, with P < 0.05 considered indicative of a significant association between the gait parameter and the respective knee function score. Model assumptions were assessed via residual diagnostics, including standardized residual plots and fitted value plots, with the expectation that residuals would be randomly distributed and independent of predicted values.

Construction of predictive model: A predictive model for knee function status based on gait parameters was constructed. A composite functional score was calculated by assigning weights of 0.4 to both the Lysholm and IKDC scores, and 0.2 to the Tegner score (Composite score = 0.4 × Lysholm + 0.4 × IKDC + 0.2 × Tegner). Based on the median value of this composite score, participants were categorized into high-function and low-function groups for subsequent logistic regression modeling.

Univariate logistic regression analyses were performed first, using gait parameters as independent variables and functional group (high vs. low) as the binary outcome (0/1). Variables with P < 0.1 in univariate analysis were included in a multivariable logistic regression model. Odds ratios (ORs), 95% confidence intervals (CIs), and *p*-values were calculated for each predictor.

Model performance evaluation: Model performance was assessed using several methods. The area under the receiver operating characteristic (ROC) curve (AUC) was calculated for both training and validation datasets using the pROC package in R, with 95% CIs reported to evaluate discriminative ability. Calibration curves were generated using the rms package to compare predicted probabilities with observed outcomes and assess model calibration. Classification performance metrics, including accuracy, sensitivity (recall), and specificity, were calculated with 95% CIs for both the training and validation sets.

Decision curve analysis (DCA) was performed to evaluate the clinical utility of the model across a range of probability thresholds by quantifying net benefit. Finally, a nomogram was constructed using the final multivariable logistic regression model via the rms package in R to provide individualized predictions of postoperative knee function recovery.

Results

Pre- and postoperative changes in gait parameters

We analyzed gait performance in 186 individuals (95 men, 91 women; mean age 35.68 ± 5.04 years; BMI 25.16 ± 2.83) undergoing autologous hamstring tendon ACL reconstruc-

Table 1. Pre- and postoperative gait parameters and knee function scores

Variables	Preoperative	Postoperative	t/z value	*p* value
Step Length	99.02 ± 20.07	105.17 ± 20.50	3.14	0.002
Step Height	19.87 ± 5.03	21.92 ± 4.84	4.29	< .0001
Impact Force	1.21 ± 0.18	1.30 ± 0.21	4.34	< .0001
Stance Phase	0.64 ± 0.03	0.66 ± 0.03	7.52	< .0001
Contact Phase	0.15 ± 0.02	0.16 ± 0.02	4.62	< .0001
Flat Phase	0.42 ± 0.05	0.45 ± 0.05	5.79	< .0001
Propulsion Phase	0.36 ± 0.03	0.35 ± 0.03	4.68	< .0001
Swing Phase	0.36 ± 0.02	0.35 ± 0.02	3.27	0.0003
Strike Angle	24.69 ± 2.28	25.62 ± 2.02	4.23	< .0001
Lift Angle	69.82 ± 5.36	71.65 ± 5.34	3.16	0.002
Max Swing Speed	4.44 ± 0.51	4.79 ± 0.50	6.8	< .0001
Lysholm Score	57.58 ± 15.54	95.00 ± 11.03	26.77	< .0001
IKDC Score	59.33 ± 14.42	87.83 ± 9.45	23.31	< .0001
Tegner Score	4.55 ± 1.46	3.40 ± 1.48	7.41	< .0001

IKDC, International Knee Documentation Committee.

tion. Quantitative gait assessments performed before and after surgery revealed consistent postoperative improvements across multiple domains of gait function and knee biomechanics.

Postoperative step length increased significantly (from 99.02 ± 20.07 cm to 105.17 ± 20.50 cm; $t = -3.14$, $P = 0.002$), accompanied by an elevation in step height (from 19.87 ± 5.03 cm to 21.92 ± 4.84 cm; $t = -4.29$, $P < 0.001$). Impact force during gait also increased (from 1.21 ± 0.18 G to 1.30 ± 0.21 G; $t = -4.34$, $P < 0.001$), indicating improved dynamic loading capacity. A modest yet statistically significant prolongation of the stance phase was observed (0.64 ± 0.03 vs. 0.66 ± 0.03; $t = -7.52$, $P < 0.001$), reflecting enhanced joint stability and load-bearing control. Furthermore, postoperative alterations in the contact phase, flat phase, strike angle, lift angle, and maximum swing speed all demonstrated significant increases ($P < 0.001$), while the propulsion and swing phases were reduced ($P < 0.001$), collectively suggesting improved coordination and neuromuscular control during gait cycles (**Table 1**; **Figure 1**).

Pre- and postoperative changes in knee function scores

The knee function scores (**Table 1**) showed significant improvement. The Lysholm score increased from 57.58 ± 15.54 preoperatively to 95.00 ± 11.03 postoperatively ($t = -26.77$, $P < 0.001$), indicating a substantial enhancement in knee capability. Similarly, the IKDC score increased from 59.33 ± 14.42 preoperatively to 87.83 ± 9.45 postoperatively ($t = -23.31$, $P < 0.001$), reflecting improvements in knee stability, activity, and function. Notably, the Tegner score reduced from 4.55 ± 1.46 before surgery to 3.40 ± 1.48 after surgery ($t = 7.41$, $P < 0.001$), suggesting a reduction in physical activity levels, despite the improvement in knee function.

Correlation between gait parameters and knee function scores

Correlation analysis was performed to assess the association between gait parameters and knee function scores (Lysholm, IKDC, Tegner) (**Figure 2**). Step length showed a positive association with both Lysholm ($r = 0.34$, $P < 0.001$) and IKDC ($r = 0.24$, $P < 0.05$) scores, indicating that increased step length contributed to knee function recovery. Similarly, step height correlated positively with Lysholm ($r = 0.22$, $P < 0.05$) and IKDC ($r = 0.11$, $P < 0.05$) scores, suggesting that improved vertical gait dynamics reflect better functional capacity.

Conversely, impact force exhibited a negative relationship with the IKDC score ($r = -0.20$, $P < 0.05$), suggesting that lower impact forces helped reduce knee joint load and promoted functional recovery. Additionally, the stance phase showed a significant negative correlation with the Lysholm score ($r = -0.22$, $P < 0.05$), while the contact phase was positively associated with the IKDC score ($r = 0.22$, $P < 0.05$) and negatively associated with the Tegner score ($r = -0.23$, $P < 0.05$). These results suggest that step length and step height are closely related to knee function recovery, while impact force, stance phase, and contact phase are associated with knee stability and functional recovery.

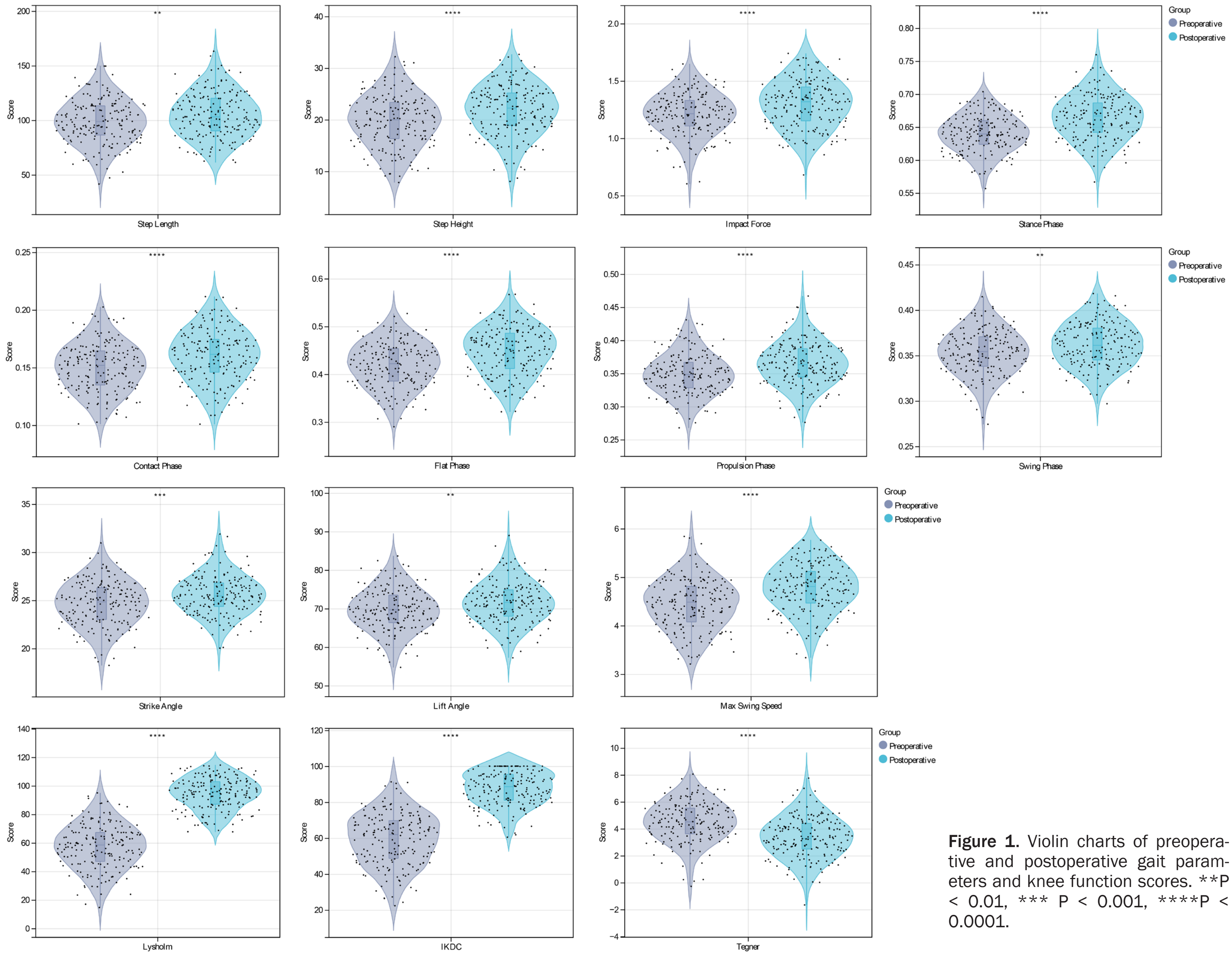

Figure 1. Violin charts of preoperative and postoperative gait parameters and knee function scores. **P < 0.01, *** P < 0.001, ****P < 0.0001.

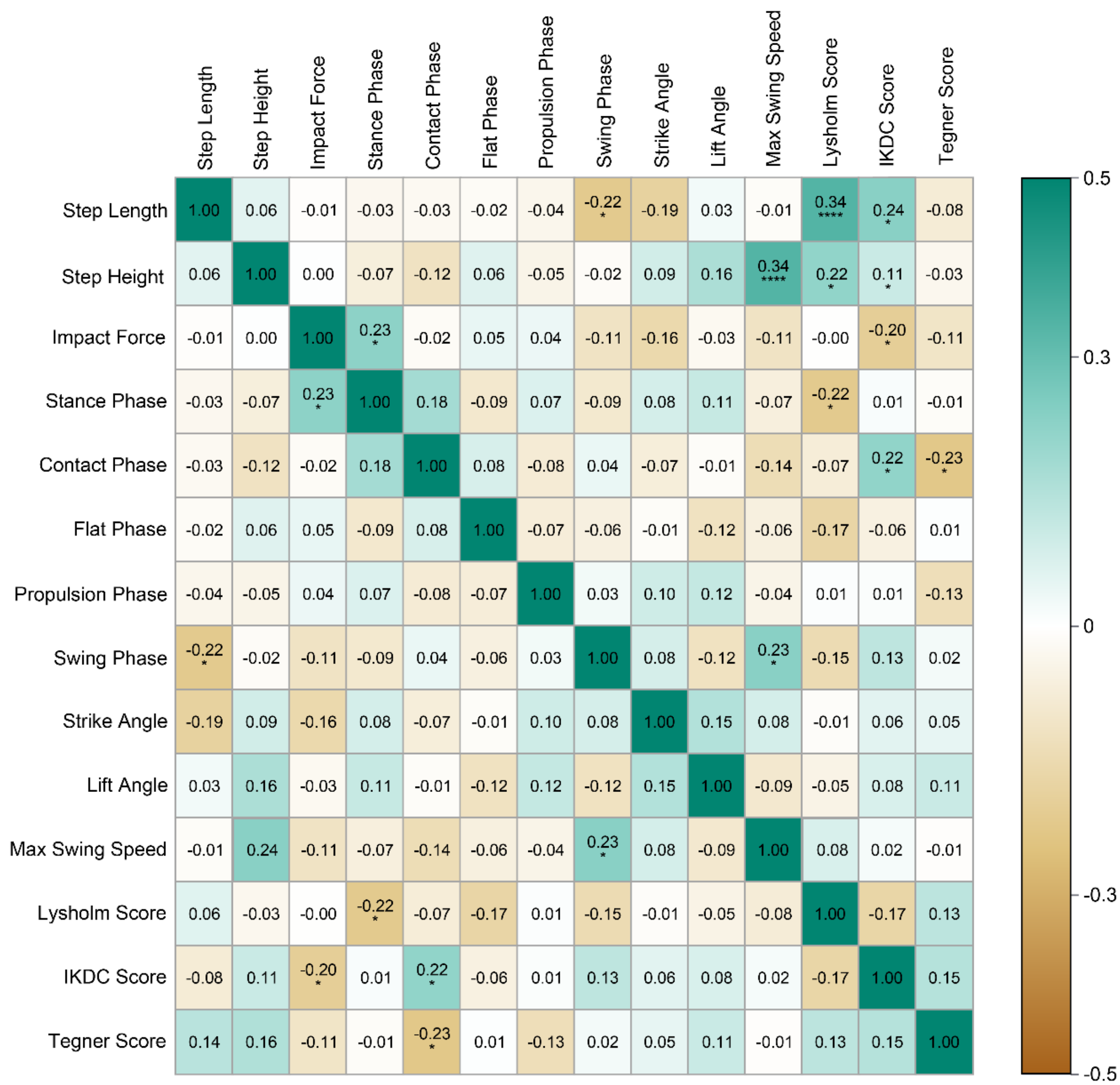

Figure 2. Pearson correlation analysis between gait parameters and knee functional scores.

Multiple linear regression analysis of the impact of gait parameters on knee function

To further elucidate the independent contributions of gait characteristics to postoperative knee function, multiple linear regression analyses were conducted using Lysholm, IKDC, and Tegner scores as dependent variables. Step length and lift angle were significant predictors of both Lysholm ($\beta = 0.25$, $\beta = 0.09$, $P < 0.05$) and IKDC scores ($\beta = 0.32$, $P < 0.01$) (**Figure 3A** and **3C**), while the flat phase and impact force were negatively correlated with the Tegner score ($\beta = -4.71$, $\beta = -1.72$, $P < 0.05$) (**Figure 3E**). Residual analysis of the regression model indicated that the residuals were randomly distributed and independent of predicted values, confirming the validity and fit of the regression model (**Figure 3B**, **3D**, and **3F**).

Construction and evaluation of the prediction model

Univariate and multivariate logistic regression analysis of gait parameters for predicting knee function scores: To assess the application of gait parameters in predicting knee function scores, we developed a prediction model based on various gait parameters (including step length, step height, impact force, etc.). In univariate analyses, several gait parameters - such as step length, impact force, stance phase,

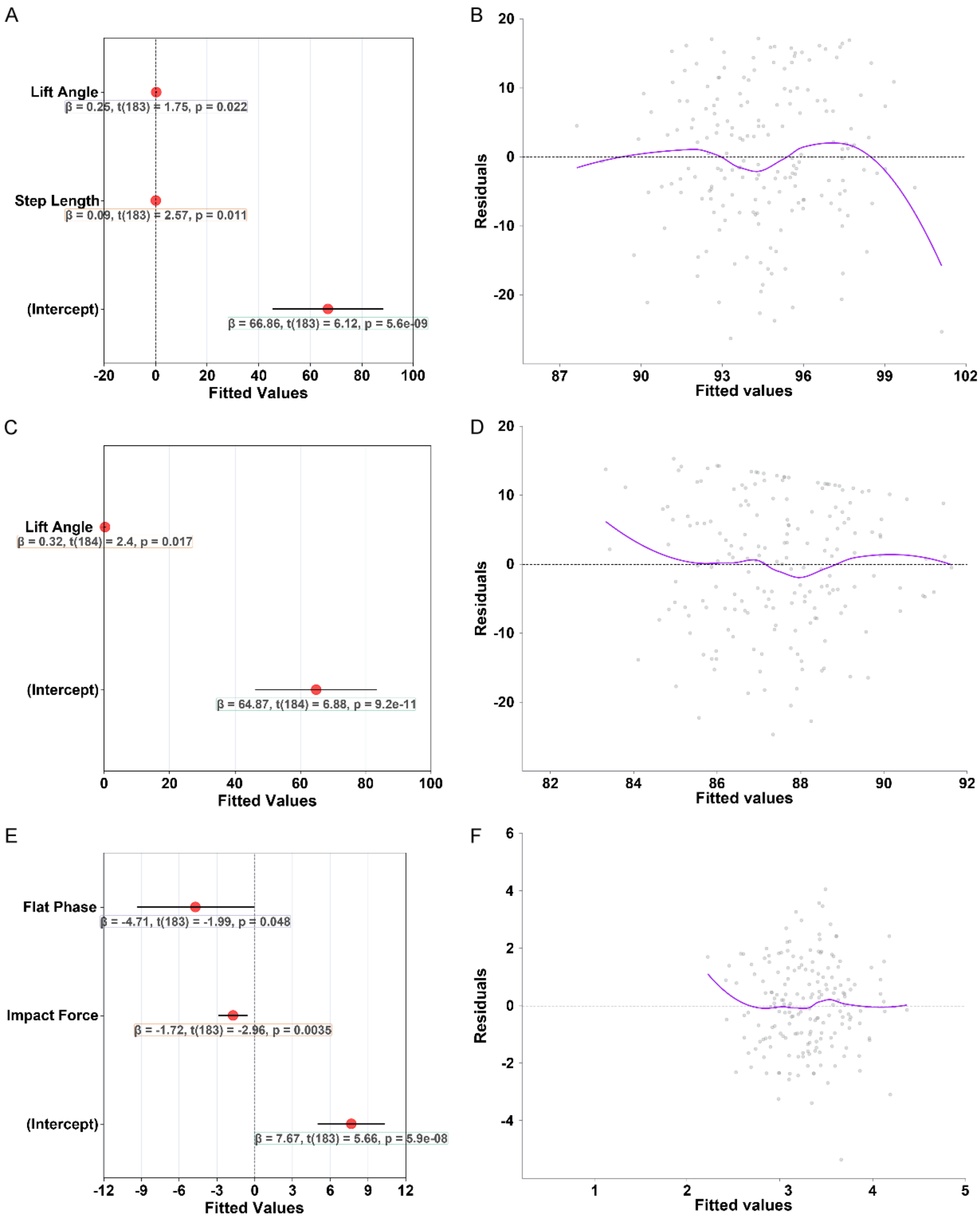

Figure 3. Multiple linear regression analysis. A and B: Regression model coefficient plots and residual plots for Lysholm scores. C and D: Regression model coefficient plot and residual plot of International Knee Documentation Committee (IKDC) score. E and F: Regression model coefficient plots and residual plots for Tegner scores.

contact phase, and propulsion phase - were significantly associated with knee function scores. Multivariate logistic regression revealed that step length remained an independent positive predictor of functional recovery (odds ratio [OR], 1.04; 95% confidence interval [CI], 1.02-1.06; P < 0.001), while impact force was inversely associated with favorable outcomes

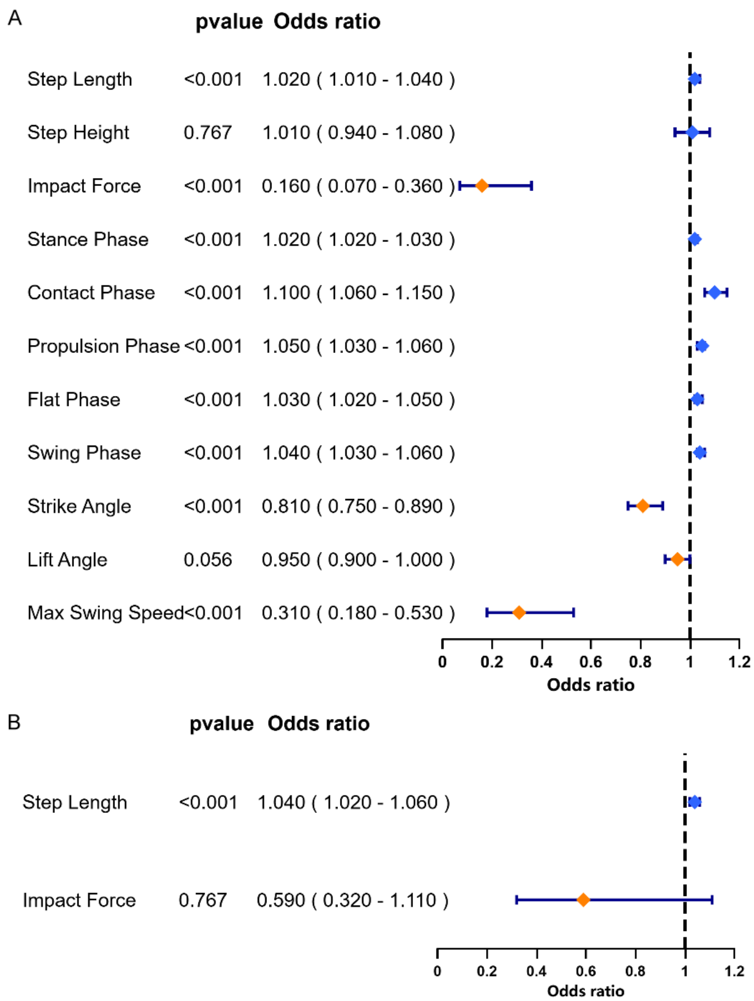

Figure 4. Univariate Logistic Regression (A) and Multivariate Logistic Regression (B) Forest Plots.

(OR, 0.59; 95% CI, 0.32-1.11; P = 0.045) (**Figure 4**). These results underscore longer step length and lower impact force as key biomechanical indicators of postoperative knee function recovery, supporting their inclusion in predictive models for clinical decision-making.

ROC curve analysis and model performance: ROC curve analysis was performed to evaluate the performance of the prediction model. The model achieved an AUC value of 0.73 (95% CI: 0.66-0.79) in the training set and 0.66 in the testing set, demonstrating good predictive accuracy (**Figure 5**). This indicates that the gait-based prediction model has strong discriminative power and can accurately forecast knee function scores. Further calibration analysis was performed by fitting calibration plots for both the training and validation groups (**Figure 6**). The calibration curves closely approximated the ideal 45-degree line, indicating that the model provides a good fit to actual outcomes.

Confusion matrix and model classification performance: To assess the discriminative capacity of the model, confusion matrix analysis was conducted for both training and validation datasets (**Figure 5**). In the training cohort, the model achieved an overall accuracy of 0.70 (95% CI: 0.64-0.75), with a sensitivity of 0.71 (95% CI: 0.62-0.81) and specificity of 0.69 (95% CI: 0.62-0.76). In the independent validation set, accuracy reached 0.65 (95% CI: 0.56-0.74), with sensitivity and specificity of 0.53 (95% CI: 0.37-0.69) and 0.72 (95% CI: 0.61-0.82), respectively (**Figure 6**). These results demonstrate that the model maintains robust predictive performance and generalizability, effectively distinguishing between individuals with favorable and suboptimal knee function recovery. To further assess clinical applicability, DCA was performed to quantify the net clinical benefit of the model across a range of threshold probabilities (**Figure 7**). The model consistently demonstrated superior net benefit compared to default strategies (i.e., treat-all or treat-none), suggesting that incorporating gait parameters meaningfully improves clinical decision-making in evaluating postoperative knee function.

Clinical net benefit and individual risk assessment: To facilitate clinical translation and enhance individualized patient assessment, a nomogram was constructed based on the final multivariate logistic regression model (**Figure 8**). The nomogram integrates key gait parameters - including step length and impact force - assigning weights proportional to their regression coefficients. Clinicians can input patient-specific gait values to derive a total score, which corresponds to the predicted prob-

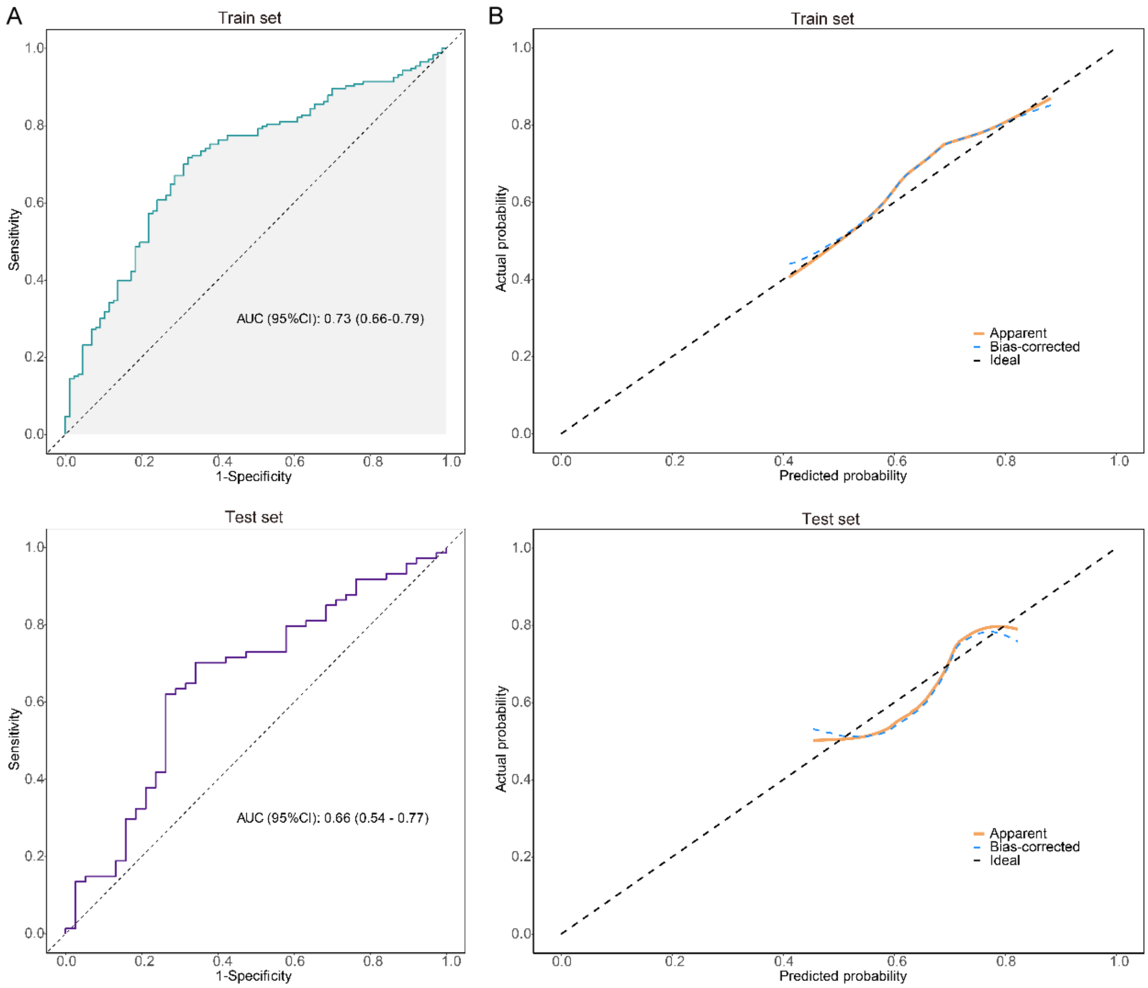

Figure 5. Model performance. A. Receiver Operating Characteristic (ROC) Curves and Area Under the Curve (AUC) Values for the Model in the Train Set (above) and Test Set (below). B. Calibration Curves for the Model in the Train Set (above) and Test Set (below). The curves should closely align with the ideal 45-degree line, reflecting the model's good calibration.

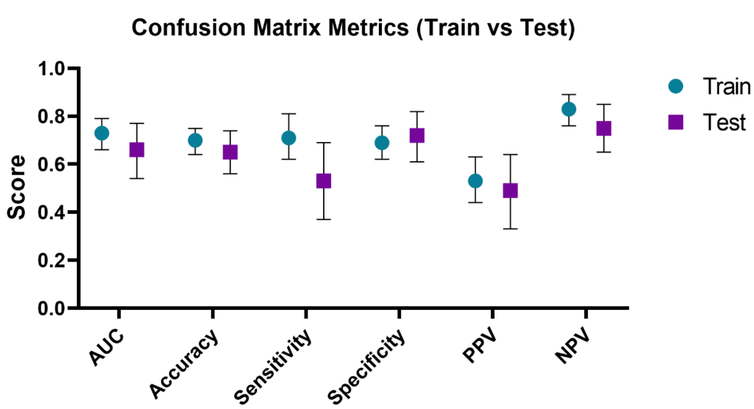

Figure 6. Confusion matrices for the model in the train and test sets. The model's performance is assessed on the basis of precision, sensitivity, and specificity, and other classification metrics. PPV, Positive Predictive Value. NPV, Negative Predictive Value.

ability of functional recovery. This graphical tool enables rapid and intuitive estimation of individual risk, supporting the formulation of personalized rehabilitation strategies. By providing a practical interface for model application, the nomogram bridges the gap between biomechanical analysis and real-world clinical decision-making.

Discussion

In this study, we systematically examined alterations in gait

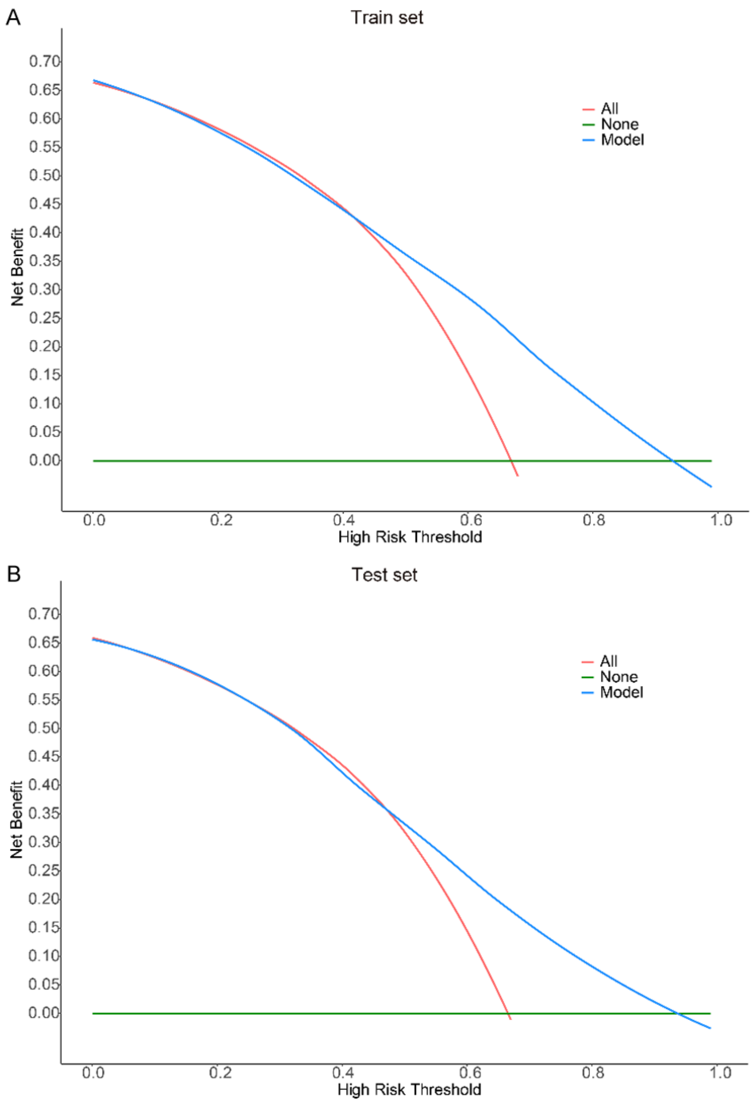

Figure 7. Decision Curve Analysis (DCA) for the Model in the Train Set (A) and Test Set (B). DCA evaluates the model's net benefit at various threshold levels, reflecting its clinical value.

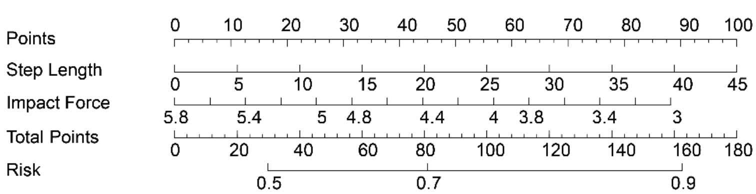

Figure 8. Nomogram for the model. The nomogram calculates the risk score based on the model's predicted risk values for individualized risk assessment.

parameters following ACL reconstruction with autologous hamstring tendon grafts and explored their associations with postoperative knee function recovery. Our findings revealed significant postoperative improvements in spatiotemporal gait parameters, particularly in step length and impact force, which showed strong correlations with established knee function metrics, including the Lysholm, IKDC, and Tegner scores. Moreover, multivariate regression analyses and predictive modeling demonstrated that select gait parameters serve as independent predictors of functional outcomes, highlighting their potential value in postoperative assessment and rehabilitation planning.

Arthroscopic ACL reconstruction using autologous hamstring tendon grafts remains the gold standard for treating ACL ruptures, offering reliable long-term outcomes in terms of joint stability and reintegration into physical activity [12]. However, surgical success does not guarantee complete recovery; the rehabilitation trajectory plays a pivotal role in determining long-term performance and quality of life. Early initiation of structured functional training has been shown to expedite return to sport and reduce the risk of reinjury [13]. Gait analysis, as a non-invasive and quantitative tool, provides objective metrics to evaluate biomechanical performance and functional readiness post-surgery. Previous research by Decker et al. emphasized the value of individualized gait retraining in enhancing neuromuscular control and accelerating functional gains [14]. Consistent with these findings, our study underscores the clinical utility of incorporating gait assessments into postoperative care protocols. Specifically, integrating real-time gait metrics into rehabilitation decision-making allows for the formulation of precision-based, personalized training programs, optimizing functional recovery and potentially mitigating long-term disability.

Following ACL injury, the common “quadriceps avoidance gait” leads to reduced quadriceps activity, resulting in compensatory gait changes [15]. This maladaptive strategy impacts multiple aspects of gait, including reductions in step length and height, as well as modifications in impact force and stance phase duration. Previous studies have demonstrated that ACL rupture not only compromises joint stability but also disrupts kinematic patterns during ambulation. Specifically, significant reductions in external knee rotation during the swing phase and tibial internal rotation during the stance phase have been reported [16]. These alterations highlight the necessity of precise, quantitative gait assessment under dynamic weight-bearing conditions, especially for early detection and correction of biomechanical abnormalities. Such measurements provide critical insights into neuromuscular deficits and can inform targeted rehabilitation strategies [17]. In line with these findings, our results revealed significant postoperative improvements in key gait parameters, including step length, step height, impact force, stance phase, and maximal swing speed, reflecting progressive restoration of joint stability and neuromuscular coordination. Notably, the observed reductions in the propulsion and swing phases may reflect enhanced efficiency in knee flexion-extension mechanics and improved gait continuity, thereby reducing reliance on compensatory strategies. These findings are consistent with the work of Knoll et al., who reported progressive gait normalization as early as three months postoperatively, although residual compensatory mechanisms may persist in some patients [18, 19].

During postoperative recovery, restoration of muscle strength and proprioceptive function is often incomplete, which may explain the persistence of abnormal gait patterns despite surgical stabilization of the joint [20]. A prospective observational study involving 143 football players at nine months post - ACL reconstruction revealed persistent gait deviations, including insufficient ankle dorsiflexion in 65% of participants and inadequate knee extension in 59.4% [21]. These findings align with our results and emphasize that normalization of gait mechanics is a gradual process requiring extended rehabilitation. Furthermore, accumulating evidence underscores the intricate relationship between gait parameters and underlying joint biomechanics. Notably, gait variability has been shown to correlate with changes in femoral cartilage composition. Specifically, reduced variability in sagittal plane kinematics is associated with an elevated risk of postoperative cartilage degeneration, suggesting that rigid or maladaptive gait patterns may impose detrimental mechanical loads on articular cartilage [22]. This indicates that gait abnormalities could serve as an early indicator of joint degeneration, supporting our hypothesis that gait parameters can predict functional recovery.

Gait analysis not only reveals kinematic and mechanical changes in the knee joint following ACL injury but also provides quantitative indicators for postoperative functional recovery [23]. In this study, the notable direct association between step length and both the Lysholm and IKDC scores further emphasizes the importance of step length in knee function recovery. An increase in step length typically reflects improved gait fluidity and stability, consistent with findings by [24], which reported a strong relationship between step length and functional recovery in ACL reconstruction patients. In another study, researchers compared knee biomechanics and muscle activity 2 years after ACL repair and reconstruction. They found that, compared to healthy controls, ACL reconstruction patients exhibited reduced knee flexion angles and moments during walking, reflecting adaptive gait changes post-surgery. The study also noted that these gait alterations were likely due to adjustments in neuromuscular control strategies, rather than solely structural limitations [25]. Furthermore, the positive correlation between step height and both Lysholm and IKDC scores suggests that improvements in knee extension are crucial for functional recovery. Increased step height reflects the restoration of knee extension range and motor control, which may be closely linked to soft tissue repair and muscle strength restoration. The inverse relationship between impact force and IKDC scores indicates that lower impact force may help reduce the burden on the knee joint, facilitating functional recovery. Previous studies have indicated that reduced impact force correlates with decreased knee joint load and enhanced joint stability [26]. Higher impact forces tend to increase knee joint stress, which may negatively affect the recovery of knee cartilage and other joint structures over time [27]. Therefore, reducing impact force should be an important goal in knee joint rehabilitation.

Research has also explored the relationship between gait variability and neuromuscular control, demonstrating that reduced gait variability is associated with joint cartilage changes. This suggests that gait variability may reflect the neuromuscular system's ability to regulate joint stability. Excessively low gait variability could indicate a decline in the flexibility of neuromuscular control systems, impairing the joint's ability to adapt to varying load environments [22]. The role of inflammatory factors, such as IL-6, may also contribute to the mechanism of gait abnormalities. A study found that IL-6 could induce the production of periostin in ACL remnants, which may contribute to post-traumatic osteoarthritis [28]. Inflammation-induced soft tissue changes and pain could affect neuromuscular control, leading to gait abnormalities. This provides a molecular-level explanation for joint degeneration and functional impairment following ACL injury.

Through multivariate regression analysis, this study further evaluated the independent predictive effect of gait parameters on knee function scores. Step length and lift angle were significant predictors of Lysholm and IKDC scores, while flat phase and impact force were negatively correlated with the Tegner score. The increase in step length and lift angle generally reflects better knee movement control and a higher level of functional recovery. The negative correlation between flat phase and impact force suggests that a longer stance phase and lower impact force may help improve knee stability, promoting functional recovery [29, 30]. These findings support the importance of gait analysis in knee joint rehabilitation and provide a theoretical basis for optimizing future rehabilitation strategies.

The predictive model reinforced the significance of gait parameters in assessing knee joint function. Using univariate and multivariate logistic regression, we developed a model to predict knee function scores based on gait parameters. The model demonstrated good predictive performance, with AUC values of 0.73 (95% CI: 0.66-0.79) in the training set and 0.66 (95% CI: 0.54-0.77) in the testing set. These results underscore the potential of gait parameters in predicting knee recovery, particularly in clinical settings where they reflect rehabilitation progress. DCA further highlighted the model's superior clinical net benefit over conventional assessments at various thresholds. This underscores the model's predictive power and clinical applicability, supporting the development of personalized rehabilitation plans. Recent attention has focused on the clinical use of gait analysis in knee rehabilitation [31, 32], and our model, especially in individualized risk assessment via nomograms, offers promising insights for precision therapy.

This study presents three key innovations: (1) the systematic use of wearable smart gait analysis technology (Sennotech Insole X 1.0) to monitor gait post-ACL reconstruction and quantify its correlation with knee function scores; (2) the development of a predictive model based on multidimensional gait parameters, enabling objective, physiological assessment of postoperative knee recovery; and (3) the clinical translation of this model into individualized rehabilitation decision-making through nomograms and DCA, addressing the gap in dynamic postoperative assessment and prognostic prediction.

Despite its contributions, the study has limitations. It is a single-center, retrospective study with potential patient selection biases, and future large-scale, multicenter prospective studies are needed to validate the findings. Additionally, factors such as activity level, psychological state, muscle strength, and ligament function were not considered, but they may influence recovery. Future research should integrate these variables to more comprehensively understand the relationship between gait and knee recovery. Furthermore, optimizing rehabilitation strategies, particularly in the early stages, through gait analysis remains a critical area for future investigation. Understanding how changes in gait parameters relate to muscle strength and neural control will inform more personalized, evidence-based rehabilitation plans.

In conclusion, this study analyzed gait parameters in patients following autologous hamstring ACL reconstruction and found significant improvements in both gait and knee joint performance postoperatively. Key gait parameter changes, such as step length, step height, impact force, and stance phase, reflect the gradual recovery of knee joint function, with notable improvements in gait coordination and stability. Increases in step length and step height were significantly correlated with knee function recovery, emphasizing their importance in knee rehabilitation. Furthermore, lower impact force and appropriate stance phases play critical roles in knee stability and contribute to recovery of mobility. Multivariate regression analysis revealed that step length is a significant independent predictor of knee function recovery, while impact force negatively correlates with knee function, providing new clinical evaluation indicators. The prediction model based on gait parameters demonstrated excellent performance in both the training and validation sets, showcasing its potential clinical application value in evaluating knee function recovery. Additionally, the construction of an individualized risk assessment tool (nomogram) based on gait parameters enables the formulation of more accurate rehabilitation treatment plans, enhancing personalized treatment effectiveness. This study provides new insights and methods for post-ACL reconstruction rehabilitation assessment and prediction, further advancing the clinical use of gait analysis in knee joint function recovery.

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Disclosure of conflict of interest

None.

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