

## Original Article

# Arthrogenic Muscle Inhibition: A Study on the Correlation Between Neuromuscular Dysfunction and Mobility limitations Following Cruciate Ligament Reconstruction Surgery

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## Abstract

**Objectives:** To explore arthrogenic muscle inhibition (AMI)'s impact on mobility after anterior/posterior cruciate ligament (ACL/PCL) reconstruction, identify early predictors of postoperative stiffness, and inform clinical rehabilitation. **Methods:** In this prospective cohort study, 146 ACL/PCL reconstruction patients were split into stiff (passive flexion <120° and extension deficit >5° at 12 weeks [T2]) and non-stiff groups. Preoperative data, knee function (ROM, gait, muscle strength, proprioception) and AMI indicators (quadriceps VA, H/M ratio) were assessed at 4 weeks (T1) and T2. Boruta, multivariate logistic, and multiple linear regression analyzed predictors. **Results:** The stiff group had longer injury-to-surgery intervals, higher patellar tendon use, worse ROM/gait/strength/AMI metrics at T1-T2. The four most important predictors for T2 stiffness were T1 passive flexion, extension deficit, H/M ratio, and VA; T1 H/M (OR = 4.82) and extension deficit (OR = 3.85) were major risks. T2 H/M correlated negatively with passive flexion ( $\beta = -0.73$ ), T1 VA with extension deficit ( $\beta = -0.38$ ). The logistic model demonstrated good predictive performance (optimism-corrected C-index = 0.890). **Conclusions:** AMI associates with post-ACL/PCL mobility issues. Four early indicators predict T2 stiffness, with H/M impacting flexion and VA affecting extension, guiding personalized rehabilitation.

**Keywords:** Arthrogenic Muscle Inhibition, Knee Ligament Reconstruction, Neuromuscular Dysfunction, Predictors, Range of Motion

## Introduction

Injuries to the knee joint cruciate ligaments including the anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) are common musculoskeletal injuries, with arthroscopic ligament reconstruction serving as the primary surgical treatment approach<sup>1</sup>. It is noteworthy that despite significant improvements in surgical techniques leading to substantial recovery for most patients, a portion

still face long-term challenges in functional restoration post-surgery. These challenges primarily manifest as limited knee joint mobility, suboptimal muscle strength recovery, and gait abnormalities<sup>2,3</sup>. Traditionally, these issues have been attributed to peripheral factors such as postoperative pain, joint swelling, muscle atrophy, or poor rehabilitation compliance. Patients undergoing ACL reconstruction with different grafts exhibit significant deficits in isokinetic muscle strength within the first year postoperatively, with no significant differences in electromyographic ratios between graft types<sup>4</sup>. However, growing evidence suggests that changes in peripheral structures alone may not fully account for the clinical challenges encountered in functional recovery, which may involve more complex central nervous system regulatory mechanisms. For instance, studies have reported that patients undergoing ACL reconstruction experience difficulties with proprioceptive reorganization and postural control. This not only affects their ability to

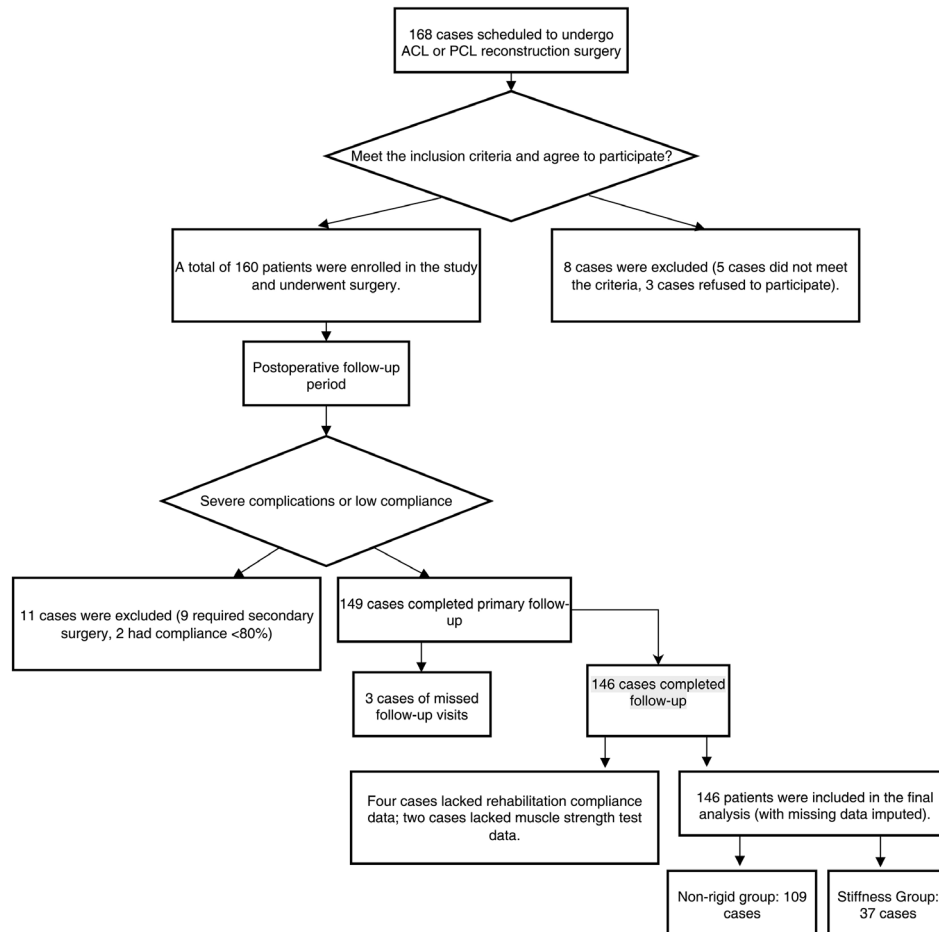
The authors have no conflict of interest.

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**Figure 1.** Flowchart of Study Participants.

adapt to balance conditions but may also further limit their motor performance and functional recovery<sup>5</sup>. Furthermore, postoperative muscle strength asymmetry and inadequate neuromuscular control are significant factors affecting patients' functional recovery<sup>6,7</sup>.

In recent years, arthrogenic muscle inhibition (AMI) has garnered significant attention as a key neurophysiological phenomenon. AMI refers to a reflexive inhibitory state triggered by abnormal afferent signals from joint proprioceptors, primarily affecting the function of muscles surrounding the joint (particularly the quadriceps). AMI refers to a reflexive inhibitory condition affecting periarticular muscles (particularly the quadriceps), originating from abnormal afferent input from joint proprioceptors<sup>8</sup>. Its core mechanism involves dysfunction in afferent-efferent pathways<sup>9</sup>. Contemporary understanding frames AMI as a complex, multi-level neuromotor dysregulation spanning spinal, brainstem, and even cortical pathways. Modern research suggests that AMI can be understood as a complex

neuromuscular dysregulation spanning the spinal cord, brainstem, and even cortical levels. Following joint injury, released inflammatory mediators and abnormal discharges from mechanoreceptors inhibit the alpha motor neuron pool via Ia inhibitory interneurons, thereby impairing voluntary muscle contraction capacity. This inhibition not only leads to muscle atrophy and decreased strength but also disrupts proprioception and motor control, ultimately hindering functional recovery.

Although AMI is considered a potential key driver of postoperative ligament dysfunction, several questions remain unresolved: First, the specific evolution of AMI across different recovery phases after cruciate ligament reconstruction and its temporal relationship with loss of ROM remain unclear. In particular, a quantitative, prospective characterization of AMI in the early postoperative phase (e.g., within the first 4-6 weeks), a critical window for rehabilitation, is lacking. Second, beyond muscle strength decline, whether and how AMI affects gait symmetry and motor control capabilities requires further quantitative

investigation. More importantly, there is a lack of evidence from prospective studies regarding whether early AMI indicators – notably, the H-reflex (assessing spinal-level excitability) and voluntary activation (VA, assessing central drive) – hold predictive value for the development of stiffness in the mid-to-long term. A simultaneous assessment of these complementary neurophysiological measures could provide a more holistic view of the mechanisms underlying AMI-related mobility limitations.

Therefore, this study aims to investigate the correlation between AMI and neuromuscular dysfunction and restricted range of motion following knee ligament reconstruction through a prospective cohort design. The study comprehensively employs neurophysiological techniques (H/M ratio), interpolation-based twitch testing, isokinetic muscle strength testing, gait analysis, and joint range-of-motion measurements to elucidate the mechanism of AMI in postoperative dysfunction from both neuromuscular control and motor function dimensions. Additionally, this study plans to preliminarily explore and construct predictive models for stiffness, providing theoretical and empirical support for developing targeted neuromuscular activation strategies for high-risk patients in the clinical early phase.

## Materials and Methods

### Participants

This study employed a prospective cohort design, enrolling patients undergoing ACL or PCL reconstruction at The Second Hospital of Longyan. Patients scheduled for ACL or PCL surgery were consecutively recruited at The Second Hospital of Longyan from June 2023 to June 2025.

Inclusion criteria: ① Age 18–45 years; ② Diagnosis of ACL or PCL rupture confirmed by MRI and clinical examination (Lachman test, anterior/posterior drawer test, pivotshift test, etc.), with planned arthroscopic ligament reconstruction surgery; ③ No other major ligament injuries (e.g., medial collateral ligament, lateral collateral ligament of grade III or higher); ④ Body mass index (BMI) between 18.5 and 28.0 kg/m<sup>2</sup> (excessive obesity affects surgical difficulty and recovery outcomes); ⑤ Informed consent and voluntary participation.

Exclusion criteria: ① History of major surgery on the same knee (e.g., ACL/PCL reconstruction, subtotal meniscectomy); ② Severe knee cartilage damage (Outerbridge grade  $\geq$  III); ③ Presence of neurological disorders affecting neuromuscular function (e.g., stroke, peripheral neuropathy), diabetic peripheral neuropathy, or rheumatic/immune-mediated diseases; ④ Contraindications to transcranial magnetic stimulation or transcutaneous electrical nerve stimulation; ⑤ Severe postoperative complications such as deep vein thrombosis or infection.

All patients underwent ligament reconstruction surgery performed by the same team of surgeons using standardized surgical techniques, followed by standardized rehabilitation

protocols established by The Second Hospital of Longyan. Patients experiencing severe postoperative complications requiring secondary surgery, those failing to adhere to the standardized rehabilitation protocol (compliance < 80%), or those lost to follow-up were excluded. For details, see the study participant flowchart (Figure 1). This study was approved by the Ethics Committee of The Second Hospital of Longyan. All research subjects signed informed consent forms.

### Clinical data collection and assessment

Demographic characteristics, injury history, and surgical information were collected during the preoperative baseline period. Core demographic information included age (years), sex, height (cm), weight (kg), and BMI (kg/m<sup>2</sup>); dominant leg, affected side (left knee/right knee), and injury-to-surgery intervals (days). Surgical information included injured ligament (ACL or PCL), graft tendon (hamstring/patellar tendon, HT/PT), and intraoperative concomitant injuries (meniscus, cartilage).

At 12 weeks postoperatively (T2), patients were grouped based on knee range of motion. Stiffness was defined as meeting both criteria: ① maximum passive flexion angle < 120° and ② passive extension deficit angle > 5°. Patients not meeting these criteria were assigned to the non-stiffness group. This definition references prior consensus on postoperative knee functional recovery, where 120° flexion represents a functional threshold for daily activities (e.g., stair climbing), and an extension deficit >5° has been demonstrated to significantly impair gait mechanics [10]. Core functional and mechanism assessment indicators include the following: 1) Knee joint function evaluation, including ROM, gait, isokinetic muscle strength, and proprioception; 2) Assessment of AMI mechanisms, including H-reflex excitability (H/M ratio) and VA of quadriceps.

All assessments were conducted by two uniformly trained rehabilitation physicians who were unaware of the group assignments. All equipment was calibrated prior to assessment. Patients received standardized instructions and underwent 1-2 practice trials to ensure comprehension of test requirements. After two assessors evaluated the same metric, the intraclass correlation coefficient (ICC) was calculated within each group to assess inter-rater reliability. When ICC > 0.9, the mean value was taken as the final result to minimize measurement bias.

### Knee joint function and ROM assessment

Assessment of mobility limitations included ROM measurement and muscle strength evaluation. At T1 and T2 postoperatively, a long-arm goniometer was used to measure the patient's maximum passive knee flexion angle and passive extension deficit angle. All measurements were centered on the lateral femoral condyle. The fixed arm was parallel to the femoral long axis (greater trochanter

to lateral condyle), and the movable arm was parallel to the tibial long axis (lateral condyle to lateral malleolus). Measurements were averaged from three trials.

**Gait analysis:** A portable pressure-sensing walkway (GAITrite Platinum, 8m) was employed. At T2, patients walked at their self-selected comfortable pace, with at least 20 valid gait cycles recorded. Analyzed parameters included gait speed (m/s), step length asymmetry ratio (affected side step length/unaffected side step length), and single-leg stance phase asymmetry ratio (affected side stance time/unaffected side stance time). Gait analysis was conducted only at T2 to compare functional outcomes between the two patient groups at that time point. This single-time-point design focused on cross-sectional comparisons of mid-term functional recovery but was not suitable for assessing longitudinal changes in gait parameters.

**Isokinetic muscle strength:** At T2, knee extension peak torque (Nm) was measured at an angular velocity of 60°/s using an isokinetic muscle strength testing system (Biodex System 4 Pro). The limb symmetry index (LSI) for the affected and unaffected sides was calculated as follows:  $LSI = [\text{Peak torque (Nm) of affected side} / \text{Peak torque (Nm) of unaffected side}] \times 100\%$ .

**Proprioception** was assessed using the passive joint repositioning test. Patients were positioned supine with an eye mask to eliminate visual interference. The examiner passively positioned the affected knee at the target angle (30° flexion), held it for 3 seconds, then returned it to full extension. Patients were instructed to actively reposition the knee to the target angle. Absolute angular error (|target angle - actual angle|) was recorded using a calibrated long-arm goniometer (minimum resolution 1°). To minimize learning effects, the order of the three tests was randomized, and patients performed one submaximal practice session before the formal tests.

#### *Postoperative standardized rehabilitation protocol*

To ensure consistency in rehabilitation interventions, all enrolled patients strictly adhered to the standardized, protocolized rehabilitation program established by The Second Hospital of Longyan. This program was developed based on international consensus and clinical guidelines and was implemented by a consistent team of experienced rehabilitation therapists. The program was guided by a timeline and functional milestones rather than solely by time. However, to maintain consistency in study observations, all patients' rehabilitation progression assessment points coincided with the study follow-up points (T1, T2).

Rehabilitation therapy included in-hospital guidance (during postoperative hospitalization) and a post-discharge plan. After discharge, patients attended three therapist-guided training sessions weekly for the first 12 weeks, with home exercises documented. All supervised training was conducted by a dedicated team of therapists to ensure consistent and standardized protocols. Compliance rates < 80% was considered an exclusion criterion (as outlined in

the exclusion criteria) to ensure comparable rehabilitation intensity between patient groups.

#### *AMI assessment*

The evaluation of neuromuscular dysfunction included maximal VA and H/M ratio.

During the measurement, the patient is instructed to "assume a seated position with the hip joint flexed at 85° and the knee joint flexed at 90°." Subsequently, a professional measures the patient's maximum voluntary isometric contraction (MVIC) of the quadriceps femoris muscle using an isokinetic dynamometer (Biodex System 4 Pro). During the MVIC process, supramaximal electrical stimulation is applied to the patient's femoral nerve via a DS7A transcutaneous nerve stimulator. Stimulation parameters are as follows: biphasic pulses with 10-millisecond intervals, 0.1-millisecond pulse width, and current intensity ranging from 70 to 120 mA. Supramaximal intensity is confirmed by observing no further increase in the twitch force plateau during incremental stimulation. Staff recorded muscle tension in both superimposed and resting states. Each test was performed three times at 2-minute intervals; the formula for calculating the optimal muscle tension ratio (VA) was:  $VA = (1 - [\text{superimposed twitch force} / \text{resting twitch force}]) \times 100\%$ . Surface electromyography (EMG) monitoring of the biceps femoris muscle was simultaneously employed throughout testing to control for the influence of synergistic contractions on measurements. When significant synergistic contraction (EMG activity exceeding 15% of resting values) was observed, the test result was manually deemed invalid, requiring retesting after the patient achieved complete relaxation.

**H/M Ratio Measurement:** During measurement, a professional guides the patient into a prone position with a pillow placed beneath the ankle joint to maintain a neutral, relaxed posture. Subsequently, the recording electrode is placed on the gastrocnemius muscle belly, the reference electrode on the Achilles tendon, and the ground electrode on the mid-calf. Data is acquired using an amplifier with a bandpass filter (10-1000Hz). The tibial nerve at the popliteal fossa is then stimulated, starting at 5mA and incrementing by 1mA until stable H waves and maximum M waves are observed. Measurements are taken at 10-second intervals for each current intensity, repeated three times, and averaged. The calculation formula is:  $H/M \text{ ratio} = H_{max} / M_{max}$ .

#### **Statistical Analysis**

This study reviewed missing data for all key variables. For continuous variables with a small number of random missing parts, mean imputation method is used for processing; If the missing rate exceeds 5%, the subject's data in that group will be excluded from the corresponding analysis. All statistical analyses are based on available complete data. All statistical analyses were performed using the R software

**Table 1.** Patient Baseline Characteristics.

Characteristic	Groups		p-value
	Stiff group n = 37	Non-stiff group n = 109	
Age (years)	33 ± 7	31 ± 8	0.284
Sex (Male/Female)			
Female	16 (43.2%)	35 (32.1%)	0.22
Male	21 (56.8%)	74 (67.9%)	
BMI (kg/m <sup>2</sup> ) dominant leg	25.14 ± 2.03	24.83 ± 2.79	0.476
Left	4 (10.8%)	12 (11.0%)	
Right	33 (89.2%)	97 (89.0%)	
Affected side			
Left	14 (37.8%)	46 (42.2%)	0.641
Right	23 (62.2%)	63 (57.8%)	
Injury-to-surgery interval (days)	43 (30, 59)	35 (25, 47)	0.026
Injured ligament			
ACL	35 (94.6%)	101 (92.7%)	> 0.999
PCL	2 (5.4%)	8 (7.3%)	
Grafted tendon (HT/PT)			
HT	24 (64.9%)	88 (80.7%)	0.048
PT	13 (35.1%)	21 (19.3%)	
Meniscus injury	24 (64.9%)	58 (53.2%)	0.217
Cartilage injury (Outerbridge ≥ II)	15 (40.5%)	34 (31.2%)	0.298

*Normally distributed data are expressed as  $\bar{x} \pm s$ ; between-group comparisons were performed using independent samples t-tests. Categorical data are presented as n (%) and analyzed using chi-square tests. BMI: Body Mass Index; ACL: Anterior Cruciate Ligament; PCL: Posterior Cruciate Ligament; HT: Hamstring Tendon; PT: Patellar Tendon.*

(version 4.3.0), with a significance level set at  $\alpha = 0.05$ . The Boruta algorithm (R package 'Boruta') and multivariate logistic regression (glm function) were employed for feature selection and predictive modeling, respectively. A random seed of 123 was set prior to running the Boruta algorithm to ensure reproducibility. Prior to regression analysis, all continuous independent variables were standardized using Z-score normalization (mean = 0, standard deviation = 1) within the study sample. Continuous variables were first tested for normality using the Shapiro-Wilk test. Normally distributed quantitative data are presented as mean  $\pm$  standard deviation ( $\bar{x} \pm s$ ), with intergroup comparisons performed using independent samples t-tests. Non-normally distributed data are presented as median (interquartile range) [M(IQR)], with intergroup comparisons performed using the Mann-Whitney U test. Categorical variables were analyzed using chi-square tests or Fisher's exact tests.

To investigate correlations among variables, Spearman's rank correlation analysis was employed. The Benjamini-Hochberg method was used for multiple testing correction of P-values to control the false discovery rate.

To construct an early prediction model for postoperative stiffness, feature selection was first performed using the Boruta algorithm based on random forests. Algorithm parameters were set as follows: 500 trees in the random

forest (ntree), 500 maximum runs (maxRuns), and a random seed of 123. Feature importance was determined based on their "hit-or-miss" values. Ultimately, the top four most important predictive variables were selected from all baseline clinical data, T1-stage joint function, and AMI indicators for subsequent multifactorial model construction. Prior to building the multifactorial logistic regression model, all continuous independent variables were standardized (mean=0, standard deviation=1). Multicollinearity was excluded using variance inflation factor (VIF), with VIF < 5 as the cutoff criterion. Based on the selected variables, a multivariate logistic regression model was established to evaluate its comprehensive predictive effect on T2-stage stiffness occurrence.

Next, model performance was assessed. Discrimination was assessed using the area under the receiver operating characteristic curve (AUC) and its 95% confidence interval. Calibration was analyzed by plotting calibration curves via the Bootstrap method (1000 replicates). Clinical utility was evaluated by plotting decision curves. Additionally, internal validation was performed using 10-fold cross-validation, reporting the optimism-corrected Harrell C-index to comprehensively evaluate model robustness and predictive accuracy.

**Table 2.** Comparison of Knee Range of Motion, Joint Function, and AMI Indicators Between the Stiff (defined as passive flexion <120° AND extension deficit >5°) and Non-Stiff Groups at 4 and 12 Weeks Postoperatively.

	Characteristic	Groups		p-value
		Stiff group n = 37	Non-stiff group n = 109	
Knee Range of Motion	T1_Maximum passive flexion angle (°)	105 ± 9	111 ± 7	< 0.001
	T2_Maximum passive flexion angle (°)	112 (110, 114)	136 (134, 137)	< 0.001
	T1_extension deficit angle (°)	5.20 (3.72, 7.07)	4.05 (3.91, 4.23)	< 0.001
	T2_extension deficit angle (°)	6.82 (5.50, 7.67)	2.47 (2.33, 2.78)	< 0.001
Joint Function	T2_gait speed (m/s)	0.92 (0.79, 1.03)	1.14 (1.09, 1.22)	< 0.001
	T2_step length asymmetry ratio	0.93 ± 0.06	0.98 ± 0.05	< 0.001
	T2_LSI (extension)	80.0 (78.0, 82.0)	91.0 (88.0, 94.0)	< 0.001
	T2_Proprioception error (°)	5.32 ± 1.51	4.56 ± 1.65	0.006
AMI Indicators	T1_H/M ratio	0.59 ± 0.11	0.44 ± 0.10	< 0.001
	T2_H/M ratio	0.51 (0.43, 0.57)	0.34 (0.29, 0.39)	< 0.001
	T1_VA	78 ± 7	88 ± 7	< 0.001
	T2_VA	82 (78, 88)	94 (92, 96)	< 0.001

T1 = 4 weeks post-surgery, T2 = 12 weeks post-surgery; Normally distributed data are expressed as  $\bar{x} \pm s$ , with intergroup comparisons performed using independent samples *t*-tests; Non-normally distributed data are presented as M (IQR) and analyzed using the Mann-Whitney U test; H/M ratio = H-wave amplitude/M-wave amplitude ratio, VA = voluntary activation, LSI = limb symmetry index.

## Results

### Comparison of baseline characteristics

At T2, patients were categorized into a stiff group (n = 37) and a non-stiff group (n = 109) based on ROM criteria. As shown in Table 1, no statistically significant differences existed between groups in age, sex, BMI, dominant leg, affected side, ligament injury type, or concomitant meniscus/cartilage injury ( $P > 0.05$ ), indicating comparable baseline characteristics. However, the injury-to-surgery interval was significantly longer in the stiff group than in the non-stiff group (43 [30, 59] days vs. 35 [25, 47] days),  $P = 0.026$ . Additionally, the distribution of graft tendon types differed significantly between groups ( $P = 0.048$ ), with a higher proportion of PT grafts used in the stiff group (35.1%) compared to the non-stiff group (19.3%).

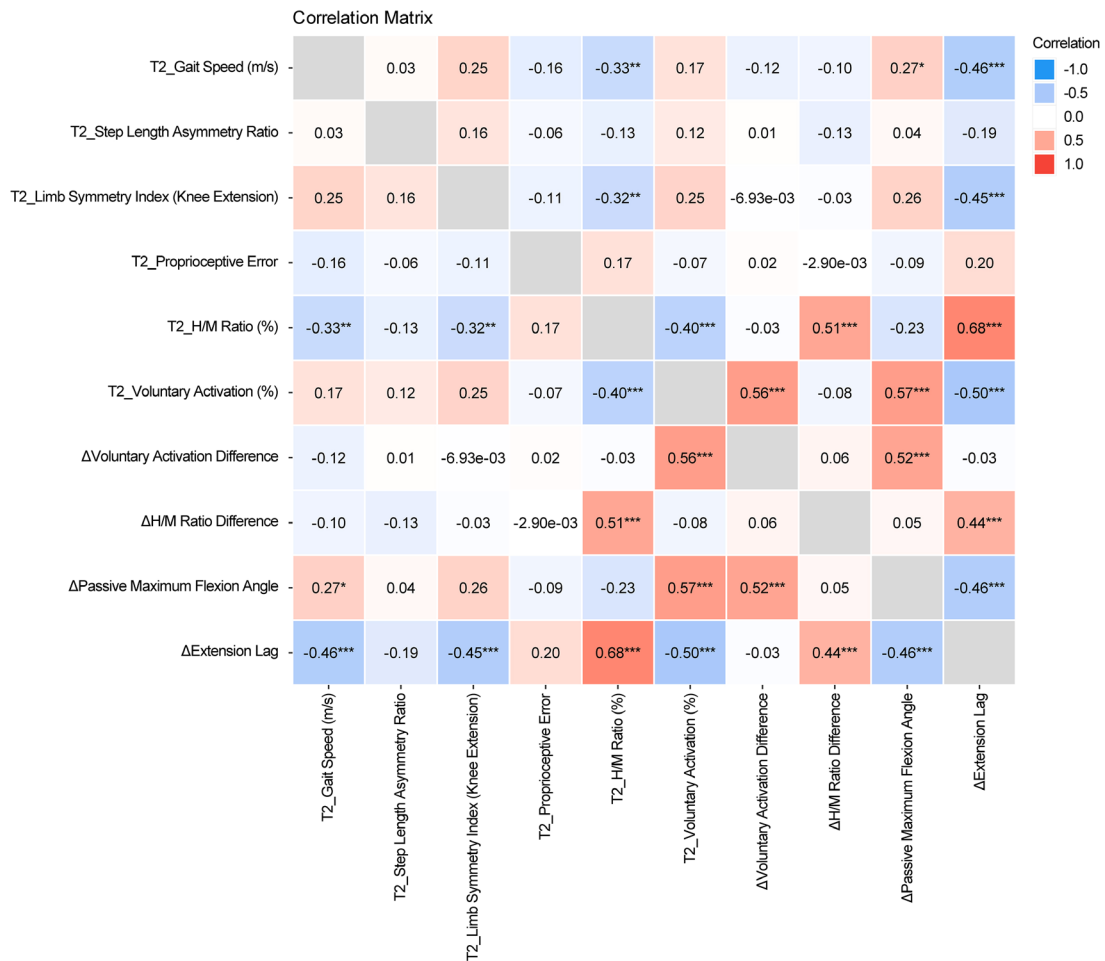
### Comparison of postoperative knee function and AMI indicators

At T1 and T2 postoperatively, the stiff group demonstrated significantly poorer outcomes than the non-stiff group across multiple joint ROM, functional, and neuromuscular inhibition metrics ( $P < 0.001$ ). As shown in Table 2, regarding joint ROM, the passive maximum flexion angle at T2 was significantly lower in the stiff group (112 [110, 114]° vs. 136 [134, 137]°), while the extension deficit angle was significantly greater (6.82 [5.50, 7.67]° vs. 2.47

[2.33, 2.78]°). In terms of joint function, the stiffness group at T2 exhibited slower gait speed (0.92 [0.79, 1.03] m/s vs. 1.14 [1.09, 1.22] m/s), lower step length asymmetry ratio (0.93 ± 0.06 vs. 0.98 ± 0.05), and lower knee extension LSI (80.0 [78.0, 82.0]% vs. 91.0 [88.0, 94.0]%). Significant differences in proprioception error were also observed between groups ( $P = 0.006$ ). Regarding AMI, the stiffness group exhibited significantly higher H/M ratios at T2 (0.51 [0.43, 0.57] vs. 0.34 [0.29, 0.39]) and significantly lower VA (82 [78, 88]% vs. 94 [92, 96]%), indicating insufficient spinal excitability inhibition and poor active activation capacity.

### Correlation analysis between AMI and knee function indicators

Spearman correlation analysis revealed a significant moderate-to-strong positive correlation between T2 AMI core indicators and concurrent improvements in knee function and ROM (Figure 2). Regarding the correlation between AMI indicators and functional performance, the H/M ratio at T2 showed significant negative correlations with both gait speed ( $r_s = -0.33$ ,  $P < 0.01$ ) and knee extension LSI ( $r_s = -0.32$ ,  $P < 0.01$ ), while exhibiting a strong positive correlation with the extension deficit angle ( $r_s = 0.68$ ,  $P < 0.001$ ). Conversely, the VA at T2 showed a positive correlation with knee extension LSI, though not statistically significant ( $r_s = 0.25$ ,  $P > 0.05$ ), and a



**Figure 2.** Correlation between AMI improvement and functional recovery of knee joint. H/M ratio = H-wave amplitude/M-wave amplitude ratio; VA = voluntary activation; LSI = limb symmetry index. Δ = T2 – T1. Spearman’s rank correlation analysis was used to assess inter-indicator associations; P values underwent multiple testing correction via BH method to control false discovery rate. Correlation coefficients denoted as “r<sub>s</sub>”. Weak correlation: |r<sub>s</sub>| = 0.1–0.3; Moderate correlation: |r<sub>s</sub>| = 0.3–0.7; Positive correlation (r<sub>s</sub> > 0), negative correlation (r<sub>s</sub> < 0). \*\* P < 0.05, \*\*\* P < 0.001.

moderate negative correlation with the extension deficit angle (r<sub>s</sub> = -0.50, P < 0.001). Regarding the association between neuromuscular function and rehabilitation improvement, analysis of the change (Δ) from 4 to 12 weeks postoperatively revealed that VA improvement (ΔVA) showed a significant positive correlation with the improvement in passive flexion angle (r<sub>s</sub> = 0.57, P < 0.001). Similarly, the decrease in the H/M ratio (ΔH/M) was positively correlated with improvement in the deficit extension angle (r<sub>s</sub> = 0.44, P < 0.001).

**Analysis of the Predictive Value of Early Postoperative Indicators for Knee Joint Stiffness**

To investigate early predictors of knee joint stiffness at 12 weeks postoperatively (T2), this study incorporated

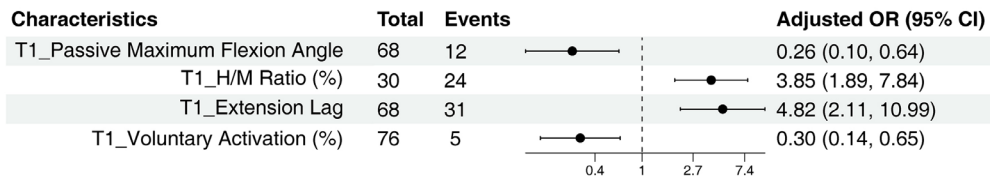
clinical baseline data along with joint ROM, function, and AMI metrics measured at T1 into the Boruta algorithm for variable screening. Results revealed the top four most significant variables (Supplementary Table 1): T1\_Passive Maximum Flexion Angle, T1\_Extension Deficit Angle, T1\_H/M Ratio, and T1\_VA.

The aforementioned variables were incorporated into a multivariate logistic regression model to assess their predictive value for stiffness at T2. Prior to analysis, all continuous variables underwent standardization. Collinearity diagnostics revealed VIF values consistently below 5, indicating no significant multicollinearity. Multivariate analysis results (Table 3) indicated that T1\_Maximum Passive Flexion Angle (OR = 0.26, 95% CI: 0.10–0.64, P = 0.003) and T1\_VA (OR = 0.30, 95% CI: 0.14–

**Table 3.** Independent Predictors of Short-Term Postoperative Stiffness (T2) Based on Multivariate Logistic Analysis of Baseline Characteristics (T1).

Characteristic	OR	95% CI	p-value
T1_Maximum passive flexion angle (°)	0.26	0.10, 0.64	0.003
T1_extension deficit angle (°)	3.85	1.89, 7.84	<0.001
T1_H/M ratio	4.82	2.11, 10.99	<0.001
T1_VA	0.3	0.14, 0.65	0.002

All continuous independent variables were standardized (mean = 0, standard deviation = 1) prior to analysis. Multicollinearity was diagnosed using variance inflation factors (VIF), with all VIF values below the threshold of 5, indicating no significant multicollinearity. CI = Confidence Interval, OR = Odds Ratio. Null deviance = 165; Null df = 145; Log-likelihood = -34.4; AIC = 78.7; BIC = 93.6; Deviance = 68.7; Residual df = 141. H/M ratio = H-wave amplitude/M-wave amplitude ratio, VA = Voluntary activation.



**Figure 3.** Forest plot of regression analysis. This forest plot displays the adjusted odds ratios (ORs) and 95% confidence intervals (CIs) for the four standardized predictors retained in the final model. All continuous predictors were standardized (mean = 0, SD = 1) prior to analysis. The plot uses a logarithmic scale for the x-axis to symmetrically represent the effect sizes. The vertical line at OR=1 represents the null value. ORs > 1 indicate increased risk, while ORs < 1 indicate decreased risk. CI = Confidence interval, OR = Odds ratio, H/M Ratio = H-reflex amplitude/M-amplitude ratio, VA = Voluntary activation.

0.65,  $P = 0.002$ ) were protective factors; T1\_Extension Deficit Angle (OR = 3.85, 95% CI: 1.89–7.84,  $P < 0.001$ ) and T1\_H/M Ratio (OR = 4.82, 95% CI: 2.11–10.99,  $P < 0.001$ ) were risk factors. All variables were statistically significant. The model demonstrated good overall fit with a bias statistic of 68.7 (df.residual = 141), AIC = 78.7, and BIC = 93.6. The model forest plot is shown in Figure 3.

**Predictive Model Performance and Internal Validation**

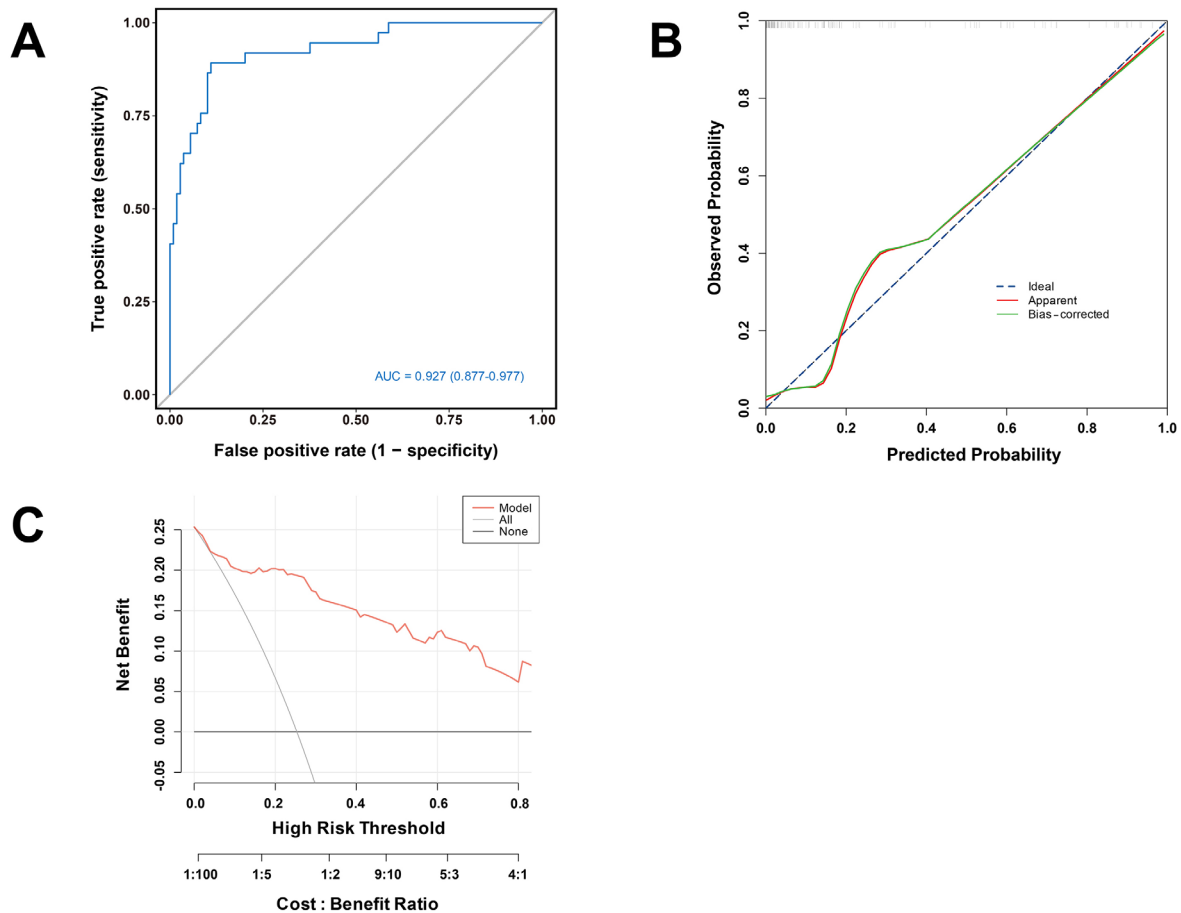
Next, we performed internal validation on the aforementioned Logit regression model. The results demonstrated that the model exhibits outstanding discriminatory capability. Specifically, the ROC-AUC reached 0.927 (95% CI: 0.877–0.977, Figure 4A). Given the category imbalance between the rigid and non-rigid groups in the data (37 vs. 109 cases) and the relatively low number of events, weighted maximum likelihood estimation was employed during model fitting to optimize parameter estimation and reduce bias. Subsequently, internal validation of the model’s calibration performance was conducted using Bootstrap sampling (1000 iterations), with the calibration curve plotted (Figure 4B). Results

demonstrated good agreement between predicted and observed probabilities. Furthermore, the calibration slope was 0.941 and the intercept was -0.018, indicating slight overfitting. However, the adjusted model maintained good predictive accuracy with a Harrell’s C index of 0.890, suggesting robust predictive capability.

Finally, we conducted DCA to evaluate clinical utility. As shown in Figure 4C, within a broad range of threshold probabilities (approximately 0.1 to 0.6), the net benefit of applying this predictive model to clinical decision-making—specifically, intensifying rehabilitation interventions for high-risk patients—exceeded that of either “universal intervention” or “no intervention” strategies. These validation results suggest that the model not only possesses potential predictive capabilities but also holds clinical decision-making value.

**Multivariate linear regression analysis of factors affecting knee joint ROM**

To identify independent factors influencing knee joint ROM at T2, standardized continuous variables were analyzed. Two multiple linear regression models (Model 1



**Figure 4.** Performance evaluation of the model predicting the risk of knee stiffness at 12 weeks post-surgery. (A) ROC curve; (B) calibration curve. Demonstrates the consistency between the model's predicted probability and the actual observed probability. The "Ideal" line represents perfect prediction, the 'Apparent' line indicates the original prediction, and the "Bias-corrected" line shows the prediction after internal validation correction via the Bootstrap method (1000 repetitions); (C) Decision Curve Analysis (DCA). Demonstrates the net benefit of the prediction model ("Model") compared to the 'All' strategy (intervention for all patients) or the "None" strategy (no intervention for all patients) at different high-risk threshold probabilities.

and Model 2) were constructed using T2 passive maximum flexion angle and T2 extension deficit angle as dependent variables, respectively, while adjusting for confounding factors.

Model 1 adjusted for confounding factors including age, sex, and injury-to-surgery interval, focusing on the impact of the H/M ratio at T2 on flexion angle. Results showed a significant negative correlation between the standardized T2\_H/M ratio and passive maximum flexion angle ( $\beta = -0.73$ , 95% CI: -0.84 to -0.62,  $P < 0.001$ ), indicating that each one-standard-deviation increase in the H/M ratio was associated with an average decrease of 0.73 standard deviations in flexion angle. The effects of age ( $\beta = -0.02$ ,  $P = 0.768$ ) and injury-to-surgery interval ( $\beta =$

$-0.03$ ,  $P = 0.579$ ) were not significant. sex gender showed borderline significance ( $\beta = 0.21$ ,  $P = 0.071$ ) but did not reach statistical significance. The model as a whole was significant ( $F = 44.1$ ,  $P < 0.001$ ), explaining 55.6% of the variance (adjusted  $R^2 = 0.543$ ).

Model 2 analyzed the effect of VA at T1 on extension deficit angle, controlling for the same confounding factors. Standardized age ( $\beta = 0.26$ , 95% CI: 0.12 to 0.41,  $P < 0.001$ ) and T1\_VA ( $\beta = -0.38$ , 95% CI: -0.52 to -0.23,  $P < 0.001$ ) were significant predictors of the extension deficit angle. Sex ( $\beta = -0.08$ ,  $P = 0.627$ ) and injury-to-surgery interval ( $\beta = 0.08$ ,  $P = 0.257$ ) had no significant effect. The model was statistically significant ( $F = 11.3$ ,  $P < 0.001$ ) and explained 24.3% of variance (adjusted  $R^2 = 0.221$ ).

**Table 4.** Correlation between Joint Range of Motion at 12 Weeks Postoperative and AMI in Multivariate Linear Regression Analysis.

Characteristic	Beta	Model 1		Beta	Model 2	
		95% CI	p-value		95% CI	p-value
Age (years)	-0.02	-0.13, 0.09	0.768	0.26	0.12, 0.41	< 0.001
sex (Male/Female)						
Female	Reference	-0.02, 0.45	0.071	Reference	Reference	0.627
Male	0.21			-0.08		
Injury-to-surgery interval (days)	-0.03	-0.15, 0.08	0.579	0.08	-0.06, 0.23	0.257
T2_H/M ratio	-0.73	-0.84, -0.62	<0.001	/	-0.52, -0.23	< 0.001
T2_VA	/			-0.38		

CI = Confidence Interval. Model 1 has T2\_Maximum passive flexion angle as the dependent variable and T2\_H/M ratio as the independent variable, with the remaining variables serving as confounding factors to correct the model. Model 2 has T2\_extension deficit angle as the dependent variable and T2\_VA as the independent variable, with the remaining variables serving as confounding factors to correct the model. Model 1:  $R^2 = 0.556$ ; Adjusted  $R^2 = 0.543$ ; Sigma = 0.676; Statistic = 44.1; p-value = <0.001; df = 4; Log-likelihood = -147; AIC = 307; BIC = 325. Model 2:  $R^2 = 0.243$ ; Adjusted  $R^2 = 0.221$ ; Sigma = 0.883; Statistic = 11.3; p-value = <0.001; df = 4; Log-likelihood = -186; AIC = 385; BIC = 403.

## Discussion

This prospective cohort study systematically investigated the mechanism and predictive value of AMI in postoperative neuromuscular dysfunction and mobility limitations following knee ligament reconstruction. Key findings suggest that AMI is associated with postoperative joint stiffness, with early-stage (4 weeks post-op) neuromuscular function indicators demonstrating substantial predictive capacity for mid-term (12 weeks post-op) functional outcomes.

Analysis of baseline data revealed that the stiff group and non-stiff group differed significantly only in the interval between injury and surgery and the type of transplanted tendon. No statistically significant differences were observed in other demographic and surgical variables, such as age and type of injured ligament. These findings suggest that the aforementioned two factors may be associated with the risk of postoperative stiffness, though caution is warranted when interpreting the specific mechanisms involved. From a pathophysiological perspective, delayed surgical timing may prolong the inflammatory response cycle in soft tissues such as the joint synovium and ligament stumps, thereby increasing the risk of fibrosis and adhesions. This could create mechanical barriers postoperatively, subsequently limiting the recovery of joint range of motion<sup>11</sup>. In ACL reconstruction surgery, preoperative ROM limitations and typical bone contusions are major risk factors for difficult postoperative rehabilitation. Particularly in patients with delayed surgery of less than 45 days, the correlation between preoperative ROM limitations and delayed postoperative recovery is especially significant<sup>12</sup>. However, this study did not assess the degree of intra-articular adhesions, making it impossible to directly confirm the

causal chain of “delayed surgery → adhesions → stiffness.” PT grafts require detachment of the PT insertion, and early postoperative peripatellar tissue edema and pain may lead patients to actively avoid knee extension<sup>13</sup>. However, this study did not include pain assessment metrics, making this mechanism a reasonable inference based on prior research rather than a directly validated conclusion of this study.

This study designated 4 weeks post-surgery (T1) as the early assessment time point and 12 weeks post-surgery (T2) as the functional outcome evaluation point. From a pathophysiological perspective, the inflammatory response typically subsides by 3–4 weeks post-surgery, while fibroblast activity increases and collagen synthesis and remodeling gradually become predominant. This phase corresponds to the clinical transition from early protective measures to active functional training. Therefore, assessment at this time point more accurately reflects the early adaptive status of the neuromuscular system<sup>14</sup>. By this stage, patients have completed early protective immobilization and transition into the rehabilitation phase of “shifting from passive to active mobility”<sup>15</sup>. From the perspective of neuromuscular control, the reduction in pain and swelling at 4 weeks postoperatively<sup>16</sup> allows AMI assessment to more accurately reflect adaptive changes in the central nervous system rather than merely analgesic effects. Therefore, selecting this time point may help identify the most representative neurophysiological indicators for predicting late-stage joint stiffness. Additionally, the 12-week postoperative time point holds significant clinical importance for functional outcome evaluation. Research indicates that 12 weeks post-surgery represents a critical juncture for evaluating functional recovery, particularly in knee and hip-related procedures. At this stage, patients’

joint range of motion and muscle strength typically reach a relatively stable plateau, providing a more accurate reflection of long-term rehabilitation outcomes<sup>17,18</sup>.

Regarding temporal correlations, at T2, the H/M ratio in the stiff group was significantly higher than in the non-stiff group, while VA was significantly lower than in the non-stiff group. Furthermore, the H/M ratio showed a strong positive correlation with extension deficit angle ( $r_s=0.68$ ), and VA exhibited a moderate negative correlation with extension deficit angle ( $r_s=-0.50$ ). This finding aligns with the “peripheral-central regulation hypothesis” of AMI. Following peripheral joint injury, elevated H/M ratios may reflect enhanced afferent signals from mechanoreceptors. This phenomenon could disrupt the inhibitory balance of spinal motor neurons, triggering excessive stretch reflexes that limit knee extension. Research indicates that peripheral joint injury is not merely a localized biomechanical issue but may also trigger chronic neuromuscular alterations associated with the loss of mechanoreceptor-mediated afferent feedback<sup>19</sup>. This perspective emphasizes that peripheral joint dysfunction should be regarded as a neurophysiological disorder rather than merely a localized injury. However, this study did not measure spinal nerve electrophysiological signals and could only indirectly infer central-level mechanisms through the H/M ratio. The decrease in VA indicates reduced activation efficiency of the motor cortex toward the quadriceps, resulting in insufficient active knee extension strength. Research indicates that patients following ACL reconstruction exhibit asymmetry in quadriceps function and cortical excitability, which may contribute to long-term joint dysfunction and increased injury risk<sup>20</sup>. Research has found that following ACL reconstruction, both the central activation ratio and MVIC torque of the quadriceps are significantly reduced, indicating decreased central nervous system activation efficiency of the quadriceps<sup>21</sup>. This decline in activation efficiency may lead to insufficient active knee extension strength. Furthermore, this inhibitory state was already evident at 4 weeks post-surgery and persisted through 12 weeks post-surgery, indicating that AMI is not a transient postoperative phenomenon but may become a persistent pathophysiological state that impedes functional recovery. Notably, this study also observed that a higher H/M ratio at T2 was significantly correlated with poorer gait speed, muscle strength asymmetry, and greater extension deficit. These findings provide support for mechanisms by which AMI impacts functional recovery: abnormal spinal reflex inhibition may disrupt normal motor control patterns, leading to gait asymmetry and impaired muscle coordination<sup>22</sup>, while reduced central activation capacity directly limits muscle force output efficiency, collectively contributing to suboptimal joint function recovery<sup>23</sup>.

In terms of dynamic correlation, the change in VA from T1 to T2 was positively correlated with improvement in passive maximum flexion angle, while the change in H/M was positively correlated with improvement in extension deficit. This finding fills a gap in previous cross-sectional

studies, suggesting a potential association between early improvement in AMI indicators and subsequent functional recovery. It provides a “time window reference” for clinical intervention—4 weeks post-surgery may be a critical juncture for AMI intervention. However, it is important to note that ‘association’ does not imply that “intervening on AMI directly improves functional recovery”; this requires validation through interventional studies.

One of the most significant contributions of this study is the establishment of a predictive model based on early indicators. Passive maximum flexion angle at T1, extension deficit angle, H/M ratio, and VA were identified as independent predictors of stiffness at 12 weeks postoperatively. Among these, the T1 H/M ratio (OR = 4.82) and extension deficit angle (OR = 3.85) demonstrated the most pronounced risk effects. This finding challenges traditional prediction models relying solely on ROM metrics, suggesting good predictive performance when combining “AMI indicators + ROM indicators” (model AIC = 78.7, adjusted  $R^2 = 0.543$ ). It clearly identifies high-risk population characteristics (e.g., PT graft, injury-to-surgery interval), providing direction for developing individualized rehabilitation plans<sup>24</sup>. It is important to emphasize that the predictive model is based on a single-center sample, and its clinical applicability requires further validation in larger, multicenter, and independent cohorts. Additionally, multiple linear regression analysis revealed that the T2 H/M ratio exerted the strongest negative influence on flexion angle ( $\beta = -0.73$ ), while T1 VA significantly negatively correlated with extension deficit ( $\beta = -0.38$ ). This suggests that flexion limitation is more closely associated with abnormal excitability of spinal motor neurons, whereas extension deficit is more closely linked to impaired active activation of the quadriceps. This distinction provides “target-specific” guidance for rehabilitation interventions.

Previous studies have predominantly used preoperative patient-reported outcome measures such as information system scores, pain, and psychological characteristics to predict postoperative function<sup>25,26</sup>. This study employed the Boruta algorithm to identify the “early AMI + mobility” combination predictive model, which demonstrated higher variance explained (adjusted  $R^2 = 0.543$ ) than models based on single baseline variables, thereby enriching the predictive indicator system. This study simultaneously evaluated peripheral (H/M ratio) and central (VA) indicators of AMI, addressing different levels of neuromuscular regulation to overcome the limitations of single-marker approaches. From a clinical practice perspective, these findings provide significant guidance. First, early postoperative (within 4 weeks) neuromuscular function assessment is crucial, with the H/M ratio and VA serving as effective evaluation tools. Second, targeted neuromuscular activation training should be initiated as early as possible, particularly interventions addressing spinal reflex inhibition and central activation capacity. Third, for identified high-risk patients, more aggressive and individualized rehabilitation protocols may be

required. Notably, this study found that the injury-to-surgery interval correlates with postoperative stiffness, suggesting that clinical practice should optimize surgical timing to avoid unnecessary delays. Furthermore, the correlation between graft tendon type (PT) and stiffness risk warrants consideration in clinical decision-making.

### Limitations

This study has several limitations. First, the single-center design and relatively small sample size, particularly the limited number of PCL-injured patients, may affect the generalizability of the findings. Second, the follow-up period was limited to 12 weeks postoperatively, which precludes assessment of the long-term evolution of AMI and its impact on persistent functional deficits. Third, gait analysis was conducted only at the 12-week timepoint, preventing insight into the longitudinal recovery of gait patterns during the critical early rehabilitation phase. Fourth, the soleus H-reflex was used as a systemic proxy for spinal-level excitability; although this is a well-established neurophysiological approach, it remains an indirect measure of quadriceps motoneuron pool excitability and may not fully capture muscle-specific inhibitory mechanisms. Fifth, proprioception was assessed only at a single angle (30° flexion) using absolute error, which limits the comprehensiveness of proprioceptive evaluation. Finally, the prediction model, though showing promising discriminative ability, has not yet been externally validated and requires further testing in independent, larger-scale cohorts to confirm its generalizability and clinical utility.

Future studies should aim to expand sample sizes through multicenter collaboration, extend follow-up durations, incorporate multi-angle proprioceptive assessments and—where feasible—direct measures of quadriceps spinal excitability, and validate the proposed predictive model in external populations. In parallel, the integration of neuroimaging techniques may help elucidate higher-level central nervous system contributions to AMI, thus informing the development of novel neuromodulatory rehabilitation strategies.

### Conclusion

In summary, this study provides evidence that AMI may play a role in functional impairment after knee ligament reconstruction. The initial H/M ratio and VA may hold predictive value for mid-term ROM recovery. Further investigation into AMI-focused interventions is warranted to determine their potential for improving rehabilitation outcomes.

### Ethics Approval

*The present study was approved by the Ethics Committee of The Second Hospital of Longyan (Approval number: No. LS-2212-HC5537). All procedures were performed in accordance with the ethical standards of the Institutional Review Board and The Declaration of*

*Helsinki (1964), and its later amendments or comparable ethical standards.*

### Consent to Participate

*Written informed consent was obtained from all patients prior to the start of the study.*

### Authors' contributions

*J.Y. Jiang and D.L. Zhang designed the research study. J.Y. Jiang, D.L. Zhang and H.F. Ye performed the research. T.X. Qiu and J.F. Zhu provided help and advice on the experiments. J.Y. Jiang, H.F. Ye and T.X. Qiu analyzed the data. J.Y. Jiang and J.F. Zhu wrote the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.*

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**Supplementary Table 1.** Feature Importance Values from Boruta Method (An Improved Random Forest Algorithm) for Variable Selection.

Vars	Mean Importance	Median Importance	Min Importance	Max Importance	Norm Hits	Decision
T1_VA	22.94119357	23.24755598	17.3848828	26.57125	1	Confirmed
T1_H/Mratio	21.66877819	22.03383206	17.9823656	25.808263	1	Confirmed
T1_Maximum passive flexion angle	14.04531143	13.93142927	11.6213853	17.627012	0.98989899	Confirmed
T1_extension deficit angle	13.8368088	13.82319988	11.3259796	16.173653	1	Confirmed
Injury-to-surgery interval(days)	1.94394481	1.89766124	-1.2054118	5.002263	0.47474747	Tentative
Age (years)	1.15569529	1.116753331	-0.9000431	2.942036	0.03030303	Rejected
BMI (kg/m <sup>2</sup> )	0.40994677	0.434094917	-2.1230093	1.561318	0	Rejected
Grafted tendon (HT/PT)	0.53107952	0.175332931	-2.0397319	2.639838	0.02020202	Rejected
Sex (male/female)	-0.23892812	0.081534218	-2.7454115	2.436272	0.03030303	Rejected
Affected side (Right/Left)	0.2644472	0.027420614	-1.0332229	1.719848	0.01010101	Rejected
Cartilage injury (Outerbridge ≥ II)	0.06594544	-0.001688008	-1.5453568	1.584641	0	Rejected
Meniscus injury	-0.08518675	-0.22032409	-2.3509037	1.923773	0.02020202	Rejected
Injured ligament (ACL/PCL)	-0.80556128	-1.020593003	-2.0250783	1.094418	0	Rejected
Dominant leg (Right/Left)	-0.99389671	-1.076126234	-2.9007711	2.20843	0.01010101	Rejected