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Transient hypercoagulability during the perioperative period of anterior cruciate ligament reconstruction: A thromboelastogram comparison between hamstring autografts and synthetic ligaments

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Abstract

Background

Deep vein thrombosis following primary anterior cruciate ligament reconstruction is a complication that is frequently underestimated in clinical practice; its core pathophysiological basis involves perioperative tissue injury and systemic coagulation homeostasis imbalance induced by ischaemia-reperfusion. Although autologous hamstring tendon grafts are widely used, the additional soft tissue damage associated with the harvesting of multiple tendon strands is thought to potentially exacerbate the hypercoagulable state during the acute phase. In contrast, synthetic grafts based on polyethylene terephthalate (PET) completely avoid donor site trauma; however, their non-biological nature has raised theoretical concerns regarding the activation of endogenous coagulation pathways upon contact. Currently, there remains a lack of quantitative comparisons and definitive conclusions regarding the specific effects of these two distinct graft options and their associated surgical trauma on the micro-coagulation dynamics during the perioperative period.

Methods

This retrospective cohort study included 407 patients who underwent primary isolated anterior cruciate ligament reconstruction, comprising 293 patients in the autologous tendon group and 114 in the synthetic ligament group. To eliminate the interference of drugs on the fibrinolytic system and the natural coagulation cascade, the prophylactic use of tranexamic acid was strictly avoided across the entire cohort. In the autograft group, a combined harvest of the semitendinosus and gracilis tendons was uniformly employed. The study quantified the duration of surgery and the decrease in haemoglobin levels across groups, and systematically assessed patients' baseline Caprini thrombosis risk scores. Hemorheological monitoring spanned three key time points: preoperatively, on postoperative day 1, and on postoperative day 3. Core viscoelastic parameters from thromboelastography and routine biochemical coagulation indices were extracted, and repeated measures analysis of variance was employed to evaluate the interaction effects of time course and graft type. **Hypothesis**: In primary anterior cruciate ligament reconstruction, the activation of the systemic coagulation system resulting from the additional soft tissue trauma and ischaemic load associated with the harvesting of the multifasciculated semitendinosus and gracilis muscles is significantly greater than the foreign body contact effect of synthetic polyethylene terephthalate (PET) materials, thereby inducing a more pronounced and transient hypercoagulable shift.

Results

There were no statistically significant differences between the two groups in terms of baseline characteristics such as age, BMI, and Caprini score (all $P > 0.05$). About surgical trauma, the autologous tendon group exhibited significantly longer operative times (42.6 ± 9.4 vs. 32.5 ± 7.8 min, $P < 0.001$) and

greater decreases in haemoglobin levels (13.9 ± 5.2 vs. 7.8 ± 4.1 g/L, P < 0.001) compared with the synthetic ligament group. On postoperative day 1, the difference in prothrombin time (PT) between the two groups was not statistically significant (10.9 ± 1.2 vs. 11.12 ± 1.0 s, P = 0.061); however, thromboelastography (TEG) revealed that the comprehensive coagulation index (CI: 2.45 ± 1.12 vs. 0.82 ± 0.94, P < 0.001) and maximum amplitude (MA: 69.1 ± 7.8 vs. 60.0 ± 5.1 mm, P < 0.001) were both significantly higher in the autologous tendon group than in the synthetic ligament group, and returned to baseline levels (CI: 0.30 ± 0.85) by postoperative day 3 in the autologous group. Multivariate regression analysis confirmed that the decrease in haemoglobin (P < 0.001) and baseline Caprini score (P < 0.001) were independent predictors of postoperative hypercoagulable states as indicated by TEG. With regard to clinical outcomes, the incidence of early postoperative distal deep vein thrombosis was significantly higher in the autologous tendon group than in the artificial ligament group (4.4% vs. 0.9%, P = 0.045).

Conclusion

This study demonstrates that, in the acute postoperative period following primary anterior cruciate ligament reconstruction, autologous grafts derived from the multifasciculated semitendinosus and gracilis muscles induce a more pronounced transient hypercoagulable state than synthetic ligaments. This microhaemodynamic differentiation is primarily driven by additional tissue trauma and blood loss, rather than foreign body activation by synthetic implants. For patients with a high Caprini thrombosis risk score, clinicians should incorporate the traumatic effects of graft harvesting as a key consideration when formulating deep vein thrombosis prevention strategies.

Study design:

Retrospective cohort study; evidence grade 3.

Introduction

Anterior cruciate ligament reconstruction is a routine procedure for restoring knee stability. Currently, autologous multi-bundle semitendinosus and gracilis tendons are widely regarded as the gold standard in this field due to their superior biomechanical properties and proven long-term graft survival rates [1]. However, the harvesting of autologous tendons is inevitably associated with disruption of the donor site anatomy and additional soft tissue trauma [2]. In recent years, artificial ligament reinforcement systems based on polyethylene terephthalate (PET) have demonstrated unique advantages in specific clinical settings by completely eliminating donor site morbidity, significantly reducing surgical exposure time, and enabling patients to return to sports activities at an early stage [3]. Nevertheless, the non-biological nature of synthetic materials has raised ongoing concerns regarding aseptic synovitis and foreign body reactions [4]. Existing literature comparing these two graft types has largely focused on knee function scores, radiographic outcomes, and medium- to long-term mechanical stability [5].

Such comparisons based on macroscopic clinical outcomes obscure the potential impact of graft harvesting and implantation procedures on perioperative microhaemodynamics. The perioperative period of anterior cruciate ligament reconstruction involves tourniquet-induced ischaemia-reperfusion, postoperative immobilisation, and local tissue trauma; these physical interventions perfectly align with the pathophysiological factors that trigger venous thrombosis [6]. Regarding graft selection, the harvesting of multi-strand autologous tendons is thought to potentially strongly activate the extrinsic coagulation pathway through the release of large amounts of tissue factors [7], whilst the implantation of synthetic materials has sparked theoretical debate regarding contact-activated endogenous coagulation cascades [8]. It remains inconclusive which of these two distinct surgical intervention modalities exerts a more pronounced disruption on systemic coagulation homeostasis.

This theoretical blind spot at the micro-pathological level has directly led to the long-standing underestimation of the risk of post-operative deep vein thrombosis following ACL reconstruction in clinical practice. Recent cohort studies using routine Doppler ultrasound screening have shown that the true incidence of asymptomatic distal deep vein thrombosis following this procedure can exceed 8% [9]. When assessing such surgery-induced, latent coagulation abnormalities, traditional free coagulation factor assays often demonstrate insufficient sensitivity. In contrast, thromboelastography, as a whole-blood viscoelasticity assessment technique, enables dynamic and comprehensive quantification of the entire haemostatic process, from the enzymatic activation of coagulation factors to the densification of the fibrin network [10]. Its clinical value in monitoring hypercoagulable states and guiding the prevention of venous thromboembolism during orthopaedic interventions has been widely validated [11].

Therefore, this study aims to combine the Caprini thrombosis risk scoring system with thromboelastography to dynamically assess and compare the evolution of perioperative coagulation profiles between the use of multi-strand semitendinosus and gracilis autografts and the use of synthetic ligaments in primary anterior cruciate ligament reconstruction. We hypothesize that the activation of the systemic coagulation system resulting from the additional soft tissue disruption and prolonged ischaemic load associated with the harvesting of multi-strand autologous tendons is significantly greater than the foreign body reaction caused by synthetic polyethylene terephthalate (PET) materials, thereby inducing a more pronounced and transient hypercoagulable shift in the acute postoperative period.

Methods

Study Design and Patient Selection

This study is a single-centre, retrospective cohort study. The study protocol was formally approved by the institution’s Ethics Review Committee prior to data collection, with an exemption from obtaining informed consent from patients (QYFYWZLL42069). The reporting of study data strictly adheres to the STROBE statement guidelines. Following approval by the institutional ethics review committee, the research team systematically reviewed the complete electronic medical records and imaging archives of

1,035 patients who underwent primary anterior cruciate ligament reconstruction between January 2020 and December 2025. The core inclusion criteria were designed to establish a homogeneous pathological and anatomical baseline; eligible subjects were required to have a first-time, isolated, complete anterior cruciate ligament rupture confirmed by magnetic resonance imaging, with fully closed epiphyses and an age between 18 and 50 years. To avoid natural interference with haemostatic homeostasis caused by acute systemic inflammatory stress following trauma or local fibrosis from chronic injury, the surgical intervention was strictly confined to the subacute elective window of 21 to 90 days post-injury. Furthermore, enrolled patients were required to have completely normal preoperative biochemical coagulation test results, with no signs of thrombosis detected on deep vein ultrasound screening of both lower limbs.

To eliminate potential confounding biases and isolate the independent haemostatic interference effects attributable to the type of graft, this study implemented extremely stringent exclusion criteria. At the level of local anatomy and surgical trauma, the study systematically excluded patients with concomitant injuries to other knee ligament structures, meniscal or articular cartilage injuries requiring suture repair or resection, and those with any history of previous knee surgery. With regard to systemic haematological and internal environmental stability, patients with a history of deep vein thrombosis or pulmonary embolism, those with congenital or acquired coagulation disorders, and those with systemic inflammatory or immune diseases such as rheumatoid arthritis were all excluded. Furthermore, patients who had received any form of anticoagulant or antiplatelet therapy within seven days prior to surgery, as well as female patients who had been continuously using oral contraceptives or hormone replacement therapy within 30 days prior to surgery, were strictly excluded to thoroughly eliminate the masking and distortion of the natural coagulation cascade by exogenous pharmacological factors. Following systematic screening against the above criteria, a total of 407 eligible patients were ultimately included to form the core analysis cohort, comprising 293 patients in the autologous multitendinous semitendinosus and gracilis graft group and 114 patients in the artificial ligament group (Fig. 1).

Surgical Techniques and Perioperative Management

All surgical procedures are performed by the same team of senior sports medicine specialists using standardised arthroscopic techniques, assisted by a pneumatic tourniquet. A pneumatic tourniquet is routinely applied to the proximal thigh during surgery, with the inflation pressure set at 250 to 280 mmHg. In the autologous tendon group, a standardised graft preparation protocol was followed, involving the combined harvesting of the semitendinosus and gracilis muscles and their braiding into a multi-strand graft. In the synthetic ligament group, polyethylene terephthalate (PET) synthetic grafts were directly implanted to avoid anatomical disruption of the donor site. To standardise the baseline for bony trauma, the diameter of the bone tunnel was strictly controlled within the range of 7.5 mm to 9.0 mm for both groups. Crucially, to completely rule out the masking and interference of antifibrinolytic drugs on the core parameters of thromboelastography, the prophylactic or therapeutic use of tranexamic acid was strictly prohibited in the perioperative period for the entire cohort. Postoperatively, patients in

both groups followed a standardised enhanced recovery after surgery (ERAS) protocol and routinely employed physical and mechanical measures, such as graduated compression stockings, for the prevention of deep vein thrombosis.

Data Collection and Haematological Assessment

The study systematically extracted and quantified patients' baseline demographic characteristics, and integrated factors such as age, body mass index, and surgical classification to precisely calculate each patient's baseline Caprini thrombosis risk score. Surgical duration and tourniquet inflation time, reflecting local trauma load, were accurately recorded. Systemic occult blood loss was quantified by calculating the decrease in total haemoglobin levels between preoperative and postoperative day 1.

Dynamic monitoring of hemorheological and routine biochemical coagulation parameters was conducted at three key time points: preoperative baseline, postoperative day 1, and postoperative day 3. The dynamic parameters extracted from this time series included the comprehensive coagulation index, maximum amplitude, and reaction time from thromboelastography, as well as routine parameters such as prothrombin time and D-dimer. In addition, all patients underwent routine Doppler ultrasound screening of both lower limbs prior to discharge to determine the final clinical outcome of asymptomatic distal deep vein thrombosis.

Statistical Analysis

Data processing and statistical modelling were performed using standardised analytical software. Continuous variables were presented as means and standard deviations following normality testing; baseline comparisons between groups were performed using independent samples t-tests or Mann-Whitney U tests. Comparisons of categorical variables were performed using the chi-square test or Fisher's exact test. To analyse the evolution of core thromboelastogram parameters across the preoperative period, postoperative day 1, and postoperative day 3, the study constructed a repeated measures analysis of variance (ANOVA) model with time and group interaction effects for longitudinal trajectory analysis. To account for potential confounding biases, the study further constructed multivariate regression models, incorporating surgical trauma markers and baseline high-risk factors such as a high Caprini score into the covariate system, to identify independent predictors of acute hypercoagulable states and deep vein thrombosis endpoints. A two-sided P-value of less than 0.05 was considered statistically significant for all statistical inferences.

Results

Comparison of Baseline Homogeneity and Surgical Trauma Burden

The 407 patients ultimately included in this cohort exhibited clinically relevant natural variation in core demographic and clinical baseline characteristics; however, no statistically significant differences were observed overall (all $P > 0.05$). Specifically, the autologous tendon group ($n = 293$) and the synthetic ligament group ($n = 114$) were comparable in terms of age (31.6 ± 6.7 vs. 30.2 ± 7.1 years, $P = 0.076$), body mass index (24.2 ± 3.3 vs. 24.8 ± 3.6 kg/m², $P = 0.124$), and baseline Caprini thrombosis risk score (1.50 ± 0.57 vs. 1.40 ± 0.58, $P = 0.122$) (Table 1).

In the assessment of surgical intervention indicators, the autologous tendon group, which utilised multi-strand tendon harvesting, exhibited greater variability and a significantly increased overall trauma load. Both the duration of surgery (42.6 ± 9.4 min vs. 32.5 ± 7.8 min, $P < 0.001$) and the inflation time of the pneumatic haemostatic band (38.4 ± 8.6 min vs. 28.6 ± 7.2 min, $P < 0.001$) were significantly longer in the autologous tendon group than in the synthetic ligament group. Furthermore, the decrease in total haemoglobin—a measure of latent blood loss—was nearly twice as high in the autologous tendon group as in the synthetic ligament group, and exhibited greater clinical variability (13.9 ± 5.2 g/L vs. 7.8 ± 4.1 g/L, $P < 0.001$).

Table 1
Baseline Demographics and Surgical Characteristics

Parameters	Autograft Group (n = 293)	LARS Group (n = 114)	P Value
Demographics and Clinical Features			
Age, years	31.6 ± 6.7	30.2 ± 7.1	0.076
Body Mass Index (BMI), kg/m²	24.2 ± 3.3	24.8 ± 3.6	0.124
Gender, n (%)			0.921
Male	173 (59.0%)	66 (57.9%)	
Female	120 (41.0%)	48 (42.1%)	
Smoking history, n (%)	77 (26.3%)	23 (20.2%)	0.248
Hypertension, n (%)	31 (10.6%)	17 (14.9%)	0.296
Diabetes mellitus, n (%)	17 (5.8%)	3 (2.6%)	0.283
Time from injury to surgery, days	55.5 ± 19.7	51.3 ± 22.4	0.078
Caprini thrombosis risk score	1.50 ± 0.57	1.40 ± 0.58	0.122
Surgical Characteristics and Trauma Loads			
Femoral and tibial tunnel diameter, mm	8.3 ± 0.4	8.2 ± 0.5	0.608
Surgical duration, minutes	42.6 ± 9.4	32.5 ± 7.8	< 0.001*
Tourniquet inflation time, minutes	38.4 ± 8.6	28.6 ± 7.2	< 0.001*
Total hemoglobin drop (ΔHb), g/L	13.9 ± 5.2	7.8 ± 4.1	< 0.001*

Notes: Data are presented as mean ± standard deviation (SD) for continuous variables, and as frequencies with percentages for categorical variables. Statistical comparisons were performed using the independent Student's *t*-test or Mann-Whitney *U* test for continuous data, and the Chi-square test or Fisher's exact test for categorical data, as appropriate. * Indicates statistical significance ($P < 0.05$).

Abbreviations: LARS, Ligament Augmentation and Reconstruction System.

Limitations of Conventional Coagulation Parameters and Differentiation of Whole Blood Rheological Profiles

At the preoperative baseline (T0), both conventional coagulation parameters and whole blood rheological indices in both groups fell within the physiological reference range (P > 0.05). During the acute stress phase on postoperative day 1 (T1), conventional decellularised coagulation parameters demonstrated significant diagnostic limitations. The difference in prothrombin time (PT) between the

two groups did not reach the threshold for conventional statistical significance (10.9 ± 1.2 s vs. 11.12 ± 1.0 s, P = 0.061), and neither group exhibited a clinically significant shortening of the activated partial thromboplastin time (APTT). Meanwhile, as a marker of the acute phase response to surgical trauma, D-dimer levels were broadly elevated in both groups; although the absolute values were relatively higher in the autologous tendon group (618.0 ± 205.7 ng/mL vs. 378.5 ± 151.2 ng/mL, P < 0.001), the high degree of overlap in their distribution weakened their specificity as an independent marker for hypercoagulability.

In contrast, thromboelastography, which integrates the physical activity of blood cells, precisely quantifies this micro-rheological differentiation. Repeated measures analysis of variance established a highly significant time-by-graft-type interaction effect for haemostatic kinetic parameters (P < 0.001). The autologous tendon group in the T1 phase exhibited a marked procoagulant shift, with its composite coagulation index (2.45 ± 1.12 vs. 0.82 ± 0.94, P < 0.001) and maximum platelet amplitude (69.1 ± 7.8 mm vs. 60.0 ± 5.1 mm, P < 0.001) significantly exceeded those of the artificial ligament group and the patients' baseline levels, and the reaction time was significantly shorter (4.18 ± 1.14 min vs. 5.47 ± 1.08 min, P < 0.001) (Table 2). In stark contrast to the distribution characteristics highly overlapping with the traditional marker D-dimer, the TEG comprehensive coagulation index demonstrated precise pathological differentiation of high-risk procoagulant phenotypes during the acute postoperative period (Figure 2).

However, by the third postoperative day (T2), the abnormally elevated parameters in the autologous tendon group showed a significant mean decline (CI decreased to 0.30 ± 0.85, MA decreased to 59.7 ± 4.2 mm) and gradually converged towards the values observed in the artificial ligament group and the physiological baseline range. This inverted 'V'-shaped trajectory objectively confirms that the acute hypercoagulable state mediated by autologous tendon harvesting possesses distinct transient physiological characteristics (Figure 3).

Table 2. Dynamic Evolution of Conventional Coagulation Markers and Thromboelastography (TEG) Parameters Across the Perioperative Period

Parameters	Timepoint	Autograft Group (n = 293)	LARS Group (n = 114)	P Value
Prothrombin Time (PT), s	T0 (Pre-op)	11.58 ± 1.00	11.71 ± 1.06	0.269
	T1 (POD 1)	10.90 ± 1.20	11.12 ± 1.00	0.061
	T2 (POD 3)	11.49 ± 0.99	11.54 ± 0.89	0.642
D-Dimer, ng/mL	T0 (Pre-op)	247.9 ± 80.0	255.9 ± 79.2	0.363
	T1 (POD 1)	618.0 ± 205.7	378.5 ± 151.2	< 0.001*
	T2 (POD 3)	405.3 ± 110.6	288.1 ± 96.3	< 0.001*
Reaction Time (R), min	T0 (Pre-op)	6.06 ± 0.85	6.00 ± 0.75	0.492
	T1 (POD 1)	4.18 ± 1.14	5.47 ± 1.08	< 0.001*
	T2 (POD 3)	5.44 ± 0.89	5.84 ± 0.77	< 0.001*
Maximum Amplitude (MA), mm	T0 (Pre-op)	55.8 ± 3.9	55.7 ± 3.6	0.778
	T1 (POD 1)	69.1 ± 7.8	60.0 ± 5.1	< 0.001*
	T2 (POD 3)	59.7 ± 4.2	56.9 ± 4.1	< 0.001*
Comprehensive Index (CI)	T0 (Pre-op)	-0.50 ± 0.84	-0.53 ± 0.84	0.739
	T1 (POD 1)	2.45 ± 1.12	0.82 ± 0.94	< 0.001*
	T2 (POD 3)	0.30 ± 0.85	-0.15 ± 0.92	< 0.001*

Note: Data are presented as mean ± SD. Comparisons between groups at each designated time point were evaluated using the independent *t*-test (with Welch's correction for unequal variances where applicable). Repeated measures ANOVA confirmed a highly significant time × group interaction for all TEG parameters, whereas conventional coagulation markers (e.g., PT) exhibited no such significant interaction. * Indicates statistical significance ($P < 0.05$).

Abbreviations: Pre-op, preoperative; POD, postoperative day; PT, prothrombin time; TEG, thromboelastography.

Independent driving mechanisms of the acute hypercoagulable state following surgery

To elucidate the underlying mechanisms of abnormally elevated comprehensive coagulation indices (CI) in the postoperative T1 phase, a multivariate linear regression model was employed. After adjusting for age and body type bias, the results confirmed that graft type was not an isolated variable. An increase in the decline in haemoglobin (β = 0.062, 95% CI: 0.044–0.080, P < 0.001) and an elevated baseline Caprini thrombosis risk score (β = 0.868, 95% CI: 0.712–1.024, P < 0.001) were identified as core independent positive predictors of postoperative hypercoagulability (Table 3). This finding reveals a synergistic effect driven by surgical trauma and blood loss in conjunction with the patient's pre-existing high-risk coagulation profile.

Table 3. Multiple Linear Regression Analysis Identifying Independent Predictors of Elevated Comprehensive Coagulation Index (CI) at Postoperative Day 1

Variables	Unstandardized β	Standard Error	95% Confidence Interval	P Value
Constant	-0.929	0.234	-1.389 to -0.469	< 0.001*
Graft Type	1.152	0.126	0.903 to 1.400	< 0.001*
Surgical Duration, min	0.001	0.005	-0.008 to 0.011	0.779
Hemoglobin Drop (ΔHb), g/L	0.062	0.009	0.044 to 0.080	< 0.001*
Caprini Thrombosis Score	0.868	0.079	0.712 to 1.024	< 0.001*

Notes: Multiple linear regression model assessing independent predictors of elevated CI at postoperative day 1. Overall model fit: Adjusted R^2 = 0.517, F = 109.6, P < 0.001. The results indicate that beyond the graft type, both the physiological trauma load (ΔHb) and the baseline thrombotic susceptibility (Caprini score) independently drive acute hypercoagulability. * Indicates statistical significance (P < 0.05).

Clinical outcomes of distal deep vein thrombosis

Standardised bilateral lower limb deep vein Doppler ultrasound screening prior to discharge revealed one case (0.9%) of sporadic, asymptomatic distal deep vein thrombosis among the 114 patients in the artificial ligament group. In contrast, the number of confirmed cases of distal deep vein thrombosis was significantly higher in the autologous tendon group, totalling 13 cases (4.4%). Confirmed cases were highly concentrated in a subgroup exhibiting extreme coagulation shift (CI > 2.5) during the T1 phase and a high Caprini score. The difference in the incidence of deep vein thrombosis between the groups was statistically significant (4.4% vs. 0.9%, P = 0.045).

Discussion

The key findings of this study indicate that, during the acute stress phase following primary isolated anterior cruciate ligament reconstruction, multi-strand autologous tendon grafts induce a more pronounced and transient systemic procoagulant shift compared to synthetic ligaments, ultimately resulting in a significantly increased incidence of distal deep vein thrombosis (4.4% vs. 0.9%, P = 0.045). Regression analysis established that this microhaemodynamic differentiation was not determined solely by the material properties of the graft, but was driven synergistically by the additional surgical trauma burden and the patient's baseline thrombophilic predisposition.

In assessing surgical stress-induced coagulation disturbances, the data from this study profoundly reveal the diagnostic limitations of routine decellularised plasma testing. Neither prothrombin time (PT) nor activated partial thromboplastin time (APTT) demonstrated differences reaching traditional statistical significance thresholds on postoperative day 1. This delayed response stems from the underlying principle of the test: the centrifugation process completely removes the rheological contribution of platelets and red blood cells, and can only simulate in vitro the isolated thrombin generation occurring during the initial 1% to 4% of the coagulation cascade [12]. Meanwhile, although D-dimer levels were elevated in both groups postoperatively, confirming widespread secondary hyperfibrinolysis induced by traumatic stress, there was significant overlap in the quartile distribution between the autologous group and the LARS group. As a lagging product of thrombus degradation, the high non-specificity of D-dimer prevents it from independently identifying hypercoagulable phenotypes that pose a genuine risk of thrombosis [13].

In contrast, thromboelastography (TEG), by integrating platelet contractility with the three-dimensional cross-linking strength of the fibrin network in real time, successfully fills this diagnostic gap. On postoperative day 1, TEG accurately captured the extremely abnormal comprehensive coagulation index (CI: 2.45 ± 1.12, P < 0.001) and significantly widened maximum amplitude (MA: 69.1 ± 7.8 mm, P < 0.001) in the autologous tendon group. This dimensional expansion at the level of whole-blood rheology not only perfectly explains why asymptomatic microthrombi frequently occur in patients with normal routine biochemical test results, but also provides precise physicochemical targets for investigating the specific interference of graft types on the coagulation system.

In exploring the specific interference of graft types on the coagulation cascade, the quantitative data from this study provide direct evidence for understanding the interactive mechanisms between trauma and coagulation. Covert tissue dissection and microvascular bed disruption during orthopaedic interventions have been widely established as core initiating factors for venous thromboembolism [14]. The harvesting of the multifasciculated semitendinosus and gracilis muscles is inevitably accompanied by significant anatomical trauma [15]. In the autologous tendon group, the decrease in total haemoglobin —representing the volume of occult blood loss—was nearly double that of the artificial ligament group (13.9 ± 5.2 vs. 7.8 ± 4.1 g/L, P < 0.001), and this indicator was confirmed as an independent predictor of abnormal TEG composite coagulation indices (P < 0.001). Extensive endothelial damage leads to the

massive release of tissue factor into the bloodstream; its binding to coagulation factor VIIa potently initiates the extrinsic coagulation cascade, thereby triggering the massive production of thrombin and the densification of the fibrin network [16]. By contrast, although synthetic non-biological materials such as polyethylene terephthalate possess the theoretical potential to activate endogenous coagulation upon contact [17], the dynamic thromboelastogram trajectories in this study confirm that, in the absence of extensive physical trauma to soft tissues, the implantation of foreign materials alone did not induce a clinically significant systemic hypercoagulable shift. This contrast clearly demonstrates that the disruption to perioperative coagulation homeostasis caused by local tissue damage and the physical release of a large number of factors far outweighs the chemical contact reactions of synthetic materials.

Dynamic monitoring at multiple pre- and post-operative time points established the transient physiological nature of this abnormal hypercoagulable state. The marked procoagulant shift observed in the autologous tendon group on postoperative day 1 rapidly subsided by postoperative day 3 (CI decreased to 0.30 ± 0.85). This inverted ‘V’-shaped kinetic trajectory closely aligns with the cycle of ischaemia-reperfusion injury induced by pneumatic tourniquets. Prolonged limb ischaemia followed by reperfusion is often accompanied by a burst release of local plasminogen activator inhibitor-1 (PAI-1) and the accumulation of reactive oxygen species; their procoagulant and antifibrinolytic effects typically reach a biological peak within 24 hours of systemic circulation reperfusion [18]. In the autologous tendon group, due to the complexity of graft preparation, the tourniquet inflation time was significantly prolonged (38.4 ± 8.6 min, $P < 0.001$). This superimposed ischaemic load, combined with the aforementioned tissue trauma, perfectly explains the extremely enlarged maximum amplitude (MA) on the TEG waveform during phase T1, whilst also corroborating the physiological pattern of coagulation network remodelling within 72 hours.

Furthermore, the data from this study reveal the amplifying effect of patients’ baseline coagulation profile during traumatic stress. Multivariate regression established that a baseline Caprini score of ≥ points is another core independent factor predicting a hypercoagulable shift in TEG ($\beta = 0.868$, $P < 0.001$). Demographic characteristics such as obesity and advancing age often indicate that the vascular endothelial system is in a state of chronic low-grade inflammation and procoagulant tendency [19,20]. When this underlying systemic physiological vulnerability encounters the acute surgical trauma of autologous tendon harvesting, it is highly prone to producing a non-linear amplification effect in the coagulation cascade. The 13 cases of deep vein thrombosis diagnosed in the autologous tendon group within this cohort were highly concentrated in the high Caprini score subgroup, representing a precise projection of this microscopic synergistic mechanism onto distal clinical complication outcomes. This finding suggests that routine sports medicine patients are not an absolutely thrombosis-immune population, and the assessment of trauma from surgical intervention must be integrated with the patient’s individual physiological baseline.

This study was subject to rigorous quality control at both the design and execution stages. Through extremely stringent inclusion and exclusion criteria, the cohort thoroughly eliminated anatomical confounding variables associated with additional trauma, such as meniscal suturing or chondroplasty

[21]. More importantly, tranexamic acid was strictly prohibited throughout the perioperative period for the entire cohort. The use of prophylactic antifibrinolytic agents has been shown to profoundly suppress multiple core parameters in thromboelastography, thereby masking the natural trauma-induced coagulation response [22]. The exclusion of this pharmacological interference ensures that the haemodynamic trajectories captured in this study represent a true physiological snapshot driven purely by graft differences. However, this study also has limitations. The retrospective design makes it difficult to completely eliminate all unmeasured residual bias; simultaneously, whilst thromboelastography can macroscopically quantify whole-blood viscoelasticity and the absolute strength of blood clots, cross-scale validation in conjunction with molecular biological markers such as the thrombin-antithrombin complex (TAT) or prothrombin fragments would further refine the microscopic mechanism of coagulation activation. Future prospective studies with large sample sizes should focus on exploring precise pharmacological prevention strategies for high-risk populations.

Conclusion

Traditional decellularised coagulation biomarkers have significant diagnostic limitations and are unable to effectively detect latent microcoagulation disorders following anterior cruciate ligament reconstruction. Whole-blood thromboelastography objectively confirmed that, compared with polyester artificial ligaments, autologous grafts of the multifibrous semitendinosus and gracilis tendons induced a more pronounced transient systemic hypercoagulable state in the acute postoperative period, ultimately resulting in a higher rate of confirmed distal deep vein thrombosis. This microhaemodynamic evolution is not primarily driven by the material properties of the graft, but rather by the additional soft tissue trauma and prolonged ischaemic load associated with multi-strand tendon harvesting; it exhibits a clear synergistic amplifying effect in individuals with a high baseline Caprini thrombosis risk score. When formulating individualised graft selection and perioperative complication management strategies, clinicians should look beyond the limitations of routine testing, carefully assess the combined risk of additional trauma from tendon harvesting and the patient’s inherent coagulopathic predisposition, and place high importance on the early warning value of comprehensive rheological monitoring.

Abbreviations

ACL: Anterior cruciate ligament

ANOVA: Analysis of variance

APTT: Activated partial thromboplastin time

BMI: Body mass index

CI: Comprehensive coagulation index

ERAS: Enhanced recovery after surgery

LARS: Ligament Augmentation and Reconstruction System

MA: Maximum amplitude

PAI-1: Plasminogen activator inhibitor-1

PET: Polyethylene terephthalate

POD: Postoperative day

Pre-op: Preoperative

PT: Prothrombin time

R: Reaction time

SD: Standard deviation

SEM: Standard error of the mean

TAT: Thrombin-antithrombin complex

TEG: Thromboelastography

ΔHb: Total hemoglobin drop

Declarations

Ethics declarations

Ethics approval and consent to participate

This study was approved by the medical ethics committee of the Affiliated Hospital of Qingdao University according to the Declaration of Helsinki, and informed consent was obtained from all individual participants included in the study. All methods were carried out in accordance with the Declaration of Helsinki. (QYFYWZLL42069)

Consent for publication

Not applicable. As this was a retrospective study using de-identified data, the requirement for individual patient consent for publication was waived by the medical ethics committee of the Affiliated Hospital of Qingdao University.

Clinical trial number:

Not applicable.

Data availability

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

Conflict of interest

The authors, their immediate families, and any research foundation with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

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Author contributions

WWX: Conceptualization, Formal analysis, Project administration, Writing- original draft. CP: Writing- original draft, Investigation. LJM: Software, Writing- original draft, Validation. XXY: Formal analysis. XHM: Conceptualization, Formal analysis. ZYX: Conceptualization, Methodology. LHP: Writing - review & editing, Supervision. FHT: Writing - review & editing, Supervision, Resource, Formal Analysis. ZX: Writing - review & editing, Supervision, Resource. QC: Writing - review & editing, Methodology, Conceptualization, Supervision.

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Figures

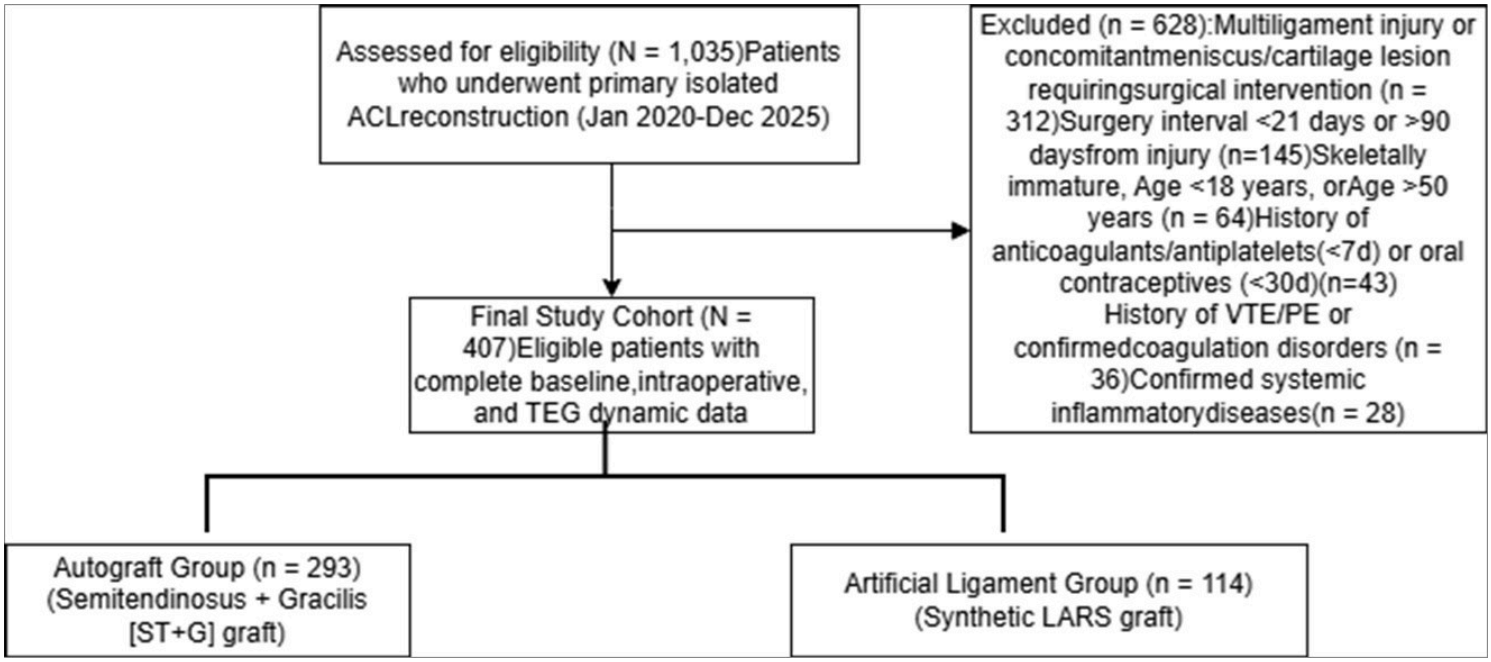


Figure 1

Legend not included with this version

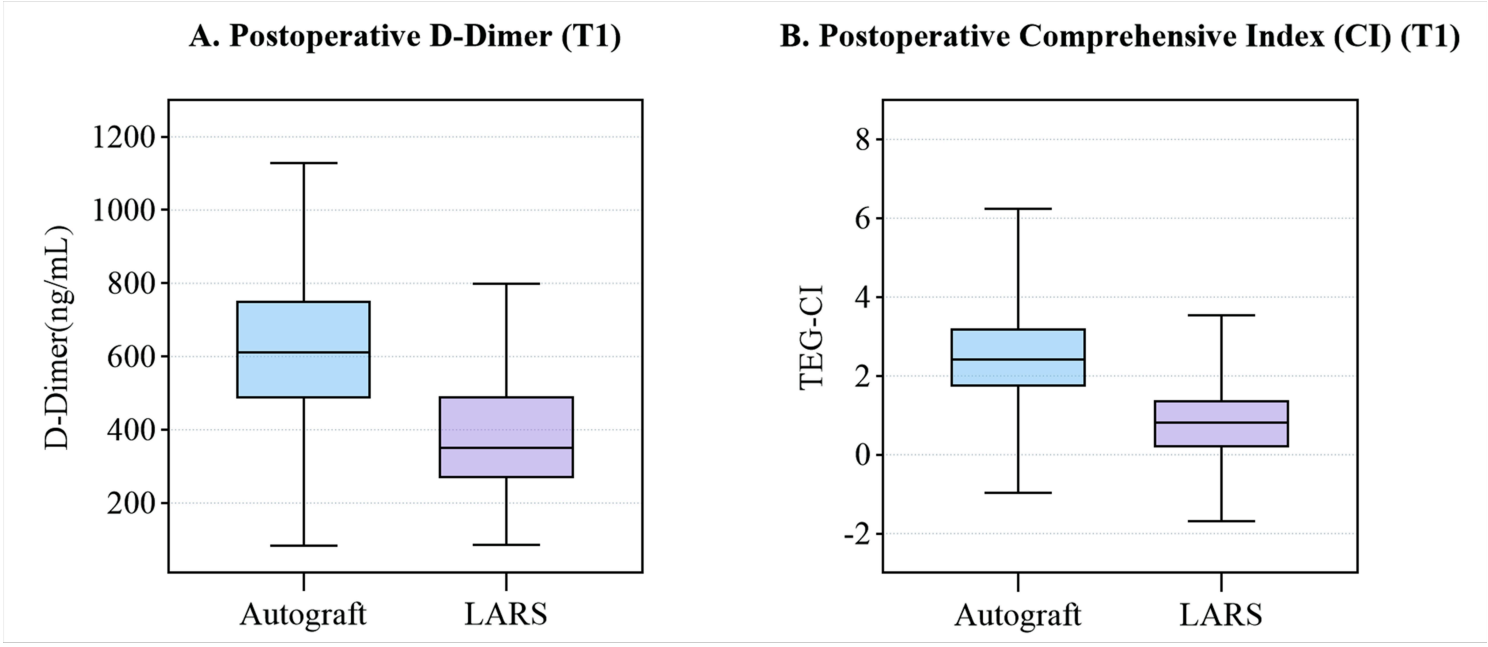


Figure 2

thromboelastography (Comprehensive Index, CI) at postoperative day 1 (T1). (A) The box-and-whisker plot overlaid with scatter points demonstrates a massive interquartile distribution overlap of D-Dimer levels between the Autograft and LARS groups, indicating low specificity for identifying clinically significant hypercoagulability. **(B)**In contrast, the Comprehensive Coagulation Index (CI) exhibits marked physiological separation, with the Autograft group's interquartile range decisively shifting upward beyond the physiological upper limit, precisely capturing the acute hypercoagulable offset induced by surgical graft harvesting. Horizontal lines within the boxes represent the median values.

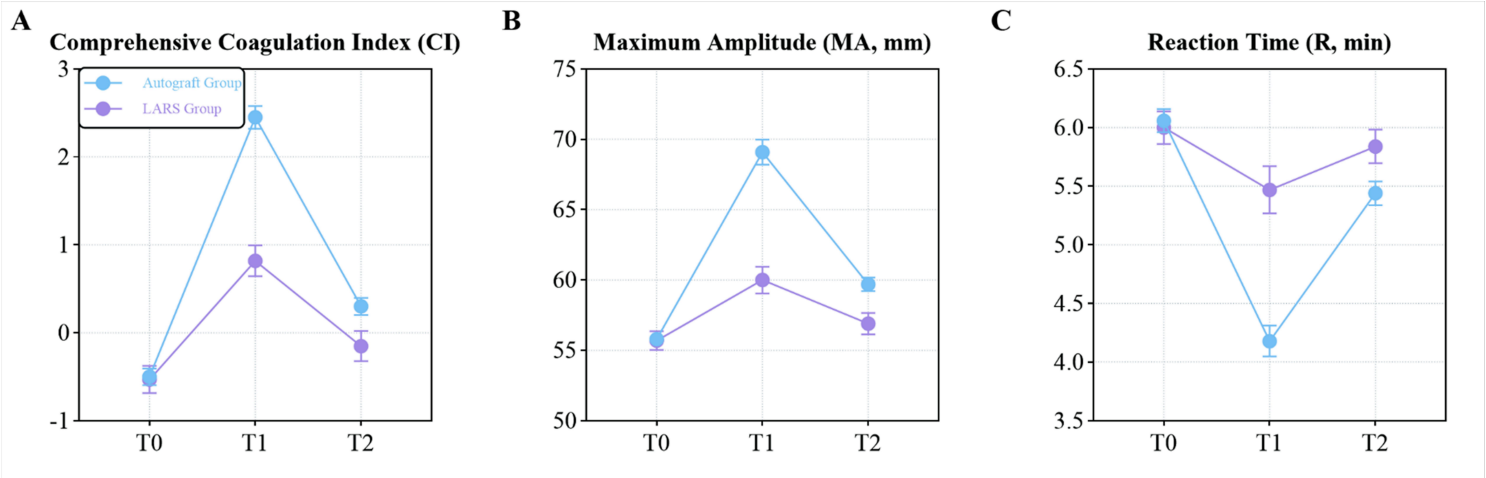


Figure 3

Dynamic time-course changes of key thromboelastography (TEG) parameters across the perioperative period. Line graphs depict **(A)** the Comprehensive Coagulation Index (CI), **(B)** Maximum Amplitude (MA), and **(C)**Reaction Time (R) at preoperative baseline (T0), postoperative day 1 (T1), and postoperative day

3 (T2). Error bars represent standard errors of the mean (SEM). The inverted "V" trajectory observed in the Autograft group's CI and MA illustrates a profound but transient hypercoagulable state triggered by surgical trauma, which rapidly converges toward the LARS group baseline by T2.