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Original Research

Dynamic knee valgus as a predictor of graft rerupture after anterior cruciate ligament reconstruction: Influence of sex and graft type

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ABSTRACT

Introduction: Dynamic knee valgus has been identified as a potential risk factor for anterior cruciate ligament (ACL) injury, but its role in predicting graft failure or contralateral rupture after anterior cruciate ligament reconstruction (ACLR) remains unclear. The purpose of this study was to evaluate dynamic valgus (DV) as a predictor of graft re-rupture and contralateral ACL injury following ACLR, and to explore whether graft type influences this association.

Methods: Prospective cohort study was conducted patients who underwent primary ACLR between 2020 and 2024. Patients with multiligament injuries, osteotomies, or revision surgeries were excluded. DV was measured during a standardized return-to-sport (RTS) drop jump test. Logistic regression was performed to assess associations with graft rerupture and contralateral ACL injury, adjusting for age, sex, body mass index (BMI), and graft type. Receiver operating characteristic (ROC) analysis was used to evaluated discriminative ability.

Results: A total of 137 patients completed follow-up at a mean of 3.0 ± 1.2 years. Most patients were male (75.9%), with a mean age of 26.7 years. Ten patients (7.3%) sustained a graft re-rupture and nine (6.6%) a contralateral rupture. The DV was an independent predictor of graft rerupture (adjusted odds ratio [aOR]: 1.07; 95% confidence interval [CI]: 1.001–1.15). In sex-stratified analyses, this association was statistically significant only among men (aOR: 1.13; 95% CI: 1.02–1.24), with an area under the curve (AUC) of 0.76. A threshold between 18° and 20° yielded a balanced sensitivity and specificity of 71% and 73%, respectively. No statistically significant differences in DV were observed across graft types.

Conclusion: DV is an independent predictor of graft rerupture after ACLR, particularly among men, where valgus angles above 18–20° markedly increase the risk of failure. These findings support the integration of DV assessment into postoperative follow-up to identify high-risk patients and to inform graft selection and rehabilitation strategies.

Level of evidence: III.

What are the new findings?

- Dynamic knee valgus is an independent predictor of graft rerupture after anterior cruciate ligament reconstruction.
- This predictive effect is sex-specific, being statistically significant in male patients but not in females. A threshold of 18–20° of dynamic valgus provides a clinically relevant balance of sensitivity and specificity (71% and 73%, respectively) for predicting graft failure in men.
- No statistically significant differences in dynamic valgus were observed across graft types.

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INTRODUCTION

Anterior cruciate ligament (ACL) injury is one of the most common ligamentous injuries of the knee, primarily affecting young athletes who participate in sports involving jumping, pivoting, or sudden changes of direction [1,2]. The injury mechanism usually occurs in the absence of direct contact, especially during deceleration, rotation, or landing movements [3,4].

Currently, anterior cruciate ligament reconstruction (ACLR) is considered the clinical gold standard for restoring mechanical stability of the joint [5]. The annual incidence of ACL injuries is estimated to range between 100,000 and 250,000 cases, with approximately 60,000 to 175,000 surgical reconstructions performed each year [6,7]. Despite advancements in surgical techniques and rehabilitation, only about 65% of patients manage to return to their preinjury competitive level, even though 88% report this expectation prior to surgery [8,9]. Moreover, the risk of ACL reinjury increases over time, with rates of 3%, 6%, and 9% at 2, 5, and 8 years, respectively [10,11].

Among the various risk factors identified, dynamic knee valgus has gained importance as it increases the load on the ACL during tasks such as cutting and landing [12–14]. This biomechanical pattern may be influenced by anatomical and neuromuscular factors such as weakness of the hip abductors, poor pelvic motor control, increased femoral anteversion, internal tibial torsion, wider pelvic width, midfoot hypermobility, and an increased Q-angle [11].

Additionally, an increase in medial knee displacement during jump landing has been associated with a 40% higher risk of ACL injury for every 1.2 cm of increased displacement [12]. This dynamic valgus (DV) pattern appears to be more prevalent in female athletes, who tend to have a larger Q-angle and lower hip abductor strength [15–17], which may partly explain the gender differences in ACL injury risk.

Therefore, the objective of the present study was to evaluate the role of DV in predicting graft rerupture or contralateral ACL injury after reconstruction, and to explore the influence of graft type on this association. The secondary objective was to compare the distribution of DV and the frequency of rerupture according to graft type.

The hypothesis was that higher DV angles during return-to-sport (RTS) testing are associated with an increased risk of graft rerupture, regardless of the graft type used.

METHODS

This study was approved by the institutional ethics committee (approval number 2013–01), and informed consent was obtained from all participants. No external funding was required for this research.

A prospective cohort study was conducted on patients who underwent ACLR between 2020 and 2024, with a minimum postoperative follow-up of one year. Patients who underwent revision ACLR, neurovascular injuries, tibial plateau fractures, multiligament reconstructions, or procedures combined with osteotomy, and those without contact information were excluded from the study.

All surgeries were performed by experienced knee surgeons (with 10+ years of experience), under general anesthesia with a thigh-high tourniquet. Graft selection was made through a shared decision-making process between the surgeon and the patient, during which the advantages and disadvantages of each graft option were thoroughly discussed.

Patients typically spent one night in the hospital and completed at least one physiotherapy session before discharge. Patients who underwent meniscal repair were immobilized with a range-of-motion (ROM) brace and had weight-bearing restrictions for six weeks, after which full ROM was allowed.

Rehabilitation protocol

Rehabilitation was divided into four main phases lasting approximately nine to twelve months in total. The initial phase (weeks 0–4) focused on pain reduction, edema control, restoration of full extension, and quadriceps activation. The intermediate phase (weeks 5–12) emphasized progressive strengthening through isometric and closed-kinetic-chain exercises, with later incorporation of open-kinetic-chain exercises between 6 and 12 weeks when tolerated [18–20]. Core stability, proprioception, and balance training were progressively added. From the fourth to the sixth month, impact and plyometric exercises were introduced [21–24], followed by sport-specific retraining and RTS testing between months 9 and 12.

Postoperative follow-ups were conducted at 2 weeks, 4 weeks, 6 weeks, 3 months, 6 months, and 1 year by the treating surgeon. After completing of the rehabilitation protocol, patients underwent magnetic resonance imaging (MRI) to assess graft ligamentization and performed RTS tests. Those who failed the tests were advised to continue rehabilitation or attend RTS sessions.

Dynamic valgus test

The DV was evaluated using a standardized drop jump test. Patients stood on a 30-cm-high box, dropped forward with both feet, landed softly, and immediately performed a maximum vertical jump. Three successful trials were recorded for each patient, and the mean valgus angle across attempts was used for analysis (Fig. 1).

Testing was performed between 9 and 12 months after surgery, once patients had passed all preliminary functional tests and were cleared for impact activities. The test was conducted on both the operative and non-operative limbs for comparison, although only the operative limb was used in the primary analysis.

Kinematic data were captured using two synchronized high-speed digital cameras (120 Hz) placed in the frontal and sagittal planes, and

Fig. 1. Evaluation of the degrees of dynamic valgus, from dropping off a 30 cm high box followed by a maximum vertical jump.

analyzed with a motion-analysis software. The hip center was estimated as the midpoint between the anterior superior iliac spines, the knee center at the midpoint between femoral condyles, and the ankle center at the midpoint between malleoli. The DV angle was defined as the angle formed by the line connecting the hip and knee centers and the line connecting the knee and ankle centers at maximal knee flexion during landing. The test is considered successful if the valgus angle is $<16^\circ$ for men and $<20^\circ$ for women [25].

Malrotation of the body or foot placement errors were corrected by repeating the trial. All recordings were anonymized and assessed by two independent observers, blinded to patient outcomes. Inter- and intra-rater reliability were evaluated using the intraclass correlation coefficient (ICC). The resulting ICC values were 0.93 and 0.89, respectively, indicating excellent reliability.

Statistical analyses

Descriptive statistics were reported as mean and standard deviation (SD) for normally distributed data or median and interquartile range (IQR) for non-normally distributed data, after assessing normality with the Shapiro–Wilk test.

Multivariable logistic regression was used to evaluate the association between DV and graft rerupture or contralateral ACL injury, adjusting for age, sex, body mass index (BMI), and graft type. Odds ratios (ORs) and 95% confidence intervals (CIs) were calculated. Subgroup analyses were performed by sex. When statistically significant, the discriminative ability of DV was assessed using receiver operating characteristic (ROC) curve analysis, with the area under the curve (AUC) reported.

A post-hoc power analysis was performed based on the observed graft rerupture rate and effect size for DV to assess the adequacy of the sample for detecting statistically significant associations. Statistical analyses were conducted using Stata version 19.0.

RESULTS

A total of 146 patients underwent ACLR between 2020 and 2024. All patients were contacted between February and April 2025 for follow-up. At final evaluation, 137 patients were available, resulting in a follow-up rate of 93.8% at a mean follow-up time of 3.0 $\pm$ 1.2 years (range: 1.1–6.8 years).

Most patients were male (75.9%), with a mean age of 26.7 years (SD: 8.9) and a mean BMI of 24.9 kg/m^2 (SD: 3.5). Prior to injury, 53.3% of patients played soccer. The most frequently used graft type was semitendinosus (STG) (61.3%), followed by bone-patellar tendon-bone (BPTB) (29.9%) and allograft (8.8%) (Table 1).

A total of 10 patients had a history of rerupture (7.3%), and 9 patients had a contralateral rupture (6.6%). The DV test demonstrated a statistically significant association with ACL graft rerupture (odds ration [OR]: 1.11; 95% CI: 1.01–1.22) and remained an independent predictor in the multivariable model after adjusting for age, sex, BMI, and graft type (adjusted odds ratio [aOR]: 1.07; 95% CI: 1.001–1.15) (Table 2).

In sex-stratified analyses, this association was not statistically significant among women (aOR: 0.91; 95% CI: 0.74–1.11) but persisted in men, where the DV test continued to act as an independent predictor of rerupture (aOR: 1.13; 95% CI: 1.02–1.24). In men, the likelihood of graft rerupture increased progressively with greater degrees of DV as demonstrated by an AUC of 0.76 (Table 3).

Concerning graft type, reruptures were more frequent among patients who received an STG graft (80% of rerupture cases), while no reruptures were observed in patients with a BPTB graft ($p = 0.03$). Allografts were used in 20% of the rerupture cases, without reaching statistical significance ($p = 0.19$). The mean graft diameter was similar between groups (9.1 versus 9.2 mm, $p = 0.57$). The mean DV was similar between patients reconstructed with BPTB grafts (14.6° $\pm$ 8.3) and those with STG grafts (14.3° $\pm$ 8.7), with no statistically significant

Table 1
Characteristics of included patients (average $\pm$ standard deviation).

Characteristics	Total population n = 137 (100%)	Rerupture		
		Yes n = 10 (7.3%)	No n = 127 (92.7%)	p-value
Sociodemographic characteristics				
Male sex	104 (75.9)	7 (70.0)	97 (76.4)	0.65
Age, years (SD)	26.7 (8.9)	26.3 (6.7)	26.8 (9.1)	0.87
BMI, kg/m2 (SD)	24.9 (3.5)	25.1 (2.5)	24.8 (3.5)	0.83
Type of sport				
Soccer	73 (53.3)	7 (70.0)	66 (52.0)	0.78
Rugby	12 (8.8)	0 (0)	12 (9.5)	
Tennis	9 (6.6)	1 (10.0)	8 (6.3)	
Skiing	7 (5.1)	0 (0)	7 (5.5)	
Hockey	7 (5.1)	0 (0)	7 (5.5)	
Basketball	5 (3.7)	0 (0)	5 (3.9)	
Padel	5 (3.7)	1 (10.0)	4 (3.2)	
Volleyball	5 (3.7)	0 (0)	5 (3.9)	
Others	14 (10)	1 (10.0)	13 (10.2)	
Surgical characteristics				
Graft type				
STG	84 (61.3)	8 (80.0)	76 (59.8)	0.06
BPTB	41 (29.9)	0 (0)	41 (32.3)	
Allograft	12 (8.8)	2 (20.0)	10 (7.9)	
Graft diameter (SD)	9.2 (7.9)	9.1 (0.9)	9.2 (0.8)	0.57
Return to sport test				
Time from surgery to testing, days (IQR)	332 (265–408)	327 (300–500)	332 (260–408)	0.50
Dynamic valgus, degrees (SD)	**14.4 (8.5)**	**19.8 (13.3)**	**14.0 (7.9)**	**0.03***
RTS	110 (80.3)	10 (100.0)	100 (78.7)	0.10
Postoperative follow-up				
Time from surgery to last FU, days (IQR)	1008 (798–1289)	1111 (917–1914)	1002 (780–1289)	0.27
Rerupture	10 (7.3)	–	–	–
Contralateral rupture	9 (6.6)	0 (0)	9 (7.1)	0.38

Legend: (*) denotes statistical significance ($p < 0.05$).
SD: standard deviation; IQR: interquartile range; BMI: body mass index; BPTB: bone-patellar tendon-bone; STG: semitendinosus-gracilis; RTS: return-to-sport; FU: follow-up.

Table 2
Multiple logistic regression for risk factors associated with graft rerupture and contralateral rupture.

Variables	Rerupture	Contralateral rupture
	Adjusted odds ratio (95 % CI)	Adjusted odds ratio (95% CI)
Male sex	0.61 (0.13–2.70)	1.02 (0.18–5.48)
Age, years	0.99 (0.92–1.07)	0.91 (0.81–1.02)
BMI, kg/m2	1.01 (0.83–1.23)	1.14 (0.95–1.37)
Type of graft	1.11 (0.37–3.36)	1.01 (0.30–3.36)
Dynamic valgus, degrees	**1.07 (1.001–1.15)**	0.95 (0.87–1.04)

BMI: body mass index; CI: confidence interval.

differences (t-test p = 0.858; Mann–Whitney p = 0.796). Median values were comparable (14.0° versus 13.0°), although the STG group exhibited higher extreme values (maximum 50° versus 34° in BPTB).

Regarding contralateral ACL injuries, 9 patients (6.6%) experienced this complication. No statistically significant differences were found in sex, age, BMI, or type of sport compared to those without a contralateral tear. There was also no statistically significant association with graft type or with the functional parameters evaluated, including DV angle (12.3° versus 14.6°, p = 0.43) or time to testing (p = 0.17). The median postoperative follow-up was 1008 days (IQR: 798–1289), with no statistically significant differences between groups with or without rerupture (p = 0.27) or with or without contralateral injury (p = 0.95).

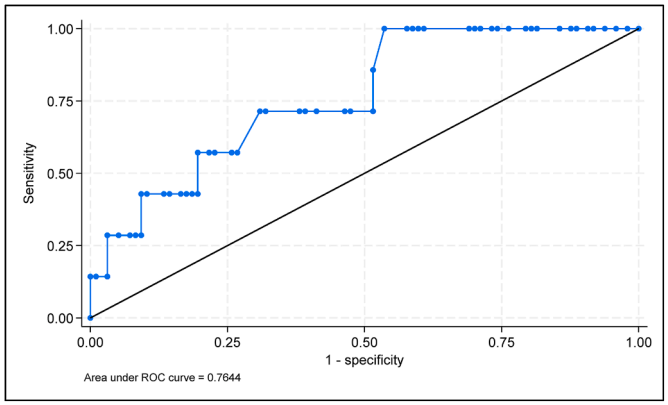
Predictive value of dynamic valgus in male patients

ROC curve analysis confirmed that DV was a statistically significant predictor of graft rerupture among male patients, with an AUC of 0.76 (95% CI: 0.59–0.93), indicating good discriminative ability. At lower thresholds, the test achieved maximal sensitivity but poor specificity, whereas higher thresholds yielded excellent specificity at the expense of sensitivity. The most clinically relevant threshold for predicting graft rerupture was between 18° and 20°, providing a sensitivity of 71% and specificity of 73%. Lower thresholds increased sensitivity at the expense of specificity, while higher thresholds improved specificity but decreased sensitivity (Table 3).

DISCUSSION

This study aimed to evaluate dynamic knee valgus as a predictive factor for graft rerupture and contralateral ACL injury in patients who underwent ACL reconstruction, considering graft type and DV testing.

Table 3
ROC curve showing the probability of graft rerupture in male patients based on dynamic valgus score.



The most important finding of this study is that in this cohort of young and active patients undergoing ACL reconstruction, DV was an independent predictor of graft rerupture. After adjustment for age, sex, BMI, and graft type, increasing degrees of valgus were statistically significantly associated with a higher risk of failure. This effect was particularly evident in male patients, where the likelihood of graft rupture increased progressively with greater valgus angles, achieving an ROC of 0.76. In contrast, this association was not statistically significant among female patients, highlighting possible sex-related biomechanical or neuromuscular differences in dynamic loading patterns. These results are consistent with previous biomechanical studies demonstrating that DV places greater stress on the ACL during landing and cutting maneuvers, thereby increasing the likelihood of injury or graft failure [12–14]. However, the available literature does not provide specific details on the percentage increase in graft rerupture risk for each additional degree of DV in this context [26]. It only refers to anatomical factors, such as an increased posterior tibial slope, which have been quantified [27].

The second finding of our study is that no statistically significant differences were observed in the degree of DV when analyzed by graft type. While one might expect an association between dynamic knee valgus and graft rerupture in patients undergoing ACLR with semitendinosus-gracilis grafts—due to strength loss of the donor site muscles (flexor group)—this could lead to an imbalance in the flexor-extensor ratio, characterized by a deficit in the flexor component. As a result, increased DV angles may occur [28], owing to diminished translational control of the knee. Another factor that could bias DV measurements and thus the association with graft rerupture risk is that patients who received a bone-patellar tendon-bone (BPTB) graft might experience anterior knee pain during single-leg-drop jump testing. This pain could limit effective eccentric control during the deceleration phase of the jump, leading to compensatory hip flexion and forward trunk lean, which may in turn impair proper knee flexion at the time of measurement (i.e. suboptimal technique). For future studies, it would be valuable not only to quantify valgus angles in the frontal plane but also to correlate them with knee and hip flexion angles in the sagittal plane. Interestingly, no reruptures were observed in patients who received a BPTB graft, and while this trend reached statistical significance in the univariate analysis (p = 0.03), it did not remain statistically significant after adjustment. This result was anticipated as biomechanical research using cadaver specimens has demonstrated that the medial flexor tendons play a crucial role in stabilizing against valgus stress [29]. This aligns with prior literature suggesting that BPTB grafts may provide superior initial fixation strength and reduced laxity compared to STG grafts, albeit with potential downsides such as anterior knee pain [19, 20].

A recent meta-analysis by Bailey et al. [30] reported lower failure rates for BPTB and quadriceps tendon grafts compared to hamstrings in young, high-demand athletes, supporting our findings. Although these results should be interpreted with caution, they provide further insight into graft selection, supporting the durability of BPTB in young, high-demand athletes despite the known drawback of anterior knee pain.

Nevertheless, the absence of BPTB re-ruptures in our series should be interpreted with caution, as the relatively low number of events (10 reruptures and 9 contralateral injuries) limits the statistical power of subgroup comparisons. The post-hoc power analysis confirmed that the study was adequately powered to detect moderate effects but underpowered for smaller subgroup differences. Therefore, the conclusions regarding graft-specific risks and sex interactions should be considered exploratory.

The integration of DV testing into postoperative follow-up may provide clinicians with a simple and reproducible screening tool to identify patients at higher risk of graft failure. Values exceeding 18–20° in male patients were associated with a substantially increased risk of rerupture, suggesting that this threshold could serve as a benchmark for

rehabilitation goals or for delaying RTS clearance. These findings highlight the importance of individualized neuromuscular training programs that address frontal-plane control and strength asymmetries.

The strengths of this study include a high follow-up rate (93.8%), a standardized rehabilitation and RTS testing protocol, and blinded dual-observer assessment with high inter- and intra-rater reliability. However, several limitations should be acknowledged. The small number of outcome events reduced the ability to identify other predictors of re-rupture or contralateral injury. In addition, although the RTS test used has been validated in previous literature [25], DV measurement was based on 2D motion capture, which, while reliable, does not fully capture out-of-plane movements. Future multicenter studies using 3D motion analysis and larger sample sizes are warranted to confirm these findings.

CONCLUSION

Dynamic knee valgus emerged as an independent predictor of graft rerupture after ACLR, particularly among male patients, where greater valgus angles were associated with a progressively increased risk of failure. The predictive accuracy of valgus assessment was confirmed with good discriminative ability (AUC 0.76), and thresholds above 18–20° may help identify patients at higher risk.

No statistically significant differences in DV were observed across graft types, although patients reconstructed with bone–patellar tendon–bone grafts experienced no re-ruptures in this cohort. These findings support the incorporation of DV assessment into postoperative follow-up to enhance risk stratification, tailor rehabilitation strategies, and inform graft selection in young, active individuals.

Given the limited number of events, further multicenter studies with larger cohorts are needed to validate these observations and establish normative valgus thresholds for safe return to sport.

Author contributions

All the authors contributed to the design, analyses and reporting for this manuscript. Both authors read and approved the final submitted manuscript.

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Declaration of competing interest

We have no conflicts of interest relevant to the content of this review.

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