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Original Research

The importance of objective functional and balance testing in pediatric anterior cruciate ligament reconstruction for a safe return-to-sport: A two-year prospective study

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ABSTRACT

Introduction/Objectives: Pediatric anterior cruciate ligament reconstruction (ACLR) outcomes, particularly long-term functional recovery and return-to-sport (RTS), remain debated and have not been well characterized in skeletally immature patients. This study evaluated functional movement competency, balance, and subjective knee function over a two-year follow-up in skeletally immature patients undergoing ACLR.

Methods: Forty-four skeletally immature patients (15 girls, 29 boys, median age 14, range 9–16) undergoing transphyseal ACLR using semitendinosus tendon autograft in a single center were prospectively assessed. Functional Movement Screen (FMS), Simple Knee Value (SKV), Single Leg Squat (SLS), and Y-Balance Test-Lower Quarter (YBT-LQ) were administered preoperatively and at 6, 12, and 24 months postoperatively. Linear mixed models (ANOVA or non-parametric tests) and post-hoc comparisons were used for statistical analysis.

Results: FMS scores improved throughout the two-year follow-up ($p = 0.024$), with increases observed from 6 months postoperatively. SKV also demonstrated continuous improvement at all time points ($p < 0.001$). However, no clinically meaningful correlation was found between SKV and FMS scores over time. SLS showed differences at 24 months for both the operated (0.6; $p = 0.004$) and contralateral leg (0.6; $p = 0.03$), though with minimal clinical relevance. YBT-LQ composite scores statistically improved bilaterally at 24 months, with minimal clinical relevance in the contralateral leg (−3.7; $p = 0.011$). The inter-limb difference in composite scores remained stable over time. YBT-LQ anterior reach distance progressively improved in the operated leg from 6 to 24 months. The inter-limb difference in anterior reach distance did not change over time.

Conclusion: Pediatric ACLR patients demonstrated progressive functional improvement over two years, with additional improvements occurring beyond 12 months, supporting the potential value of extended rehabilitation and reassessment. The lack of correlation between subjective and objective measures underscores the need for comprehensive assessments, including functional tests, for safe RTS decisions, as subjective knee perception poorly reflects actual movement capacity.

Level of evidence: II.

INTRODUCTION

Anterior cruciate ligament (ACL) injuries are increasingly prevalent in skeletally immature athletes, posing major challenges to long-term musculoskeletal health and sustained sport participation [1,2]. Pediatric ACL reconstruction (ACLR) has become the standard of care for these injuries, and has increased substantially over the past two decades [3], with the objective of restoring knee stability and facilitating return to sport (RTS) [4].

Despite advances in surgical techniques and rehabilitation protocols, optimal timing and criteria for RTS after pediatric ACLR remain

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What are the new findings?

- Functional movement competency improves progressively over two years after pediatric anterior cruciate ligament reconstruction, with additional improvement after twelve months
- Subjective knee function improves at each follow-up but does not reflect objective movement capacity
- Extended rehabilitation and repeated objective testing may provide valuable support for return-to-sport decision-making in skeletally immature patients

debated, and long-term functional recovery is still incompletely characterized in skeletally immature patients [4,5]. A major concern is whether RTS criteria derived from adult populations can be safely applied to pediatric athletes, whose ongoing growth, skeletal maturation, and neuromuscular development may influence both recovery trajectories and reinjury risk [4,5].

A critical area of uncertainty lies in the relationship between subjective knee function, as reported by patients, and objective measures of functional performance [6–8]. Relying solely on subjective reports may not accurately reflect true movement competency and could lead to premature or unsafe RTS decisions [9].

Furthermore, the progression of functional recovery beyond the first year post-surgery, a crucial period for skeletal maturation and neuromuscular adaptation, is not fully understood [10]. Recognizing RTS as a continuum, rather than a singular event, necessitates the integration of objective functional assessments with patient-reported measures and psychological readiness scores [10,11].

Therefore, this prospective study aimed to evaluate the longitudinal changes in functional movement competency, balance, and subjective knee function over a two-year follow-up in skeletally immature patients undergoing ACLR.

The primary objective was to define the two-year trajectory of recovery using a comprehensive assessment battery including the Functional Movement Screen (FMS), Simple Knee Value (SKV), Single Leg Squat (SLS), and Y-Balance Test–Lower Quarter (YBT-LQ). The secondary objective was to determine the correlation, if any, between objective functional measures (FMS) and subjective knee perception (SKV) at each time point.

METHODS

Study design and setting

This prospective cohort study was conducted at a tertiary pediatric orthopedic center between September 2017 and April 2019. Data were collected preoperatively and at 6, 12, and 24 months postoperatively. This study was approved by the Institutional Review Board (RnIPH 2019-56). Informed consent was obtained from all patients and their legal guardians prior to enrollment.

Participants

Fifty skeletally immature patients undergoing primary ACLR were consecutively recruited. Inclusion criteria were: age under 16 years; primary symptomatic ACL rupture confirmed by clinical examination, Magnetic Resonance Imaging (MRI), and arthroscopy; skeletal immaturity confirmed by the presence of open distal femoral and proximal tibial physes on anteroposterior and lateral knee radiographs on the day of surgery.

Exclusion criteria included: previous knee surgery on the ipsilateral knee, concomitant ligament injuries requiring surgical intervention, and history of active infection or inflammatory disease; neuromuscular disorders and ACL agenesia.

Only patients who completed all four follow-up assessments were included in the analysis. Two fellowship-trained pediatric orthopedic surgeons specialized in knee sports injuries performed clinical assessments and surgery and managed recruitment.

Surgical procedure

All ACLR procedures were performed as previously described by Lehoczky et al. [12], whose technique demonstrated similar return-to-sport outcomes regardless of associated meniscal repair. A quadrupled semitendinosus autograft was used with adjustable suspensory fixation on both the femoral and tibial sides. Growth disturbance risk was minimized by protecting the perichondral ring and limiting tunnel diameter to 9 mm [13]. Meniscal tears were repaired as indicated using all-inside and outside-in techniques.

Rehabilitation protocol

Weight-bearing was allowed as tolerated with a hinged knee brace for the first 4 weeks, regardless of meniscal status. Early goals were full knee extension and quadriceps activation. Range-of-motion exercises started on postoperative day 1, with no restrictions after isolated ACL reconstruction and flexion limited to 120° for 3 months after meniscal repair.

Outpatient physical therapy began at discharge and included progressive strengthening, mobilization, proprioception, and plyometrics (2–4 supervised sessions/week, 45–75 min). This was guided by detailed written instructions provided to patients, families, and therapists. Rehabilitation progression was individualized based on functional test results at each follow-up. When performance was unsatisfactory, targeted recommendations were provided to address specific deficits and ensure adequate recovery before progression.

Return to pivoting and contact sports was permitted at 6 and 12 months, respectively, if clinical criteria were met (no effusion, near-full range of motion, controlled single-leg squat, pain-free running and landing, and successful sport-specific training). Functional test results were not used as standardized criteria for return-to-sport decision-making. However, when performance was clearly abnormal, return to sport was postponed based on clinical judgment.

Outcome measures

Functional movement competency was assessed using the FMS, a standardized test of fundamental movement patterns [14]. The FMS, comprising seven dynamic tests (deep squat, hurdle step, inline lunge, active straight-leg raise, shoulder mobility, trunk stability push-up, and rotary stability), evaluates strength, flexibility, range of motion, coordination, balance, and proprioception. Each test was scored on a 0–3 scale (total score 0–21): 0 = pain, 1 = inability, 2 = compensation, 3 = correct execution (maximum total score of 21). The FMS, a reliable and efficient tool also used in pediatric patients, identifies dysfunctions and asymmetries related to injury risk [15].

Subjective knee function was evaluated using the SKV, a patient-reported measure quantifying their perception of knee functionality as a percentage [16]. Scores range from 0 to 100, with 100 indicating normal function.

The SLS test is a movement control test often used in clinical practice and research to assess frontal plane knee control, regional interdependence, and intersegmental coordination [17]. The participants completed the test barefoot, wearing tight shorts and a sports bra. All participants were provided with standard instructions on how to complete the SLS test. The testers were placed three meters directly in front of the participants.

The subjects were asked to complete a quarter squat. Visual inspection was used to ensure participants squatted to 60° of knee flexion. If correction was needed, the rater would give verbal cues to increase or decrease knee flexion on subsequent squats. SLS test consisted of evaluation of 8 variables about foot movement, knee movement, pelvic movement, trunk alignment, and presence of painful movement during the test (Supplementary material Fig. S1). Each item was scored on a 0–1 scale: 1 indicated compensatory movement, while 0 denoted correct execution. Consequently, the more dysfunctional the movement, the greater the number of positive criteria.

Dynamic balance was assessed using the YBT-LQ, a standardized protocol for evaluating single-limb dynamic stability [18,19]. Participants stood on a central platform and reached with the contralateral leg in three directions: anterior, posteromedial, and posterolateral. After a standardized warm-up and practice trials, three maximum reach attempts were recorded for each direction. If a participant failed to maintain single-leg stance, return to the starting position, or touched the reaching foot to the ground, the trial was discarded. Both legs were tested, and maximum reach distances were normalized to individual limb length and averaged to calculate a composite score [20]. While the composite score offers a general summary of overall performance, the anterior reach component of the YBT-LQ is particularly valuable clinically. It correlates with ankle weight-bearing dorsiflexion range of motion (DROM) and single-limb balance (SLB), and demonstrates stronger predictive validity for injury risk, especially when asymmetries are present [21,22].

Evaluators were licensed athletic trainers (master's degree) who had undergone training in the testing methods. The SKV was collected before the functional tests. All functional assessments were consistently performed first on the healthy leg and then on the operated leg to ensure standardization of the procedure. The participants were evaluated while performing FMS, SLS test and YBT-LQ consecutively on the same day.

Statistical analysis

Statistical analyses were performed using R Studio software (R version 4.4.2). The distribution of numerical variables was evaluated by visual inspection of Q–Q plots and by the Shapiro–Wilk test. Descriptive statistics were used to characterize the dataset and were reported as median and interquartile range (IQR) for numerical variables and as absolute frequencies with percentages for categorical variables. In contrast, results derived from analytical and comparative statistical models are presented as mean differences with corresponding 95% confidence intervals (95% CI), as appropriate.

The evolution of a numerical score over time (4 time points) was analyzed on a per-protocol basis, excluding patients with missing data. The main analysis was based on a mixed linear regression model accounting for repeated measures. The adequacy of the model was checked by studying the residuals (normality, homogeneity, outliers). In the event of validation, an ANOVA was performed, followed by multiple comparisons using the Tukey procedure. If the model assumptions were not satisfied, a Friedman test was applied, followed by post-hoc Conover tests with Holm-Bonferroni correction.

In the study, the correlation between FMS score and SKV score was assessed at each time point by simple linear regression and Spearman correlation. In the absence of statistically significant correlations, the comparison of slopes over time was not pursued.

The sample size was based on consecutive eligible patients treated during the study period; no a priori power calculation was performed. The statistical significance threshold was set at 5%.

RESULTS

Fifty patients (median age 14 years, range 9–16) underwent ACLR between September 2017 and April 2019 (Table 1). At 24 months, six patients were excluded (three re-ruptures (6%) and three lost to follow-up), leaving 44 patients (88%) for analysis. No major postoperative complications, including infection or neurovascular injury, were observed during the follow-up period.

Functional Movement Screen (FMS) and Simple Knee Value (SKV)

Functional Movement Screen (FMS) and the Simple Knee Value (SKV) were assessed preoperatively and at 6, 12, and 24 months (Supplementary material - Table 1s). FMS changed over time ($p = 7.124 \times 10^{-6}$), with a statistically significant improvement from 12 to 24 months (adjusted $p = 0.024$). The preoperative-to-6-month difference was not statistically significant (mean difference −0.4; 95% confidence interval (CI): [−1.1, 0.2]; adjusted $p = 0.30$) (Fig. 1A).

SKV improved over time ($p < 2.2 \times 10^{-16}$), with statistically significant increases across follow-ups (all adjusted $p < 0.001$), including 12 versus 24 months ($p < 0.05$) (Fig. 1B).

Correlation between FMS score and SKV score for each time

The association between FMS and SKV was weak and inconsistent across time points (Fig. 2). No statistically significant relationships were observed preoperatively or at 6 months. At 12 and 24 months, regression slopes reached statistical significance but were small (0.08 and 0.07, respectively) and correlations remained weak; overall, no clinically meaningful correlation was identified.

Single Leg Squat (SLS)

The Single Leg Squat (SLS) test showed a time effect in both limbs (operated $p = 0.003$; contralateral $p = 0.02$) (Fig. 3 and Supplementary material Table S2). The only significant pairwise difference was

Table 1
Demographic and physical characteristics of the enrolled population. BMI= Body Mass Index.

	Total (N = 44)
Sex, N (%)	
Male	29 (65.9)
Female	15 (34.1)
Age at surgery (years), median (IQR)	14 (2)
[min–max]	[9–16]
Time trauma-surgery (days), median (IQR)	182.5 (164.8)
[min–max]	[48–1754]
BMI (kg/m^2), median (IQR)	20.4 (3.7)
[min–max]	[15.9–28.8]
Level of sport at time of injury [29], N (%)	
Level I	28 (65.1)
Level II	10 (23.3)
Level III	4 (9.3)
Level IV	1 (2.3)
Preoperative activity level – median Tegner score (IQR)	9 (2)
[min–max]	[3–10]
Side, N (%)	
Right	17 (38.6)
Left	27 (61.4)
Associated meniscal injury, N (%)	19 (43.1)
Associated cartilage injury, N (%)	6 (13.6)

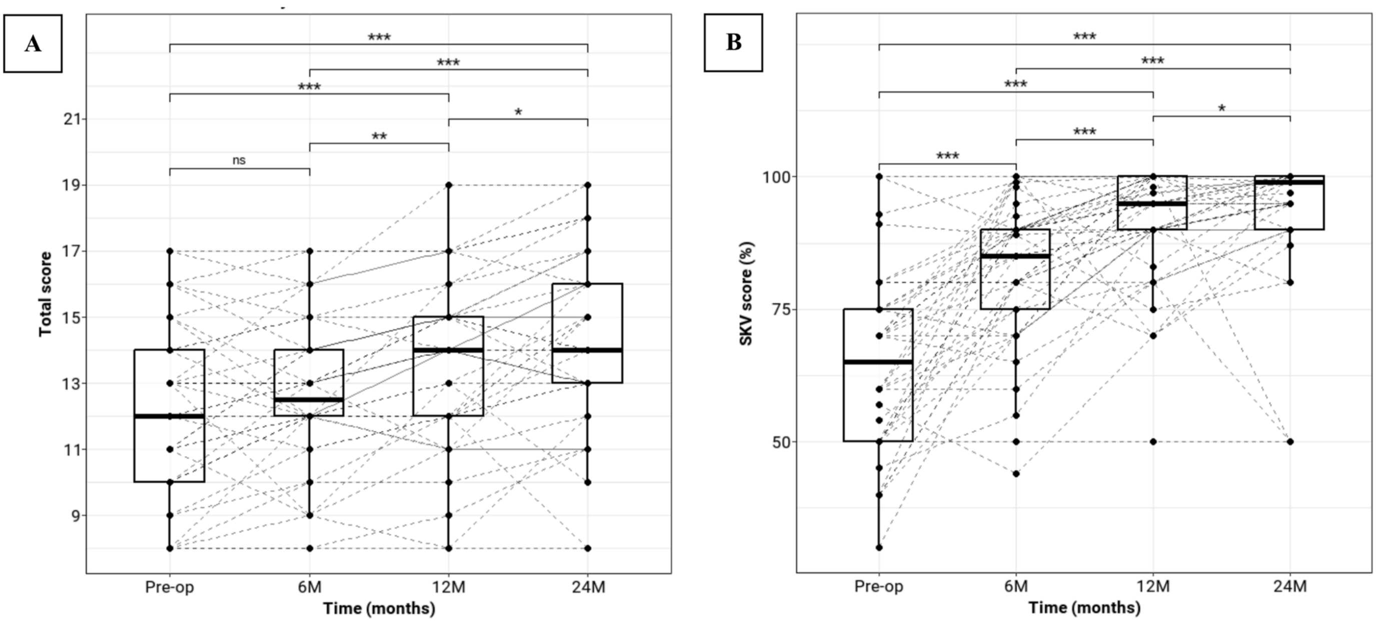

Fig. 1. Evolution of total Functional Movement Screen (FMS) scores (A) and Simple Knee Value (SKV) scores (B) over time. Box plots illustrating the distribution of scores at pre-operative, 6, 12, and 24 months post-surgery, with individual patient trajectories shown as dotted lines. Significance levels are denoted as follows: * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, ns = not statistically significant.

preoperative versus 24 months for both the operated (mean difference 0.6; 95% CI: [0.2, 1.1]; adjusted $p = 0.004$) and contralateral limb (mean difference 0.6; 95% CI: [0.05, 1.1]; adjusted $p = 0.03$). However, while statistically significant, the clinical relevance of this difference remains limited, as a 0.6-point gain may not reflect a meaningful improvement in functional performance. No other comparisons were statistically significant.

Y-Balance Test-Lower Quarter (YBT-LQ)

The Y-Balance Test-Lower Quarter (YBT-LQ) composite scores changed over time (operated $p = 0.002$; contralateral $p = 0.003$) (Fig. 4 and Supplementary material Table S3). In the operated limb, improvements were observed from preoperative to 24 months (adjusted $p = 0.011$) and from 6 to 24 months (adjusted $p = 0.002$), suggesting a meaningful improvement in dynamic balance of the operated leg by the 24-month follow-up.

In the healthy limb, small differences were detected from preoperative to 12 months (mean difference −3.0; 95% CI: [−5.3, −0.7]; $p = 0.006$) and to 24 months (−3.7; 95% CI: [−6.4, −1.0]; $p = 0.004$). The interlimb composite difference did not change over time ($p = 0.15$). These small declines may have limited clinical relevance, as a decrease of 3 points on this scale remains questionable.

The Y-Balance Test-Lower Quarter (YBT-LQ) anterior scores changed over time in both limbs (operated $p = 0.005$; contralateral $p = 0.004$) (Fig. 5 and Supplementary material Table S4). In the operated limb, anterior reach improved from preoperative to 24 months (adjusted $p = 0.028$) and from 6 to 24 months (adjusted $p = 0.003$). No statistically significant differences were found between the earlier time points (pre-op, 6, and 12 months), suggesting that improvements in anterior reach became evident only in the long term.

In the contralateral limb, only the preoperative-to-24-month comparison was statistically significant (adjusted $p = 0.002$). Other pairwise comparisons did not reveal statistically significant changes, suggesting a more stable performance over time in the healthy leg.

Interlimb anterior reach score difference (operated minus contralateral leg) remained stable ($p = 0.54$) throughout the follow-up period.

DISCUSSION

This study prospectively evaluated the functional outcomes of skeletally immature patients following ACLR over a two-year period, utilizing a comprehensive assessment battery that included FMS, SKV, SLS, and YBT-LQ.

The key findings highlight a trajectory of progressive functional improvement, with additional improvements observed beyond the first year post-surgery, highlighting the potential value of extended patient monitoring up to two years post-ACLR, as patients may not be fully recovered at one year. Secondarily, our study observed a lack of correlation between objective and subjective functional measures, underscoring the importance of integrating objective functional measures in RTS assessment and indicating that patients' perception of knee health may not align with their actual movement competency.

FMS scores demonstrated a statistically significant improvement throughout the two-year follow-up, with increases observed from 6 months postoperatively. SKV also demonstrated continuous improvement at all time points. Previous research has indicated that at an average of 9 months post-operatively, composite FMS scores in adolescent patients suggested an elevated risk for lower extremity injury, based on established cut-off scores (total score ≤14 out of 21), compared to adults [15]. This highlights that even several months after surgery, functional movement competency in young individuals may not have fully recovered, potentially differing from recovery patterns observed in adults. Our study demonstrated improvements in FMS scores throughout the two-year follow-up, with increases observed from 6 months post-operatively and continuing also after 12 months. Mayer et al. demonstrated that there was no difference in objective test results (FMS and YBT-LQ) between patients released versus not released to RTS, based solely on the clinical assessment of an orthopedic surgeon [23]: at six months, this finding suggests that the average patient in both groups may have an increased risk of lower extremity injuries, highlighting the need for more comprehensive return-to-sport criteria. This protracted timeline of functional recovery could potentially be related to the delayed nature of ACL graft ligamentization in young patients. As Accadbled et al. highlighted [24], the biological process of ACL graft ligamentization is gradual, typically occurring between 12 and 24

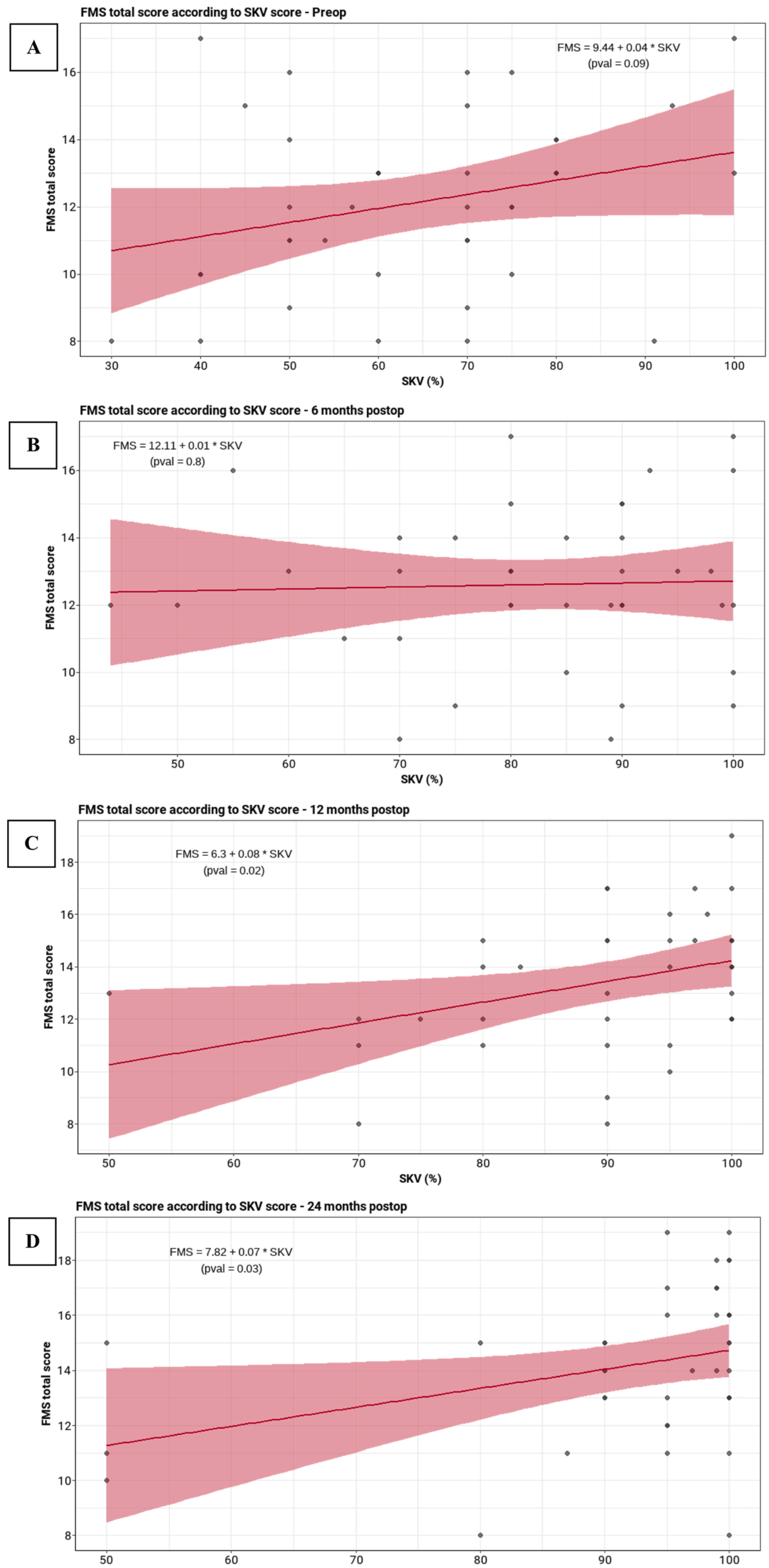

Fig. 2. Correlation between total Functional Movement Screen (FMS) score and Simple Knee Value (SKV) over time. Scatter plot depicting the relationship between FMS and SKV scores: red line representing linear regression fit and the shaded red area indicating the 95% confidence interval. Individual patient data points are shown as gray dots. A = pre-surgery, B = 6 months post-surgery, C = 12 months after surgery, D = 24 months after surgery.

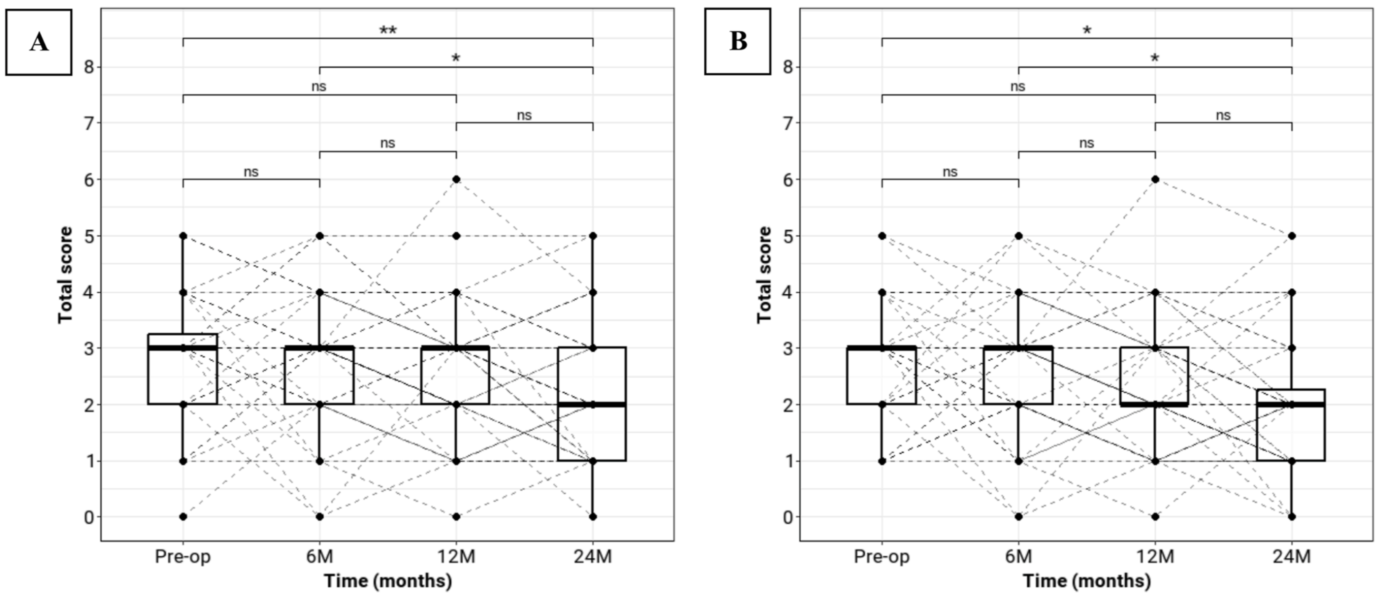

Fig. 3. Evolution of Single Leg Squat (SLS) scores for the operated (A) and healthy (B) legs over time. Box plots illustrating the distribution of scores at pre-operative, 6, 12, and 24 months post-surgery, with individual patient trajectories shown as dotted lines. Significance levels are denoted as follows: * = $p < 0.05$, ** = $p < 0.01$, ns = not statistically significant.

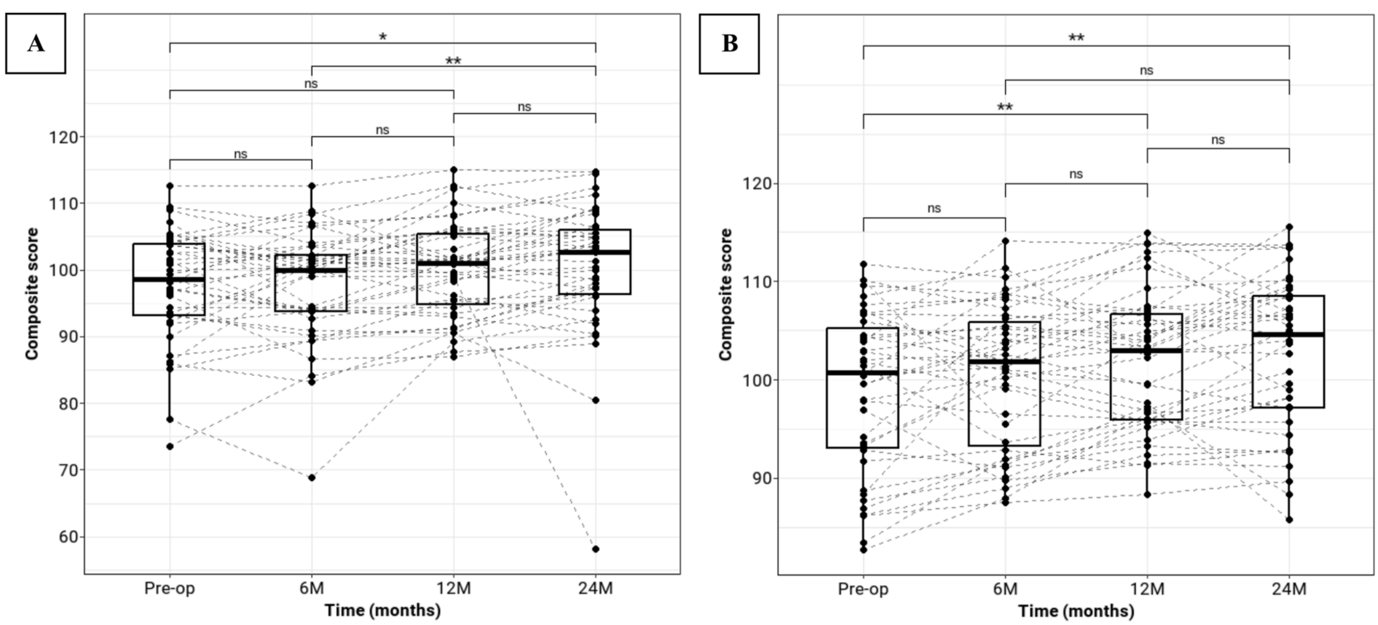

Fig. 4. Evolution of Y-Balance Test-Lower Quarter (YBT-LQ) composite scores for the operated (A) and healthy (B) legs over time. Box plots illustrating the distribution of scores at pre-operative, 6, 12, and 24 months post-surgery, with individual patient trajectories shown as dotted lines. Significance levels are denoted as follows: * = $p < 0.05$, ** = $p < 0.01$, ns = not statistically significant.

months following surgery. This suggests that both the degree of residual knee laxity and the graft's MRI signal characteristics could be important factors to consider when determining a patient's readiness for sports resumption. Therefore, continued functional improvement in our cohort, even at 24 months, might reflect these ongoing graft maturation processes.

However, despite the statistical significance of the improvements in both FMS and SKV scores, only weak correlations were observed between these two measures over time, reaching statistical significance at later follow-up points but with low slopes and questionable clinical relevance. While simplified assessments of objective passive stability (e.g., joint laxity) [25], isometric strength [7], global function (e.g., timed hop tests) [26], biomechanical variables (e.g., flexion angle, joint excursion, stiffness) [27] and knee-specific forces during dynamic movements [6] have demonstrated some correlation with subjective functional ability in adults, our study revealed a lack of correlation between subjective patient-reported outcomes and objective functional measures in skeletally immature patients. This discrepancy highlights the need for caution when extrapolating findings from adult studies to the pediatric population.

This observation highlights a crucial clinical consideration: a pediatric patient's subjective feeling of improvement or reduced symptoms

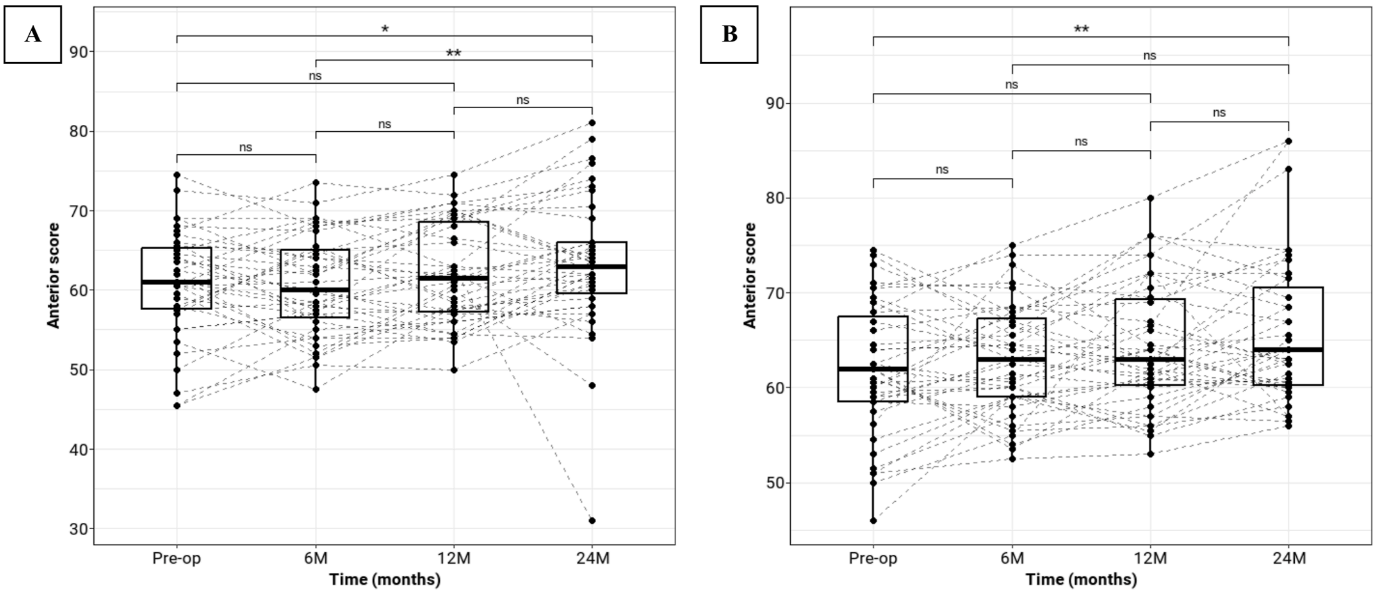

Fig. 5. Evolution of Y-Balance Test-Lower Quarter (YBT-LQ) anterior scores for the operated (A) and healthy (B) legs over time. Box plots illustrating the distribution of scores at pre-operative, 6, 12, and 24 months post-surgery, with individual patient trajectories shown as dotted lines. Significance levels are denoted as follows: * = $p < 0.05$, ** = $p < 0.01$, ns = not statistically significant.

does not guarantee a corresponding improvement in objective functional capacity. Young athletes may feel their knee has recovered but still exhibit functional deficits that increase their risk of re-injury upon return to sport. Therefore, relying solely on how the patient "feels" is insufficient for determining readiness to return to sport. Objective functional testing is essential to provide a comprehensive evaluation of the athlete's movement competency and to ensure a safe return to sport.

The weak association between FMS and SKV scores could also be attributed to the problematic data distribution, with a limited number of low SKV values, and the unsatisfactory visual representation. These factors limit the interpretation of the statistically significant associations observed at 12 and 24 months.

SLS scores showed statistically significant differences at 24 months for both the operated and contralateral legs, indicating improvement in single-leg stability and strength. However, these improvements were of minimal clinical relevance (95% CI: [0.2; 1.1] and 95% CI: [0.05; 1.1]), respectively. Although SLS scores showed statistically significant changes at 24 months, the magnitude of improvement was small and may not translate into substantial functional benefits for patients. Moreover, no statistically significant differences in SLS scores were observed within the first year post-surgery for either leg. Consistent with our findings, Batti et al. demonstrated that in an adult population, knee valgus angle during SLS remained relatively constant at 6 and 12 months post-ACLR [28]; this period coincides with a critical phase in rehabilitation when many athletes resume athletic activities [28]. This observation underscores the importance of longer-term follow-up in assessing functional recovery following ACLR in skeletally immature patients, as clinically relevant changes may occur beyond the commonly reported one-year mark.

YBT-LQ composite scores statistically improved bilaterally at 24 months, with minimal clinical relevance observed in the contralateral leg. YBT-LQ anterior reach distance also progressively improved in the operated leg from 6 to 24 months, with the inter-limb difference in anterior reach distance not changing over time. These findings suggest that dynamic balance, as measured by the YBT-LQ, continues to improve up to two years post-surgery, particularly in the operated limb. The improvement in anterior reach distance in the operated leg from 6 to 24 months highlights the importance of continued rehabilitation and neuromuscular adaptation during the second year post-ACLR.

This study has several limitations: first, the relatively small sample size, even within a tertiary referral center, represents a major limitation. Additionally, a priori power analysis was not conducted before study initiation, which may have impacted the robustness of statistical conclusions. Although several outcomes reached statistical significance, the magnitude of change was relatively small, particularly for FMS, SLS, and YBT-LQ, raising questions about their clinical relevance. Moreover, no well-established minimal clinically important difference (MCID) exists for these measures in pediatric populations, limiting the interpretation of their clinical significance. Furthermore, the observed improvements in functional outcomes may be partially influenced by physiological growth and neuromuscular maturation inherent to adolescence, representing a potential confounding factor. Given the lack of longitudinal normative data on FMS, SLS, and YBT-LQ performance in healthy pediatric populations, it was not possible to distinguish between true postoperative recovery and age-related functional development. Lastly, psychological readiness and self-efficacy in return-to-sport decisions were not assessed in this study. Future research with larger sample sizes, extended follow-up periods, and the integration of advanced biomechanical and psychological assessments will be crucial in refining RTS criteria and optimizing rehabilitation strategies in pediatric ACLR patients.

Despite limitations, the findings of this study have several important clinical implications. First, they support the potential value of extended rehabilitation and functional testing beyond the first year post-ACLR in skeletally immature patients. Additional functional improvements can occur between one and two years following surgery, highlighting the importance of continued monitoring and intervention during this period. Second, the lack of correlation between subjective and objective measures underscores the need for comprehensive assessments that include objective functional tests, such as FMS, SLS, and YBT-LQ, in addition to patient-reported outcomes, for safe RTS decisions. Relying solely on subjective knee function may lead to inaccurate evaluations of an athlete's readiness to return to sport.

CONCLUSION

In conclusion, this study demonstrates that skeletally immature patients undergoing ACLR exhibit progressive functional improvement over two years, with additional improvements occurring beyond 12 months.

The lack of correlation between subjective and objective measures highlights the need for comprehensive assessments, including functional tests, for safe RTS decisions, as subjective knee perception poorly reflects actual movement capacity. These findings support the potential value of extended rehabilitation and reassessment in this population.

Author contributions

Crippa Marco: Methodology, Visualization, Writing – original draft. Turati Marco: Conceptualization, Methodology, Writing – original draft. Flumian Clara: Formal Analysis, Methodology. Doumerc Jeremy: Conceptualization, Investigation. Hennart Benoit: Investigation. Accadbled Franck: Conceptualization, Funding Acquisition, Investigation, Project Administration, Resources, Writing – review & editing.

All authors read and approved the final manuscript.

Ethical review committee statement

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Declaration of generative AI and AI-assisted technologies in the writing process

No use of any generative AI or AI-assisted technologies to write this manuscript.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Franck ACCADBLED reports financial support and equipment, drugs, or supplies were provided by Zimmer Biomet. Franck ACCADBLED reports a relationship with Zimmer Biomet that includes: consulting or advisory. Franck ACCADBLED reports a relationship with Orthofix that includes: consulting or advisory. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jisako.2026.101149.

References

[1] Kooy CEVW, Jakobsen RB, Fenstad AM, et al. Major increase in incidence of pediatric ACL reconstructions from 2005 to 2021: a study from the Norwegian knee ligament register. Am J Sports Med 2023;51(11):2891–9. https://doi.org/10.1177/03635465231185742.

[2] Duart J, Rigamonti L, Bigoni M, Kocher MS. Pediatric anterior cruciate ligament tears and associated lesions: epidemiology, diagnostic process, and imaging. J Child Orthop 2023;17(1):4–11. https://doi.org/10.1177/18632521231153277.

[3] Turati M, Crippa M, Nicolaou N, et al. An increase in paediatric arthroscopy in Europe: experience of the EPOS sport study group. J Child Orthop 2024;28. https://doi.org/10.1177/18632521241302997.

[4] Lorange JP, Senécal L, Moisan P, Nault ML. Return to sport after pediatric anterior cruciate ligament reconstruction: a systematic review of the criteria. Am J Sports Med 2024;52(6):1641–51. https://doi.org/10.1177/03635465231187039.

[5] Matsuzaki Y, Chipman DE, Hidalgo Perea S, Green DW. Unique considerations for the pediatric athlete during rehabilitation and return to sport after anterior cruciate ligament reconstruction. Arthrosc Sports Med Rehabil 2022;4(1):e221–30. https://doi.org/10.1016/j.asmr.2021.09.037.

[6] Smale KB, Conconi M, Sancisi N, et al. Relationship of knee forces to subjective function Pre- and Post-ACL reconstruction. Med Sci Sports Exerc 2020;52(6):1338–46. https://doi.org/10.1249/MSS.0000000000002258.

[7] Bodkin S, Goetschius J, Hertel J, Hart J. Relationships of muscle function and subjective knee function in patients after ACL reconstruction. Orthop J Sports Med 2017;5(7):2325967117719041. https://doi.org/10.1177/2325967117719041.

[8] Wilk KE, Romaniello WT, Soscia SM, Arrigo CA, Andrews JR. The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-reconstructed knee. J Orthop Sports Phys Ther 1994;20(2):60–73. https://doi.org/10.2519/jospt.1994.20.2.60.

[9] Sugimoto D, Heyworth BE, Carpenito SC, Davis FW, Kocher MS, Micheli LJ. Low proportion of skeletally immature patients met return-to-sports criteria at 7 months following ACL reconstruction. Phys Ther Sport 2020;44:143–50. https://doi.org/10.1016/j.ptsp.2020.05.007.

[10] Greenberg E.M., Dyke J., Link M., Todd Lawrence J., Ganley T. Understanding the progression of function and psychological readiness of pre-adolescent athletes following anterior cruciate ligament reconstruction. Orthop J Sports Med 2022;10(5_suppl2):2325967121S00471. https://doi.org/10.1177/2325967121S00471.

[11] Mercurio AM, Scott EJ, Sugimoto D, et al. Assessing the impact of psychological readiness on performance and symmetry in functional testing after ACL reconstruction in pediatric and adolescent patients. Orthop J Sports Med 2024;12(9):23259671241274768. https://doi.org/10.1177/23259671241274768.

[12] Lehoczky G, Flumian C, Sales de Gauzy J, Accadbled F. Similar return-to-sports after anterior cruciate ligament reconstruction with or without meniscal repair in skeletally immature patients: a prospective, comparative cohort study. J Pediatr Orthop 2025;45(5):e473–9. https://doi.org/10.1097/BPO.0000000000002912.

[13] Bolzinger M, Thevenin Lemoine C, Flumian C, Nicolaou N, Sales de Gauzy J, Accadbled F. Analysis of growth after transphyseal anterior cruciate ligament reconstruction in children. J Pediatr Orthop 2023;43(9):537–42. https://doi.org/10.1097/BPO.0000000000002484.

[14] Chorba RS, Chorba DJ, Bouillon LE, Overmyer CA, Landis JA. Use of a functional movement screening tool to determine injury risk in female collegiate athletes. N Am J Sports Phys Ther 2010;5(2):47–54. https://pubmed.ncbi.nlm.nih.gov/21589661/.

[15] Boyle MJ, Butler RJ, Queen RM. Functional movement competency and dynamic balance after anterior cruciate ligament reconstruction in adolescent patients. J Pediatr Orthop 2016;36(1):36–41. https://doi.org/10.1097/BPO.0000000000000402.

[16] Marot V, Justo A, Alshanquiti A, et al. Simple knee value: a simple evaluation correlated to existing knee PROMs. Knee Surg Sports Traumatol Arthrosc 2021;29(6):1952–9. https://doi.org/10.1007/s00167-020-06281-1.

[17] Di Paolo S, Musa F, d'Orsi GM, et al. A comprehensive two-dimensional scoring system to assess the single-leg squat task in football players. Knee 2024;48:52–62. https://doi.org/10.1016/j.knee.2024.02.016.

[18] Plisky PJ, Gorman PP, Butler RJ, Kiesel KB, Underwood FB, Elkins B. The reliability of an instrumented device for measuring components of the star excursion balance test. N Am J Sports Phys Ther 2009;4(2):92–9. https://pubmed.ncbi.nlm.nih.gov/21589661/.

[19] Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star excursion balance test as a predictor of lower extremity injury in high school basketball players. J Orthop Sports Phys Ther 2006;36(12):911–9. https://doi.org/10.2519/jospt.2006.2244.

[20] Butler RJ, Lehr ME, Fink ML, Kiesel KB, Plisky PJ. Dynamic balance performance and noncontact lower extremity injury in college football players: an initial study. Sports Health 2013;5(5):417–22. https://doi.org/10.1177/1941738113498703.

[21] Plisky P, Schwartkopf-Phifer K, Huebner B, Garner MB, Bullock G. Systematic review and meta-analysis of the Y-Balance test lower quarter: reliability, discriminant validity, and predictive validity. Int J Sports Phys Ther 2021;16(5):1190–209. https://doi.org/10.26603/001c.27634.

[22] Hoch MC, Hoch JM, Powden CJ, Gabriel EH, Welsch LA. Anterior reach and symmetry on the Y-Balance test are related to dorsiflexion range of motion but not single-limb balance in physically active young adults. Int J Athl Ther Train 2021;26(2):101–5. https://doi.org/10.1123/ijatt.2020-0004.

[23] Mayer SW, Queen RM, Taylor D, et al. Functional testing differences in anterior cruciate ligament reconstruction patients released versus not released to return to sport. Am J Sports Med 2015;43(7):1648–55. https://doi.org/10.1177/0363546515578249.

[24] Accadbled F, Lescot T, Nicolaou N, et al. Knee anterior laxity and graft maturation after transphyseal anterior cruciate ligament reconstruction. J Pediatr Orthop 2025;45(5):281–6. https://doi.org/10.1097/BPO.0000000000002888.

[25] Snyder-Mackler L, Fitzgerald GK, Bartolozzi AR, Ciccotti MG. The relationship between passive joint laxity and functional outcome after anterior cruciate ligament injury. Am J Sports Med 1997;25(2):191–5. https://doi.org/10.1177/036354659702500209.

[26] Logerstedt D, Grindem H, Lynch A, et al. Single-legged hop tests as predictors of self-reported knee function after anterior cruciate ligament reconstruction: the Delaware-Oslo ACL cohort study. Am J Sports Med 2012;40(10):2348–56. https://doi.org/10.1177/0363546512457551.

[27] Smale KB, Alkjaer T, Flaxman TE, Krogsgaard MR, Simonsen EB, Benoit DL. Predicting post-operative functional ability from pre-operative measures in ACL-injured individuals. Scand J Med Sci Sports 2020;30(1):166–73. https://doi.org/10.1111/sms.13549.

[28] Batty LM, Feller JA, Damasena I, et al. Single-leg squat after anterior cruciate ligament reconstruction: an analysis of the knee valgus angle at 6 and 12 months. Orthop J Sports Med 2020;8(8). https://doi.org/10.1177/2325967120946328.

[29] Hefti F, Müller W, Jakob RP, Stäubli HU. Evaluation of knee ligament injuries with the IKDC form. Knee Surg Sports Traumatol Arthrosc 1993;1(3-4):226–34. https://doi.org/10.1007/BF01560215.