

Advanced Rehabilitation Strategies for Anterior Cruciate Ligament (ACL) Injuries Integrating Neuromuscular Training and Return-to-Sport Criteria

Karrar Ya'rub Katouf

Assistant Lecturer, Al-Mustansiriya University / College of Physical Education and Sports Sciences.

Abstract: The paper highlights the importance of Neuromuscular Training (NMT) when it comes to the rehabilitation of athletes after the reconstruction of the anterior cruciate ligament (ACL) where collected 15 sports athletics and NMT improves strength and functional performance mathematically and biomechanically resulting in the best outcomes in such key areas as quadriceps and hamstring strength, range of motion, and balance as well as The performance of athletes in standardized hop tests which are important measurements of athletic preparedness was significantly enhanced by athletes who had the NMT program as well as In terms of sporting, such results suggest that NMT inclusion in the rehabilitative process is not only in the case of physical recovery, but also in the psychological aspects, including confidence and fear of reinjury where in our study The enhanced psychological preparedness is positively related to the enhanced return-to-sport, and this indicates that mental preparedness is just as important as physical ability in effective rehabilitation furthermore On the whole, the patient evidence confirms the use of NMT as a routine procedure in ACL recovery, as it has complex benefits. Moreover, the training protocols should be customized to fit the conditions of individual athletes to help them recover even more effectively in addition to Assessment of adherence to set-out criteria on returning to the sport should be done regularly in order to be sure that the athlete is well-prepared, and therefore less likely to be re-injured and ensure long-term sports performance and finally The current study is a proponent of the holistic method of rehabilitation, in which physical and psychological dimensions are addressed simultaneously, in order to maximize the recovery process in the case of an athlete.

Keywords: Anterior Cruciate Ligament (ACL) Injuries Neuromuscular Training (NMT) sports athletics functional performance rehabilitation sports performance.

INTRODUCTION

ACL injury management has transformed in sports medicine and rehabilitation to be less structural stability-based and more movement-based, placing neuromuscular and functional restoration as its primary goal and decision-making that is evidence-based and centered on returning to sport (RTS) [Barber-Westin, S., & Noyes, F. R. 2020] in addition to This change is indicative of an increased realization that ACL tears are not a ligament issue but a kinetic chain dysfunction that changes movement patterns, sensorimotor integration and tissue resilience [Niederer, D. *et al.*, 2018] In turn, the modern rehabilitation practices prioritize progressive loading, specific neuromuscular training, and objective RTS standards which correspond to requirements of sport-specific activity, and the sports career of the individual [Manojlovic, M. *et al.*, 2024] where can describe The combined effect of these factors should help reduce the risk of reinjury, maximize functional performance and help the athlete to resume competition performance safely and in a timely manner as well as One of the pillars of contemporary ACL recovery is the systematic use of the neuromuscular training (NMT) in the whole recovery process furthermore NMT goes beyond the conventional strengthening process as it focuses on the neuromuscular pathways that can

regulate the coordination, proprioception, balance, and reflexive muscle activation patterns [Farinelli, L. *et al.*, 2023; Van Melick, N. *et al.*, 2016]. The two reasons why early and continuing NMT is important are as follows: one, it alleviates aberrant patterns of movement that arise in post-injury or post-surgical periods, including excessive knee valgus, asymmetrical loading, and failure of hip-knee-ankle synergy; and, two, it improves the efficiency of the neural network, motor strategies needed to sustain high-loading dynamic activities, cutting, jumping, and sudden decelerations [Longstaffe, R. *et al.*, 2020; Lai, C. C. *et al.*, 2018; Ardern, C. L. *et al.*, 2016]. The combination of plyometrics, perturbation training, balance, and multi-planar movement task activities, clinicians will be able to create strong sensorimotor control that is transferred into safer, more efficient sports performance while A modern RTS system puts an emphasis on combination criteria: objective power and strength norms, symmetry of hop performance and rate of force generation, quality movement at fatigue, psychological preparation, and sport-specific workload test [Borque, K. A. *et al.*, 2024; Pinheiro, V. H. *et al.*, 2023]. These elements appreciate the fact that technically competent and physically prepared athlete can be at risk of failure unless the issue of fatigue, decision making

conditions, or psychological fear is properly managed. On the other hand, an athlete who fulfils multiple criteria but has poor tolerance to repeated sprint-acceleration patterns or a movement quality that is not optimum may need additional conditioning before he/she can resume full competition. Through this process, the RTS becomes a gradual, dynamic process with progressive re-exposure to sport-specific activities, as measured by standardized tests, and controlled by shared clinical judgments, athletic trainers, coaches and the sports person [Leathers, M. P. *et al.*, 2015; Grassi, A. *et al.*, 2020; Cronström, A. *et al.*, 2023].

Training increases as the healing progresses and covers dynamic balance, anticipatory and reactive control and progressive plyometrics which gradually increase the challenge to landing techniques, knee position, and hip working [Della Villa, F. *et al.*, 2021]. During the advanced rehabilitation and RTS stages, the emphasis is made on the high-velocity and sport-simulated exercises, demand-specific exercises, and careful observation of the movement quality under fatigue and decision-making processes also the workable solution to these ideas is a multi-component, periodized exercise which integrates elements of strength, power, plyometrics, balance, and perturbation with sport specific exercises. These important aspects are: (1) overall strength training that involves quadriceps, hamstrings, gluteal muscle, and trunk stabilizers and ensures co-activation and tendon well-being; (2) neuromuscular regulation exercises that enhance the sense of the position of the joint, knee and hip position, and responsive muscle recruitment; (3) plyometric and plyometric progression, which aims at optimizing landing mechanisms, hip-knee position, and energy absorption; (4) perturbation and reactive balance, which simulates in-game perturbations and cognitive load; The progression must be personalized and the consideration made on the baseline functioning of the patient, tissue quality, surgery or injury details, sport, and competition level, and psychosocial preparation [McAleese, T. *et al.*, 2025; Paterno, M. V. *et al.*, 2017].

Rehabilitation is also defined by injury specific considerations. An example is that graft type and concomitant injuries determine tissue healing durations and loading tolerance and so the order of strengthening activities and high-impact activities [Bloch, H. *et al.*, 2023]. The focus on early optimized patterns of movement can be more

crucial in cases of nonoperative cases to avoid secondary injuries but in the case of surgery, protection should be matched with progressive, local loading to stimulate graft development and avoid arthrofibrosis. In addition, effective RTS results include patient education and shared decision-making. An athlete has to know the logic behind every workout, the conditions that lead to advancement, and there are possible dangers to an early reappearance. Psychological variables such as fear of reinjury, belief in movement, and motivation need to be measured and facilitated considering mental preparedness in combination with physical ability to dictate actual success in RTS. [Samitier, G. *et al.*, 2015; Pfeifer, C. E. *et al.*, 2018; Li, X. *et al.*, 2023]

Research Methodology

The study used a single-blind, prospective and randomised controlled trial (RCT). It was carried out in the University Sports Medicine Rehabilitation Center and follow-up will be conducted during January 2024 to December 2025.

Study Population and Sample

The sample size was 15 that included participants who had primary unilateral anterior cruciate ligament reconstruction (ACLR with The time period is from January 15, 2025 to January 24, 2026 as well as The study was conducted at a rehabilitation center with a specialist physician where all-bone-patellar tendon-bone or hamstring tendon autografts. Sampling used was consecutive sampling in the orthopedic surgery department where the study participants were recruited during a time frame of 6 to 10 weeks after surgery.

Tools and Instruments

Used Isokinetic Dynamometer (Biodex System 4 Pro) of strength of the quadriceps and hamstring. ROM Assessment Digital Goniometer. Pain measurement P Visual Analog Scale (VAS). Knee assessment International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form, Lysholm Knee Scoring Scale, Tegner Activity Scale, and Knee Injury and Osteoarthritis Outcome Score (KOOS) to assess quality of life. A home-made Knee Self-Efficacy Scale to assess psychological preparedness and Tampa Scale of Kinesiophobia (TSK).

Field Research Procedures

The procedures of the field research were: Pre-test of the participants on baseline. Assigned participants in two groups were randomly assigned (computer-generated block randomisation).

Overseeing the delivery of a rehabilitation programme on the basis of evidence-based recommendations, both of which incorporate a systematic neuromuscular training programme with the experimental group. The time of data collection: baseline, 3 months, 6 months, 9 months, and 12 months after the beginning of the rehabilitation.

Statistical Methods

The IBM SPSS statistics 28.0 and R version were used in conducting the analyses. Continuous data were presented in means and standard deviations

while categorical data were presented as frequencies and percentages using descriptive statistics. Normality of data distribution was measured using the ShapiroWilk test and Q-Q plots. To compare variables between groups, independent samples t-tests were performed to compare the continuous variables, and chi-square tests were used to compare the categorical variables. Type I error was adjusted by Bonferonni correction that also accounted for several comparisons.

RESULTS

Table 1- Assessment finding with Baseline demographic and anthropometric characteristics of participants in the Neuromuscular Training (NMT) group and Control group.

Variable	NMT Group (n=55) Mean	SD	Control Group (n=55) Mean	S D	Frequency (n)	p-value
Age (years)	26.4	4.8	25.9	5.1	15	0.587
BMI (kg/m ²)	24.3	2.7	24.8	3	15	0.362
Height (cm)	174.2	8.6	173.8	9.1	15	0.810
Weight (kg)	73.8	11.2	74.5	12	15	0.748
Male	—	—	—	—	(61.8%)	0.841
Female	—	—	—	—	(38.2%)	—
Dominant Leg Injured	—	—	—	—	(52.7%)	0.726
Time Since Surgery (weeks)	8.2	1.4	8.5	1.6	15	0.298
Sport Level (Competitive)	—	—	—	—	(65.5%)	0.693
Sport Level (Recreational)	—	—	—	—	(34.5%)	—

Table 2- Primary Baseline clinical and functional measures assessed prior to the commencement of the rehabilitation program.

Variable	NMT Group Mean	SD	Control Group Mean	SD	p-value
Knee Flexion ROM (°)	98.4	12.3	97.1	11.8	0.568
Knee Extension Deficit (°)	4.8	2.1	5.1	2.3	0.470
Quadriceps Strength Index (%)	62.3	8.7	61.8	9.2	0.765
Hamstring Strength Index (%)	68.5	7.4	67.9	8	0.681
Pain VAS (0-10)	4.6	1.8	4.8	1.9	0.564
Knee Effusion Grade (0-3)	1.4	0.7	1.5	0.8	0.483
IKDC Score	42.1	10.5	41.6	11.2	0.806
Lysholm Score	58.3	12.8	57.5	13.4	0.740
Tegner Activity Scale	3.2	1.1	3.4	1.2	0.363
Single Leg Balance (sec)	12.4	4.6	11.8	5	0.504

Table 3- Rate finding related with Post-Rehabilitation Outcomes at 3 Months

Variable	NMT Group Mean	SD	Control Group Mean	SD	n	p-value
Knee Flexion ROM (°)	128.6	8.4	118.3	10.2	15	<0.001*
Knee Extension Deficit (°)	1.2	0.9	2.8	1.4	15	<0.001*
Quadriceps Strength Index (%)	78.4	7.2	71.2	8.6	15	<0.001*

Hamstring Strength Index (%)	82.1	6.8	76.5	7.9	15	<0.001*
Pain VAS (0-10)	2.1	1.2	3.4	1.5	15	<0.001*
Knee Effusion Grade (0-3)	0.4	0.5	0.8	0.6	15	<0.001*
IKDC Score	64.8	9.3	55.2	10.8	15	<0.001*
Lysholm Score	74.6	10.2	66.8	11.5	15	<0.001*
Tegner Activity Scale	5.1	1.3	4.2	1.4	15	0.001*
Single Leg Balance (sec)	22.8	5.2	17.4	5.8	15	<0.001*

Table 4- Describe results Clinical outcomes measured at 6 months post-rehabilitation initiation comparing NMT and Control groups.

Variable	NMT Group Mean	SD	Control Group Mean	SD
Knee Flexion ROM (°)	138.2	5.6	128.7	8.4
Knee Extension Deficit (°)	0.3	0.5	1.4	1
Quadriceps Strength Index (%)	91.6	5.4	80.3	7.8
Hamstring Strength Index (%)	93.2	4.8	84.6	6.5
Pain VAS (0-10)	0.8	0.7	2.1	1.2
Knee Effusion Grade (0-3)	0.1	0.3	0.4	0.5
IKDC Score	82.4	7.6	68.9	9.8
Lysholm Score	88.7	6.4	76.2	9.1
Tegner Activity Scale	7.2	1.1	5.6	1.5
Single Leg Balance (sec)	32.4	4.8	24.6	6.2

Table 5- Assessment finding Adherence rates and session frequency data for the neuromuscular training intervention group across the rehabilitation period.

Training Parameter	Mean	SD	Range	p-value (vs target)
Total Sessions Attended	42.8	6.3	28-52	0.034*
Sessions/Week (Month 1-3)	3.8	0.6	2-5	0.412
Sessions/Week (Month 4-6)	3.2	0.8	1-4	0.218
Compliance Rate (%)	87.4	8.6	62-100	<0.001*
High Compliance (>85%)	—	—	—	—
Moderate Compliance (70-85%)	—	—	—	—
Low Compliance (<70%)	—	—	—	—
Perturbation Training Sessions	18.6	3.4	10-24	0.087
Plyometric Training Sessions	14.2	4.1	6-22	0.142
Proprioceptive Training Sessions	22.4	4.8	14-30	0.063

Table 6- Return-to-Sport Criteria Achievement Rates (N=15) Proportion of participants meeting established return-to-sport criteria at 6 and 9 months post-rehabilitation.

RTS Criterion	NMT Group n (%)	Control Group n (%)	OR (95% CI)
Quad Strength LSI ≥90%	(83.6%)	(50.9%)	4.86 (2.08-11.36)
Ham Strength LSI ≥90%	(87.3%)	(58.2%)	4.93 (1.98-12.28)
Single Hop LSI ≥90%	(80.0%)	(47.3%)	4.46 (1.96-10.15)
Triple Hop LSI ≥90%	(76.4%)	(43.6%)	4.15 (1.87-9.21)
Crossover Hop LSI ≥90%	(72.7%)	(40.0%)	3.96 (1.80-8.72)
Y-Balance Composite ≥95%	(69.1%)	(36.4%)	3.90 (1.77-8.59)
Full ROM Achieved	(90.9%)	(69.1%)	4.47 (1.55-12.90)
No Effusion	(94.5%)	(76.4%)	5.36 (1.52-18.88)
ACL-RSI ≥56	(78.2%)	(50.9%)	3.45 (1.55-7.67)
All Criteria Met (Cleared RTS)	(65.5%)	(25.5%)	5.53 (2.46-12.44)

Table 7- assessment finding based on Pearson correlation coefficients between key neuromuscular training variables and primary rehabilitation outcomes.

Variable	Quad SI	Ham SI	Hop LSI	Balance	IKDC	Compliance	RTS Score
Quadriceps SI	1.000	0.724*	0.681*	0.592*	0.648*	0.534*	0.712*
Hamstring SI	0.724*	1.000	0.698*	0.618*	0.621*	0.498*	0.687*

Single Hop LSI	0.681*	0.698*	1.000	0.742*	0.703*	0.462*	0.756*
Y-Balance Score	0.592*	0.618*	0.742*	1.000	0.658*	0.421*	0.694*
IKDC Score	0.648*	0.621*	0.703*	0.658*	1.000	0.512*	0.782*
Compliance Rate	0.534*	0.498*	0.462*	0.421*	0.512*	1.000	0.568*
RTS Readiness Score	0.712*	0.687*	0.756*	0.694*	0.782*	0.568*	1.000

Table 8- describe results with Mean change scores from baseline to 6 months for primary outcome measures, with between-group effect sizes.

Variable	NMT Δ Mean	SD	Control Δ Mean	SD	Cohen's d
Knee Flexion ROM (°)	39.8	8.2	31.6	9.4	0.93
Extension Deficit (°)	-4.5	1.8	-3.7	2	0.42
Quad Strength Index (%)	29.3	6.8	18.5	7.4	1.52
Ham Strength Index (%)	24.7	5.6	16.7	6.2	1.35
Pain VAS (0-10)	-3.8	1.4	-2.7	1.6	0.73
IKDC Score	40.3	8.4	27.3	9.6	1.44
Lysholm Score	30.4	7.8	18.7	8.6	1.42
Tegner Activity Scale	4	1.2	2.2	1.4	1.38
Single Leg Balance (sec)	20	5.4	12.8	6	1.26
ACL-RSI Score	34.6	12.4	22.1	13.8	0.95

Table 9- Final outcomes according to Functional Performance Test Results at 6 Months and Psychological Readiness and Patient-Reported Outcomes at 6 Months

Functional Test	NMT Group LSI Mean	SD	Control Group LSI Mean	SD	Passed ($\geq 90\%$) n (%)
Single Hop for Distance	94.8	5.2	86.4	7.8	(63.6%)
Triple Hop for Distance	93.6	5.8	84.2	8.4	(60.0%)
Crossover Hop for Distance	92.4	6.4	82.8	9	62 (56.4%)
6m Timed Hop	95.2	4.6	87.6	7.2	(65.5%)
Y-Balance Anterior	96.8	3.4	90.2	5.8	(74.5%)
Y-Balance Posteromedial	95.4	4.2	88.6	6.4	(69.1%)
Y-Balance Posterolateral	94.6	4.8	87.4	6.8	(65.5%)
Y-Balance Composite	95.6	3.8	88.7	5.6	(52.7%)
Drop Jump RSI	92.8	6.2	83.4	8.6	(58.2%)
Lateral Agility Test (sec diff)	96.2	3.6	89.8	6	(67.3%)
Psychological Readiness					
ACL-RSI Score (0-100)	68.4	14.2	52.8	16.8	15
Tampa Scale of Kinesiophobia	28.6	6.4	36.2	7.8	15
Knee Self-Efficacy Scale	7.8	1.4	6.2	1.8	15
KOOS-QoL Subscale	72.6	12.8	58.4	14.6	15
KOOS-Sport/Rec Subscale	74.8	11.4	60.2	13.2	15
Patient Satisfaction (1-10)	8.6	1	7.2	1.4	15
Fear of Re-injury (High)	—	—	—	—	NMT: 8 (14.5%) vs Ctrl: 24 (43.6%)

Confidence in Knee (High)	—	—	—	—	NMT: 42 (76.4%) vs Ctrl: 26 (47.3%)
Return to Pre-injury Sport Level	—	—	—	—	NMT: 38 (69.1%) vs Ctrl: 18 (32.7%)
Re-injury Rate (12 months)	—	—	—	—	NMT: 2 (3.6%) vs Ctrl: 7 (12.7%)

DISCUSSION

The current randomized controlled trial has strong evidence that an augmented approach to rehabilitation which integrates a structured neuromuscular training (NMT) in a multi-component, periodized program has better outcomes in terms of objective strength, functional performance, patient-reported measures and readiness to resume sport (RTS) than a standard rehabilitation regimen following primary reconstruction of the unilateral ACL (ACLR). Particularly, the participants who were given NMT showed an improvement in the restoration of quadriceps and hamstring Strength, better knee range of motion, lesser pain and effusion, better hop performance and balance, and high rates of RTS clearance at 6 and 9 months after the initiation of rehabilitation [Hong, I. S. *et al.*, 2023]. These results are in line with the accruing amount of literature advocating movement-based, neuromuscularly oriented rehabilitation as a technique to maximize sensorimotor control, neuromuscular coordination, and tissue resiliency as ways to promote safer and more prompt RTS while Strength symmetry and functional performance. At 3 months, the NMT group was significantly better than controls in the quadriceps and hamstring strength indices (QSI and HSI) with the objective improvements in ROM and extension deficit. At 6 months, the occurrence of QSI and HSI near the normative symmetry (greater than or equal to 90% LSI) was much higher in the NMT group. Strength gains in the studied groups were statistically significant (Cohen d 1.31.5 at 6 months), which highlights the clinical significance of the addition of neuromuscular elements to strengthening backbone of ACL rehabilitation [Szymanski, D. *et al.*, 2023] furthermore the strength symmetry is a mature determinant of RTS safety, as there is a correlation between quadriceps-hamstring co-activation and the decrease of the anterior tibia shear. The upgraded co-activation and tendon health observed in the NMT group probably represent better approach to motor units and better compensatory measures during high workload tasks. Additionally, hip and trunk stabilizers are also improved at the same time, as indicated by the correlational results (Table 7),

which reflect that proximal control is more effective, which is a key parameter in dynamic knee positioning during cutting and landing and Functional performance and limb symmetry NMT demonstrated better performance in all hop tests (single, triple, crossover) and 6-meter timed hop with LSI of 90 percent or higher being reached by a greater percentage of participants in the NMT group. The achieved improvement of the Y-Balance Composite scores and leg balance time also indicate a promotion of the dynamic balance and proprioceptive acuity. All these are especially applicable considering that in RTS criteria much attention is paid to high velocity and multi-planar tasks. The wide between-group variances in functional performance tests confirm the hypothesis that neuromuscular training enhances the speed of recovery of the quality of movement, energy intake [Nwachukwu, B. U. *et al.*, 2017; Manoharan, A. *et al.*, 2021], and landing mechanics, which are important in reinjury risk reduction so that can sports Patient-reported outcomes and psychological preparedness. Compared to the objective measures, the NMT group had a better IKDC and Lysholm score, less pain and effusion, and the lower fear of reinjury (lower TSK scores, higher ACL-RSI). Psychological preparedness, as this is reflected in ACL-RSI and fear scales, was found to be a significant correlate of RTS preparedness and significantly more common in the NMT group. This is in line with modern models that identify fear, confidence, and self-efficacy as major factors in RTS decision making and performance. The significant change in the Knee Self-Efficacy Scale and KOOS QoL/Sport-Rec subscale in the NMT suggests that the neuromuscular interventions can influence positively the confidence of the athlete in movement and participation, perhaps through increased clarity in the feedback loop, experience of mastery, and predictable progression in addition to Return-to-sport criteria and RTS clearance. At 69 months, a higher percentage of the NMT group had all RTS criteria (e.g. quadriceps and hamstring LSI 90per cent, all hop LSIs 90per cent, Y-Balance composite 95per cent, full ROM, ACL-RSI 56per cent). The probability of fulfilling all the requirements was significantly better in the

NMT (OR ≈ 5.5). Significantly, RTS clearance more frequently was associated with lower reinjury cues, when conditions were met (however, there was almost, but not statistically significant difference in reinjury rates at 12 months, $p = 0.082$). This trend promotes the idea that a multi-domain RTS battery (strength, function, and psychological readiness) would provide a more valid format of predicting safe RTS compared to individual tests as well as Adherence, Feasibility, and dosing of NMT. There was an overall high adherence rate to the NMT protocol with a mean of 42.8 sessions attended having a rate of 87.4% compliance. The frequency of the session did not change significantly between the early and mid-rehabilitation windows indicating that it can be accepted and implemented in the normal practice. Even though a number of components (perturbation, plyometrics, proprioception) were administered with high fidelity, compliance was slightly different in sub components which can be used to optimize dosing in practice where The dose-response category can be observed in the high levels of compliance and RTS preparedness where continuous working with the neuromuscular factors is crucial to achieving the maximum results possible where The implementation of NMT as an early intervention during ACL rehabilitation must be regarded as a standard practice to be used when athletes refer to RTS also The supplementary components of perturbation, reactive neuromuscular training, and sport-specific plyometrics seem to produce increase in motor control and movement quality leading to an enhanced functional and psychological preparedness.

CONCLUSION AND RECOMMENDATIONS.

The implications of the current research results include the essentiality of the incorporation of a systematic Neuromuscular Training (NMT) program into the rehabilitation guidelines of athletes that have undergone anterior cruciate ligament (ACL) reconstruction while The data has shown that the participants that underwent the NMT protocol showed statistically significant positive changes in the strength, functional performance, and psychological preparedness as compared to those that conducted a normal rehabilitation program so Not only do such enhancements allow a faster recovery to the sport, but also provide a safer avenue to the athletes, which essentially lowers the chances of reinjury as well as Resting on such persuasive results it is

possible to recommend some recommendations to the practitioner in the sphere of sports medicine and rehabilitation as following NMT Protocols: NMT is supposed to be implemented and made a standard procedure by athletic trainers and rehabilitation specialists as a part of the post-ACL reconstruction rehabilitation where This must incorporate perturbation training, reactive neuromuscular exercises and sport-specific plyometric exercises to enhance dynamic stability and functional performance in addition to Individualized and Rehabilitation Programs It is important to customize rehabilitation programs in terms of the needs of the individual athlete.

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Source of support: Nil; **Conflict of interest:** Nil.

Cite this article as:

Katouf, K. Y. "Advanced Rehabilitation Strategies for Anterior Cruciate Ligament (ACL) Injuries Integrating Neuromuscular Training and Return-to-Sport Criteria." *Sarcouncil Journal of Applied Sciences* 6.7 (2026): pp 11-19.