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Effects of a 16-Week Rehabilitation Program Incorporating Functional Training on Knee Range of Motion and Isokinetic Strength after ACL Reconstruction in Female Team Sport Athletes

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Abstract: Standard physiotherapy protocols show limited efficacy in restoring isokinetic symmetry within competitive timelines after ACL reconstruction (ACLR) in elite female team-sport athletes, while integrated combined approaches remain underexplored in this population. The study aimed to evaluate the effects of a 16-week progressive combined physiotherapy and sport-specific functional training protocol on isokinetic knee flexion, extension, and frontal-plane strength parameters and bilateral deficit following ACLR in senior female handball and basketball players. Fifty-two elite female athletes with documented ACLR were allocated to an experimental group (EG, n = 26) following a progressive combined protocol (physiotherapy: functional training ratio transitioning 80:20 - 50:50 - 20:80) or a control group (CG, n = 26) following standard rehabilitation. Isokinetic assessment was performed using the Biodex System 4 Pro at baseline (Ti) and post-intervention (Tf). Paired and independent-samples t-tests, Cohen's d effect sizes, and Bonferroni-corrected compar-isons (α = 0.00125) were applied. Both groups showed significant within-group improve-ments across all variables ($p < 0.001$). The EG demonstrated greater absolute gains than the CG in knee extension, flexion, and frontal-plane muscles across most parameters, though substantial baseline differences between groups limit causal interpretation. Bilat-eral deficit was significantly reduced in both groups, with no significant between-group differences, except for hip abduction at Tf ($p = 0.037$, not surviving Bonferroni correction). Residual deficit values exceeded the 15% clinical reinjury risk threshold in both groups at Tf.

Keywords: ACL reconstruction; isokinetic strength; knee flexion; knee extension; functional training; female athletes

1. Introduction

Anterior cruciate ligament (ACL) rupture is one of the most common and severe musculoskeletal injuries in high-performance team sports, with a disproportionately high incidence among female athletes [1–3]. Epidemiological data consistently indicate that female athletes are at higher risk of injury, and quadriceps strength asymmetry at the time of return to sport is associated with poorer knee function 1 year post-surgery

[4,5]. The technical and physical demands of team sports subject the knee joint to repetitive and unpredictable mechanical stress, substantially increasing the risk of ACL injury [6,7]. Despite advances in surgical technique and postoperative care, reinjury rates of 15–25% have been reported in athletes returning to pivoting sports, and a substantial proportion fails to return to their pre-injury performance level, with long-term sequelae, including post-traumatic osteoarthritis and persistent muscle dysfunction [6,7,8–10].

Traditional post-ACL rehabilitation protocols include exercise-based physical therapy that emphasizes isolated neuromuscular re-education, progressive resistance strengthening, and open- and closed-kinetic-chain exercises in controlled, low-load environments. Although this approach has demonstrated effectiveness in restoring core muscle strength and joint stability, its limitations in preparing for the multidirectional, sport-specific, and competitive neuromuscular demands have become increasingly evident in team sports [11,12].

Integrating sport-specific functional training (FT) into the post-ACL rehabilitation continuum is a promising approach. Functional training, tailored to the kinematic and kinetic demands of handball and basketball, includes plyometric exercises, change-of-direction drills, reactive agility tasks, and sport-specific movement patterns that progressively challenge the neuromuscular system under sport-specific conditions. This neuromechanical specificity has been theorized to accelerate the restoration of reactive muscle stiffness, anticipatory postural adjustments, and dynamic knee stabilization strategies—all critical factors at risk of ACL injury [11,13–15]. For handball and basketball, this integration has particular clinical significance, given the biomechanical complexity of these sports, which manifests as multidirectional stresses on the reconstructed knee [12, 13].

The progressive loading model adopted—with a transition from a predominantly kinesiotherapy-based 80:20 ratio in the initial phase to a predominantly functional 20:80 ratio in the final phase—ensures that neuromuscular and biomechanical demands align with the tissue healing process. Post-ACLR rehabilitation protocols based on clinical criteria that establish progression milestones aligned with the biological healing process represent the recommended approach for optimizing variable outcomes observed in current practice and reducing the risk of reinjury [16,17] Clinicians should distance themselves from strictly chronological frameworks and instead follow guidelines that allow progression based on proven improvements in strength, edema, proprioception, pain, and range of motion, with objective quantitative and qualitative criteria met prior to return to sport [18]. The structure of our experimental protocol adheres to these principles by conditioning progression between phases on objective clinical parameters rather than fixed time markers.

Functional training for team-sport athletes requires deliberate modifications to standard sport-specific exercises to eliminate biomechanical risk factors incompatible with the current postoperative stage. In the initial phases of rehabilitation, this adaptation involves replacing high-impact, ballistic, and high-speed exercises with low-impact, speed-controlled analogs [19,20]. As rehabilitation progresses and isokinetic strength indices converge toward symmetry, these adaptations are gradually phased out, and exercises are progressively transitioned to competition-representative forms. Key milestones in the post-ACLR rehabilitation process include the introduction and progression of running, plyometric training, and sport-specific change-of-direction activities. The return-to-sport process is recommended to be structured in three phases—return to participation, return to sport, and return to performance—with progression of muscle performance variables on a continuum. Neuromuscular training significantly reduced the overall risk of knee injury and the specific risk of ACL injury in sport athletes [21-25]. High adherence to the protocol was identified as the most effective determinant of outcomes, supporting the principle that the gradual, supervised progression used in the present study maximizes the intervention's effectiveness [21,22].

A critical review of the literature reveals significant methodological gaps in post-ACL rehabilitation for female team sport athletes. Existing studies examine physical therapy and functional training separately, without investigating their structured integration in a population of senior handball and basketball players. Although general rehabilitation protocols propose a progressive transition from predominantly physical therapy-based approaches to predominantly functional approaches, no previous study has empirically investigated whether a structured progression of the ratio (80/20 - 50/50 - 20/80) produces superior isokinetic symmetry results compared to an exclusively kinesiotherapy-based control condition. The assessment of isokinetic strength of the quadriceps and hamstrings, combined with sport-specific functional tests, represents the main pillars of monitoring progress in post-ACLR rehabilitation, within a continuum that includes sport-specific rehabilitation, strength and function assessment, and gradual participation in competitive activity [23-25]. However, isokinetic dynamometry remains underrepresented as a primary measurement in studies on women's team sports. Although isokinetic dynamometry is frequently used in research to assess quadriceps and hamstring strength, isokinetic devices have limitations in clinical practicability related to cost, portability, and space, and in current practice, manual muscle strength testing remains predominant, with significant methodological limitations [26,27]. Existing studies in women's team sports rely predominantly on functional performance tests as criteria for return to sport, with few incorporating standardized isokinetic dynamometry. Isokinetic reference values for the quadriceps and hamstrings in female athletes practicing pivoting sports show considerable inter-individual variability, underscoring the need for sport-specific normative values, which remains an uncovered methodological priority in the current literature [28-30]. The heterogeneity of the samples limits the clinical applicability of the conclusions, while the absence of intra-protocol monitoring hinders the understanding of the temporal dynamics of muscle symmetry restoration.

Despite the substantial body of research on post-ACLR recovery in team sports, integrated, sport-specific protocols remain underexplored, particularly among senior elite athletes. The present study addresses this gap through three distinct methodological contributions. The first introduces a dual, progressive protocol that combines structured physical therapy with functional training tailored to the specific biomechanical demands of sports. The second dimension involves progressively modulating the ratio between the two components over 16 weeks, following the principles of progressive overload and rehabilitative periodization, with progression criteria based on objective clinical parameters, consistent with the criteria-guided recovery paradigm. The goal of any criteria-based guideline is to maximize the patient's response to exercise at the current level of function while minimizing the risk of injury to healing tissue. The third dimension quantifies efficacy using standardized isokinetic dynamometry within a controlled comparative design, providing methodological validity and direct practical relevance for clinicians and physical therapists managing post-ACL sports reintegration, regardless of the sport. Post-ACLR rehabilitation for elite athletes must be designed in reverse of the demands of the sport and the athlete's position, integrating the principles of the Control-Chaos Continuum and the Return-to-Sport Continuum as a framework for navigating sport-specific progression [31-34].

The aim of the study was to evaluate the impact of a 16-week post-ACLR recovery protocol that integrates structured physiotherapy with adapted functional training exercises on joint strength and mobility in senior female handball and basketball athletes.

Research hypotheses:

H 1: The experimental group, which follows the combined physiotherapy and functional training protocol adapted to the specifics of team sports (handball and basketball), will register, at the end of the 16 weeks of intervention, a significantly greater increase in muscle strength indices and lower joint mobility, compared to the control group following standard recovery.

H 2: Both groups will show significant improvements in isokinetic parameters (muscle strength and joint mobility) from baseline (Ti) to endpoint (Tf), with different amplitudes depending on the type of protocol followed, with a higher amplitude anticipated in the experimental group.

2. Material and Methods

2.1 Study Design

A quasi-experimental study with a pre-test/post-test design and a control group was used. The selected tests were administered pre-intervention (Ti) and post-intervention (Tf) at the conclusion of the 16 weeks. The inclusion of the control group enabled the distinction between the specific effects of the combined protocol and those of standard recovery, providing a comparative framework for interpreting the results. Data collection and the implementation of the intervention programs took place over a total duration of 1 year. This extended duration was necessary to ensure recruitment of a sufficient number of participants who met all inclusion criteria, given the specificity of the diagnosis and the required level of performance. During the 16 weeks of intervention, isokinetic assessments were performed at the TI and TF time points for each individual case, in accordance with the protocol established prior to the study. The study's protocol complied with the Declaration of Helsinki and was approved by the Ethics Committee of the Faculty of Physical Education and Mountain Sports, Transilvania University of Brașov, No. 312/19.12.2025.

2.2 Participants

The study included 52 senior female athletes who played handball and basketball and had a history of ACL reconstruction (Table 1). The experimental group (EG) consisted of 26 senior female elite competitive handball and basketball players (first league) with a history of ACL reconstruction who followed an experimental protocol combining physical therapy and specific functional training exercises throughout the intervention period. The control group (CG) included 26 senior female competitive handball and basketball players (second league) with the same diagnosis who followed the standard ACL recovery protocol exclusively. Common characteristics of both groups were as follows: age between 19 and 28 years, at least 10 years of athletic experience in handball or basketball, normal body weight, very good physical condition prior to the injury, and informed consent to participate in the study. Inclusion criteria: autograft type (biceps femoris tendon graft (BPTB) or quadriceps tendon graft), a post-operative interval of 48 hours at inclusion, absence of other associated musculoskeletal conditions that could have influenced the study, such as athletic performance, isokinetic and active performance. Confirmation of ACL reconstruction. Athletes with post-operative complications, neurological conditions, or concomitant trauma to the contralateral lower limb were excluded.

The sample size was determined a priori for a two-tailed independent-samples t-test, using Relative Strength (RS, N/kg) at knee extension of the surgical limb (S_L) as the primary outcome—the parameter with the highest clinical relevance for the risk of

ACL re-rupture (Grindem et al., 2016). Based on the literature on post-ACL rehabilitation interventions in elite female athletes, a large, clinically significant effect was anticipated (Cohen's d = 0.8). The calculation parameters were: $\alpha = 0.05$ (two-tailed), statistical power $(1-\beta) = 80\%$, and expected effect d = 0.8, the required sample size of n = 25 participants per group. Accounting for an anticipated 10% dropout rate, the adjusted number was 28 participants per group (80% power).

Table 1. Demographic characteristics of the study groups

Characteristics	GE	GC
Age (X±SD)	20,23±1,32	21,43±1,76
Sports experience	10,2 years	10,3 years
Weight	67,78 kg	69,12 kg
Height	169 cm	172 cm
Graft type – quadriceps tendon graft	Patellar tendon graft (PTG) - 14 Quadriceps tendon graft - 12	Patellar tendon graft (PTG) - 13 Quadriceps tendon graft - 13
Post-surgical interval to start therapy	48 hours	48 hours

GE- experimental group, GC – control group

2.3 Intervention protocol

The experimental intervention protocol (Table 2) was conducted over 16 consecutive weeks, with 3 sessions per week, each lasting 45-60 minutes, for a total of 48 supervised sessions. Each session was structured into three phases: warm-up (5-10 min), core exercise intervention (35-45 min), and recovery (5-10 min). The protocol was organized into three progressive phases, characterized by a gradual change in the ratio between physiotherapy (PT) exercises and adapted functional training (FT), following the principles of progressive overload and neuromuscular readaptation after anterior cruciate ligament reconstruction.

The transition from KT-dominant to FT-dominant training was guided by criteria for pain-free execution (≤3/10 on the Numerical Pain Rating Scale), restoration of range of motion, and adequate neuromuscular control in each phase, consistent with current evidence-based ACL rehabilitation guidelines.

Physical Therapy (KT) Exercises – Physical therapy exercises were selected and progressively structured across the three phases of the protocol to reduce pain, restore range of motion, strengthen muscles, and improve neuromuscular control of the lower limb after ACL reconstruction.

Functional Training (FT) Exercises – FT exercises were adapted from handball-specific movement patterns and introduced progressively to restore dynamic neuromuscular control, sport-specific coordination, and athletic performance capacity. All FT exercises were modified to eliminate high-impact or high-load elements that were incompatible with the current stage of ACL rehabilitation.

Table 2. Structure and progression of the 16-week combined intervention protocol applied to the experimental group

Phase	Weeks	Sessions /Weeks	Duration	Report KT	Report FT	Main objectives
Phase I – Initial Recovery	1–4	12/4	45–60 minutes	80%	20%	Pain reduction, ROM, recovery, basic neuromuscular control
Phase II – Transition	5–10	18/6	45–60 minutes	50%	50%	Consolidation of muscle strength, initiation of sport-specific movement patterns
Phase III – Functional Integration	11–16	18/6	45–60 minutes	20%	80%	Restoration of isokinetic symmetry, dynamic neuromuscular control and sport-specific reintegration

KT = Kinetotherapy; FT = Functional training; ROM = Range of motion

Session structure: Each session followed a standardized structure to ensure consistency for all participants. The warm-up phase (5-10 min) consisted of progressive joint mobilization and cardiovascular activation. The intervention program (35-45 min) incorporated physiotherapy (KT) and functional training (FT) exercises according to the phase-specific ratio, always starting with physiotherapy (KT) exercises, which require greater neurological precision and motor control, followed by functional training (FT) exercises. The relaxation phase (5-10 min) included static stretching, breathing exercises, and foam rolling for myofascial recovery. In accordance with established safety criteria, exercise progression was allowed only in the absence of pain exceeding 3/10 on the Numerical Pain Rating Scale and with complete resolution of symptoms within 24 hours after the session.

2.4. Assessment Tools

The tests evaluated in the study were: Knee Flexion Test, Knee Extension Test, Abduction Test, and Adduction Test. Specialized isokinetic dynamometry equipment (Biodex System 4 Pro) was used for these evaluations.

The following test parameters were evaluated for this study:

- Maximum force (N): The maximum torque generated during a maximum voluntary contraction of the knee flexors and extensors, recorded separately for each limb.
- Reference Value (RV): Standardized force values established for the evaluated population, used as a reference point for comparing individual performance.
- Percentage of Reference Value (%RV): Each participant's maximum force, expressed as a percentage of the reference value, enabling standardized comparison with normative expectations.
- Relative Strength (RS) (N/kg): The ratio of maximum torque to body mass, providing a normalized strength index that takes into consideration the interindividual anthropometric differences.
- The Knee Deficiency Index was calculated separately for knee flexion and extension, quantifying the percentage difference in maximum torque between the surgical and non-surgical limbs. Values exceeding 10–15% are typically considered clinically significant deficits and are associated with an increased risk of re-injury. This index was assessed at both Ti and Tf to monitor the restoration of bilateral symmetry throughout the protocol.

2.5. Statistical Analysis

Statistical analysis was performed using SPSS version 26. Descriptive statistics were calculated for all evaluated isokinetic parameters, including the arithmetic mean ($\overline{X}$), standard deviation (SD), and variance, providing a complete characterization of the groups at both evaluation times (Ti and Tf). Normality of the data distribution was assessed using the Shapiro-Wilk test, recommended for small sample sizes ($n = 18$ per group). All values obtained from the Shapiro-Wilk test exceeded the 0.05 significance threshold for all parameters and both groups (GE and GC) at Ti and Tf, confirming that the data distributions do not depart significantly from normality and justifying the use of parametric statistical tests. To compare pre–post evolution within the same group, the paired-samples t-test was used, and to compare differences between the experimental group and the control group at the same time of assessment, the independent-samples t-test was used. The effect size was calculated using Cohen's d index ($d = \Delta X / SD\Delta$) and interpreted according to standard conventions: $d < 0.2$, negligible effect; 0.2–0.5, small effect; 0.5–0.8, medium effect; 0.8–1.2, large effect; $d > 1.2$, very large effect. The adopted statistical significance threshold was $\alpha = 0.05$. Given the large number of simultaneous comparisons (n = 40 tests for paired t-test and n = 40 tests for independent t-test), Bonferroni correction for multiple comparisons was applied, with an adjusted threshold α_Bonf = 0.05 / 40 = 0.00125 for each family of tests. Results are reported with both the nominal threshold ($p < 0.05$) and the Bonferroni threshold ($p < 0.00125$) for comparability with the existing literature. For each comparison, the 95% confidence interval (95% CI) was calculated as the lower limit (LL) and the upper limit (UL); non-inclusion of zero indicates statistical significance.

3. Results

Tables 3, 5, 7, and 9 present the results of the Paired t-test statistical analysis, while Tables 3, 6, 8, and 10 present the results of the Independent t-test analysis.

Table 3. The paired T-test: Knee flexion test

Leg	Group	Var.	X̄Ti	X̄Tf	ΔX	SD Δ	t	IC 95% (LL; UL)	p	d Cohen
S_L	GE	MF	305.328	389.273	83.945	43.825	9.767	(66.244; 101.646)	<0.001	1.915
		RV	134.593	187.055	52.462	16.936	15.795	(45.621; 59.302)	<0.001	3.098
		%RV	237.461	308.978	71.517	23.127	15.768	(62.176; 80.858)	<0.001	3.092
		RS	4.759	5.815	1.056	0.427	12.603	(0.883; 1.228)	<0.001	2.472
	GC	MF	249.994	315.198	65.204	30.951	10.742	(52.702; 77.705)	<0.001	2.107
		RV	119.374	159.247	39.873	12.901	15.76	(34.663; 45.084)	<0.001	3.091
		%RV	198.582	267.875	69.293	21.171	16.689	(60.742; 77.845)	<0.001	3.273
		RS	3.735	4.313	0.578	0.36	8.186	(0.433; 0.724)	<0.001	1.605
NS_L	GE	MF	446.266	454.957	8.691	2.894	15.311	(7.522; 9.86)	<0.001	3.003
		RV	216.58	221.288	4.708	1.508	15.92	(4.099; 5.318)	<0.001	3.122
		%RV	360.577	367.914	7.337	2.324	16.095	(6.398; 8.276)	<0.001	3.157
		RS	6.765	6.908	0.143	0.05	14.447	(0.123; 0.163)	<0.001	2.833
	GC	MF	365.328	372.16	6.832	1.973	17.66	(6.035; 7.629)	<0.001	3.463
		RV	184.394	188.113	3.719	1.199	15.813	(3.235; 4.204)	<0.001	3.101
		%RV	313.064	319.379	6.315	2.135	15.079	(5.452; 7.177)	<0.001	2.957
		RS	5.038	5.143	0.104	0.038	14.117	(0.089; 0.119)	<0.001	2.769

S_L - Surgical limb; NS_L - Non-surgical limb, GE – experimental group GE, GC – control group MF – Maximum force; TF – The Reference value; %RV - Percentage of reference value (%RV); RS - Relative force; Δ – difference; X - arithmetic mean, SD - standard deviation; IC – confidence interval, LL - lower limit, UL - upper limit; Ti – initial test, Tf – final test; t – Student's t-test value, p – probability level.

In the Knee flexion test, the paired t-test revealed statistically significant improvements ($p < 0.001$) for all measured variables (MF, RV, %RV, RS) in both groups and on both limbs, with 95% confidence intervals excluding zero in all cases (Table 3), confirming reliable pre-to-post change within each group. Cohen's d values in this dataset reach very large magnitudes (d = 1.6–3.5 across groups and variables), which should be interpreted with caution: in small samples, d is strongly inflated by low within-group variance and does not directly reflect clinical magnitude of change. Clinical interpretation should prioritize the absolute mean differences and their 95% CIs. On the surgical limb, GE achieved a mean increase in MF of 83.945 N·m (95% CI: 66.244–101.646) compared to 65.204 N·m (95% CI: 52.702–77.705) in GC; both CIs are narrow and exclude zero, confirming reliable within-group gains, though the difference between groups must be read alongside the pre-existing baseline advantage of GE. For %RV, gains were 71.517% (95% CI: 62.176–80.858) in GE and 69.293% (95% CI: 60.742–77.845) in GC; the substantially overlapping CIs indicate that the practical within-group difference between protocols is modest for this variable. From a rehabilitation standpoint, both absolute MF gains exceed 60 N·m on the surgical limb, representing clinically meaningful strength recovery relative to the normative thresholds used in return-to-sport assessment. On the non-surgical limb, gains were small and comparable between groups (MF: GE +8.691 N·m, 95% CI: 7.522–9.860 vs. GC +6.832 N·m, 95% CI: 6.035–7.629), consistent with both protocols producing similar and limited adaptations in the unaffected limb, as expected.

Table 4. Independent T-test: Knee flexion

Comparison	Var.	X̄A	X̄B	ΔX	t	IC 95% (LL; UL)	p	d Cohen
GE vs GC · S_L · Ti	MF	305.328	249.994	55.334	4.066	(27.996; 82.672)	<0.001	1.128
	RV	134.593	119.374	15.22	3.289	(5.926; 24.513)	0.002	0.912
	%RV	237.461	198.582	38.88	3.696	(17.705; 60.055)	<0.001	1.025
	RS	4.759	3.735	1.024	4.552	(0.571; 1.478)	<0.001	1.263
GE vs GC · S_L · Tf	MF	389.273	315.198	74.075	3.976	(36.616; 111.534)	<0.001	1.103
	RV	187.055	159.247	27.808	4.714	(15.947; 39.668)	<0.001	1.307
	%RV	308.978	267.875	41.103	3.247	(15.623; 66.583)	0.002	0.9
	RS	5.815	4.313	1.502	6.03	(1.001; 2.003)	<0.001	1.672
GE vs GC · NS_L · Ti	MF	446.266	365.328	80.938	3.703	(36.997; 124.879)	<0.001	1.027
	RV	216.58	184.394	32.186	4.432	(17.58; 46.791)	<0.001	1.229
	%RV	360.577	313.064	47.512	2.988	(15.533; 79.492)	0.004	0.829
	RS	6.765	5.038	1.726	5.84	(1.131; 2.321)	<0.001	1.62
GE vs GC · NS_L · Tf	MF	454.957	372.16	82.797	3.735	(38.231; 127.362)	<0.001	1.036
	RV	221.288	188.113	33.175	4.456	(18.202; 48.148)	<0.001	1.236
	%RV	367.914	319.379	48.535	2.987	(15.855; 81.215)	0.004	0.828
	RS	6.908	5.143	1.765	5.85	(1.158; 2.372)	<0.001	1.622

S_L - Surgical limb; NS_L - Non-surgical limb; GE – experimental group, GC – control group, MF - Maximum force; RV - Reference value; %RV - Percentage of reference value (%RV); RS - Relative force; Δ – difference; Δ – difference; X – arithmetic mean, SD – standard deviation; Ti – initial test, Tf – final test; CI – confidence interval, LL – lower limit, UL – upper limit; t – Student's t-test value, p – probability level.

In the Knee flexion test, the independent t-test confirmed that the EG and CG differed significantly at both Ti and Tf across all comparisons ($p \le 0.004$), with 95% confidence intervals excluding zero in all cases (Table 4). Importantly, significant between-group differences were already present at Ti across all variables on both limbs — for example, MF S_L: ΔX = 55.334 N·m (95% CI: 27.996–82.672) and RS S_L: ΔX = 1.024 N/kg (95% CI: 0.571–1.478) — indicating that the groups were not equivalent at baseline. These pre-existing differences are the primary lens through which Tf comparisons must be read: the intergroup differences at Tf (e.g., RS S_L: ΔX = 1.502 N/kg, 95% CI: 1.001–2.003) cannot be attributed to the intervention alone, as they largely reflect the baseline advantage of GE. Clinically, the near-identical 95% CI widths between Ti and Tf for the same variables confirm that the magnitude of between-group separation was preserved throughout the intervention period rather than amplified by the experimental protocol — consistent with both groups improving at a comparable rate. Cohen's d values at Tf are presented in the table for reference only; their magnitude reflects the pre-existing group separation and should not be interpreted as evidence of differential treatment effectiveness or clinical superiority of either protocol.

Table 5. Paired t-test: Knee extension

Leg	Group	Var.	X̄Ti	X̄Tf	ΔX	SD Δ	t	IC 95% (LL; UL)	p	d Cohen
S_L	GE	MF	509.23	614.054	104.824	29.393	18.185	(92.952; 116.696)	<0.001	2.116
		RV	269.601	350.183	80.582	14.945	27.494	(74.546; 86.618)	<0.001	2.014
		%RV	204.33	289.599	85.268	14.118	30.796	(79.566; 90.971)	<0.001	2.134
		RS	8.269	9.592	1.323	0.522	12.917	(1.112; 1.534)	<0.001	2.533
	GC	MF	446.516	542.902	96.387	22.332	22.007	(87.366; 105.407)	<0.001	1.316
		RV	242.915	307.948	65.032	18.601	17.827	(57.519; 72.545)	<0.001	1.496
		%RV	170.993	244.901	73.908	16.797	22.436	(67.124; 80.693)	<0.001	1.352
		RS	6.713	7.829	1.116	0.472	12.059	(0.926; 1.307)	<0.001	2.365
NS_L	GE	MF	707.541	721.455	13.914	4.549	15.595	(12.076; 15.751)	<0.001	1.673
		RV	404.313	411.828	7.515	2.215	17.304	(6.621; 8.41)	<0.001	2.017
		%RV	335.782	342.655	6.874	1.726	20.308	(6.177; 7.571)	<0.001	1.983
		RS	11.087	11.318	0.231	0.087	13.512	(0.196; 0.266)	<0.001	2.651
	GC	MF	618.408	631.776	13.368	4.398	15.5	(11.592; 15.144)	<0.001	1.971
		RV	354.409	361.347	6.938	2.226	15.89	(6.039; 7.837)	<0.001	2.472
		%RV	283.572	289.565	5.993	2.096	14.58	(5.147; 6.84)	<0.001	2.015
		RS	9.035	9.212	0.176	0.062	14.554	(0.151; 0.201)	<0.001	1.615

S_L - Surgical limb; NS_L - Non-surgical limb; GE - Experimental group; GC – Control group; MF - Maximum force; RV - Reference value; %RV - Percentage of reference value (%RV); RS - Relative force; Δ – difference; X - arithmetic mean, SD - standard deviation; Ti – initial test, CI - confidence interval, LL - lower limit, UL - upper limit; Ti – initial test, Tf – final test; t – Student's t-test value, p – probability level.

The paired t-test revealed statistically significant improvements ($p < 0.001$) for all variables in the Knee extension test (MF, RV, %RV, RS) in both groups and on both limbs, with 95% confidence intervals excluding zero in all cases (Table 5). The primary basis for clinical interpretation is the absolute mean gain and its 95% CI, not the Cohen's d values, which reach very large magnitudes in this dataset (d = 1.3–2.5) owing to low within-group variance and should not be used to rank clinical effectiveness. On the surgical limb, GE achieved a mean MF increase of 104.824 N·m (95% CI: 92.952–116.696) and GC achieved 96.387 N·m (95% CI: 87.366–105.407); the narrow, non-overlapping CIs confirm reliable within-group gains in both groups, while the difference between them (~8.4 N·m) should be contextualized against the pre-existing baseline non-equivalence. The %RV gain was 85.268% (95% CI: 79.566–90.971) in GE vs. 73.908% (95% CI: 67.124–80.693) in GC; the non-overlapping confidence intervals here suggest a more meaningful absolute difference in normative recovery, but the pre-existing %RV advantage of GE at Ti (204.33 vs. 170.993 for GC) limits causal attribution. From a rehabilitation perspective, both groups achieved absolute MF gains above 90 N·m on the knee extension surgical limb, indicating that both protocols support meaningful quadriceps strength recovery — a parameter directly relevant to reinjury risk and return-to-sport decision-making. On the non-surgical limb, gains were small and comparable between groups, consistent with expected contralateral maintenance adaptations under both protocols.

Table 6. Independent T-test: Knee extension

Comparison	Var.	X̄A	X̄B	ΔX	t	IC 95% (LL; UL)	p	d Cohen
GE vs GC · S_L · Ti	MF	509.23	446.516	62.714	1.796	(-7.434; 132.862)	0.079	0.498
	RV	269.601	242.915	26.685	2.987	(8.729; 44.642)	0.004	0.828
	%RV	204.33	170.993	33.337	2.909	(10.312; 56.362)	0.005	0.807
	RS	8.269	6.713	1.556	2.987	(0.509; 2.602)	0.004	0.828
GE vs GC · S_L · Tf	MF	614.054	542.902	71.152	2.014	(0.191; 142.112)	0.049	0.559
	RV	350.183	307.948	42.235	5.254	(26.071; 58.399)	<0.001	1.457
	%RV	289.599	244.901	44.698	3.365	(18.021; 71.374)	0.001	0.933
	RS	9.592	7.829	1.763	3.509	(0.754; 2.772)	<0.001	0.973
GE vs GC · NS_L · Ti	MF	707.541	618.408	89.133	2.218	(8.413; 169.853)	0.031	0.615
	RV	404.313	354.409	49.904	4.726	(28.671; 71.137)	<0.001	1.311
	%RV	335.782	283.572	52.21	3.311	(20.541; 83.879)	0.002	0.918
	RS	11.087	9.035	2.052	3.472	(0.865; 3.239)	0.001	0.963
GE vs GC · NS_L · Tf	MF	721.455	631.776	89.679	2.199	(7.769; 171.589)	0.033	0.61
	RV	411.828	361.347	50.481	4.72	(28.977; 71.985)	<0.001	1.309
	%RV	342.655	289.565	53.09	3.323	(20.998; 85.182)	0.002	0.922
	RS	11.318	9.212	2.107	3.491	(0.894; 3.319)	0.001	0.968

GE – experimental group, GC – control group, MF – maximum force; RV – reference value; %RV – percentage of reference value (%RV); RS – Relative force; Δ – difference; Δ – difference; X – arithmetic mean, SD – standard deviation; Ti – initial test, Tf – final test; CI – confidence interval, LL – lower limit, UL – upper limit; t – Student's t-test value, p – probability level.

The independent t-test for the knee extension test showed no statistically significant difference for absolute MF on the surgical limb at Ti (p = 0.079; 95% CI: −7.434 to 132.862), the only variable where the groups were comparable at baseline in this test (Table 6). This baseline equivalence for MF S_L is clinically important: it means that for this specific variable, post-intervention between-group differences can be interpreted with less confounding than for other variables. For all other variables at Ti — RV, %RV, and RS on both limbs — significant baseline differences were already present (p ≤ 0.005), with 95% CIs excluding zero, confirming that GE started with a meaningful advantage. At Tf, intergroup differences persisted and were precisely estimated for several variables: RV on S_L showed ΔX = 42.235 N·m (95% CI: 26.071–58.399) and RS on S_L showed ΔX = 1.763 N/kg (95% CI: 0.754–2.772), both with narrow CIs. However, since comparable between-group gaps were present at Ti, these Tf differences reflect preserved baseline non-equivalence rather than a differential treatment response. For MF at Tf, the 95% CI is very wide on both limbs (S_L: −7.434 to 142.112 at Ti; S_L: 0.191–142.112 at Tf), indicating low precision for this estimate and warranting caution in interpretation. Cohen's d values are included in the table for completeness; their magnitude should not be used to infer clinical superiority of either protocol, particularly given the baseline non-equivalence and the absence of formal Group × Time interaction testing.≤ 0.005; d between 0.807 and 0.963), confirming that the EG began with an advantage for most variables. At Tf, intergroup differences persisted for most variables. The 95% confidence intervals for RV at Tf (S_L: 26.071–58.399; NS_L: 28.977–71.985) and for RS (S_L: 0.754–2.772; NS_L: 0.894–3.319) exclude zero and show substantial absolute differences; however, given that comparable differences were already present at Ti, these findings reflect preserved baseline non-equivalence rather than differential treatment response. For MF at Tf on both limbs (S_L: 95% CI: 0.191–142.112; NS_L: 7.769–171.589), the wide confidence intervals indicate low precision and caution is warranted. Cohen's d values are reported for reference; comparison of d magnitudes between variables or time points should not be used to infer relative clinical importance in the absence of formal interaction testing.

Table 7. Paired t-test: Adduction and Abduction

Test	Group	Var.	X̄Ti	X̄Tf	ΔX	SD Δ	t	IC 95% (LL ; UL)	p	d Cohen
ADD (Adductor)	GE	%MF	887.794	905.182	17.388	6.365	13.93	(14.818 ; 19.959)	<0.001	2.732
		RV	701.053	715.713	14.66	4.13	18.099	(12.992 ; 16.328)	<0.001	3.550
		%RV	228.622	233.15	4.528	1.564	14.761	(3.896 ; 5.159)	<0.001	2.895
		RS	13.712	13.997	0.284	0.079	18.38	(0.252 ; 0.316)	<0.001	3.605
	GC	%MF	799.052	816.277	17.225	4.024	21.829	(15.6 ; 18.851)	<0.001	4.281
		RV	610.46	622.466	12.006	3.307	18.512	(10.67 ; 13.342)	<0.001	3.631
		%RV	198.137	202.228	4.09	1.197	17.427	(3.607 ; 4.574)	<0.001	3.418
		RS	12.312	12.579	0.267	0.07	19.502	(0.239 ; 0.296)	<0.001	3.825
ABD (Abductor))	GE	%MF	914.531	932.714	18.183	3.494	26.532	(16.771 ; 19.594)	<0.001	5.203
		RV	674.193	687.128	12.935	4.023	16.397	(11.31 ; 14.56)	<0.001	3.216
		%RV	178.53	182.097	3.567	0.892	20.38	(3.206 ; 3.927)	<0.001	3.997
		RS	14.005	14.301	0.296	0.093	16.306	(0.259 ; 0.334)	<0.001	3.198
	GC	%MF	818.395	835.183	16.788	5.325	16.076	(14.637 ; 18.939)	<0.001	3.153
		RV	606.86	618.652	11.792	3.325	18.082	(10.448 ; 13.135)	<0.001	3.546
		%RV	158.555	161.704	3.149	0.744	21.582	(2.848 ; 3.449)	<0.001	4.233
		RS	12.174	12.412	0.238	0.07	17.36	(0.209 ; 0.266)	<0.001	3.404

EG – experimental group, CG – control group MF – Maximum force; RV – Reference value; %RV – Percentage of reference value (%RV); RS – Relative strength; Δ – difference; X – arithmetic mean, SD – standard deviation; Ti – initial test, CI – confidence interval, LL – lower limit, UL – upper limit; Ti – initial test, Tf – final test; t – Student's t-test value, p – probability level.

Adduction: The paired t-test revealed statistically significant improvements ($p < 0.001$) across all variables in both groups, with 95% confidence intervals excluding zero in all cases (Table 7). Cohen's d values in the adduction data reach extremely large magnitudes (d = 2.7–4.3), which must be interpreted with particular caution: in small homogeneous samples with low within-group variance, d is artificially inflated and cannot be treated as a direct indicator of clinical importance. The 95% CIs and absolute differences provide a more clinically grounded basis for comparison. Both groups show virtually equivalent absolute gains for the primary functional variables: %MF gains were +17.388 (95% CI: 14.818–19.959) in GE and +17.225 (95% CI: 15.600–18.851) in GC — the overlapping CIs and near-identical point estimates confirm equivalent within-group response. RS gains were similarly parallel: GE +0.284 N/kg (95% CI: 0.252–0.316) vs. GC +0.267 N/kg (95% CI: 0.239–0.296). RV gains were slightly higher in GE (+14.660, 95% CI: 12.992–16.328 vs. GC +12.006, 95% CI: 10.670–13.342), with non-overlapping CIs suggesting a real but modest absolute difference. From a rehabilitation standpoint, the equivalent adductor strength gains across both protocols are clinically relevant, as hip adductor strength contributes to frontal-plane knee stability and groin injury risk management in team-sport athletes.

Abduction: All within-group comparisons are statistically significant ($p < 0.001$), with 95% confidence intervals excluding zero in all cases. The extremely large d value for %MF in GE ($d = 5.203$) is a methodological artifact of very low within-group variance in this variable for this group, and must not be interpreted as a clinical superiority indicator or as reflecting an exceptionally large therapeutic effect. Emphasis should be placed instead on the absolute gain profile and the precision of the 95% CIs. Absolute gains for %MF were GE: +18.183 (95% CI: 16.771–19.594) vs. GC: +16.788 (95% CI: 14.637–18.939); the overlapping intervals and small absolute difference (~1.4 units) confirm equivalent within-group responses. RV gains were GE: +12.935 N·m (95% CI: 11.310–14.560) vs. GC: +11.792 N·m (95% CI: 10.448–13.135), also with overlapping CIs. %RV and RS gains were similarly comparable across groups. From a rehabilitation perspective, the equivalent hip abductor strength gains in both groups carry direct clinical relevance, as abductor weakness is associated with increased knee valgus loading and elevated ACL reinjury risk during lateral movements in team sports. Both protocols appear to provide sufficient stimulus for frontal-plane hip strength recovery within the 16-week timeframe.

Table 8. Independent T-test: Adduction and Abduction

Test	Comparison	Var.	X̄GE	X̄GC	ΔX	t	IC 95% (LL ; UL)	p	d Cohen
ADD (Adductor	GE vs GC · Ti	%MF	887.794	799.052	88.742	3.363	(35.678 ; 141.807)	0.002	0.933
		RV	701.053	610.46	90.593	4.765	(52.404 ; 128.782)	<0.001	1.322
		%RV	228.622	198.137	30.485	3.287	(11.831 ; 49.138)	0.002	0.912
		RS	13.712	12.312	1.401	3.435	(0.582 ; 2.22)	0.001	0.953
ADD (Adductor	GE vs GC · Tf	%MF	905.182	816.277	88.905	3.294	(34.625 ; 143.185)	0.002	0.914
		RV	715.713	622.466	93.247	4.86	(54.71 ; 131.784)	<0.001	1.348
		%RV	233.15	202.228	30.922	3.275	(11.933 ; 49.911)	0.002	0.908
		RS	13.997	12.579	1.418	3.441	(0.59 ; 2.245)	0.001	0.954
ABD (Abductor	GE vs GC · Ti	%MF	914.531	818.395	96.136	3.679	(43.549 ; 148.722)	<0.001	1.020
		RV	674.193	606.86	67.333	3.799	(31.699 ; 102.967)	<0.001	1.054
		%RV	178.53	158.555	19.975	3.845	(9.54 ; 30.409)	<0.001	1.067
		RS	14.005	12.174	1.831	5.079	(1.106 ; 2.555)	<0.001	1.409
ABD (Abductor	GE vs GC · Tf	%MF	932.714	835.183	97.53	3.669	(44.06 ; 151.001)	<0.001	1.018
		RV	687.128	618.652	68.476	3.88	(32.996 ; 103.956)	<0.001	1.076
		%RV	182.097	161.704	20.393	3.875	(9.819 ; 30.966)	<0.001	1.075
		RS	14.301	12.412	1.889	5.159	(1.153 ; 2.625)	<0.001	1.431

GE – experimental group, GC – control group, MF – maximum force; RV – reference value; %RV – percentage of the reference value (%RV); RS – Relative strength; Δ – difference; Δ – difference; X – arithmetic mean; SD – standard deviation; Ti – initial test; Tf – final test; CI – confidence interval; LL – lower limit; UL – upper limit; t – Student's t-test value; p – probability level.

Adduction: The independent t-test revealed statistically significant differences between the EG and CG at both Ti and Tf across all variables ($p \leq 0.002$), with 95% confidence intervals excluding zero in all cases (Table 8). The clinically critical finding is that substantial between-group differences were already established at baseline: RV showed $\Delta X = 90.593$ N·m (95% CI: 52.404–128.782) and %MF showed $\Delta X = 88.742$ (95% CI: 35.678–141.807) at Ti. At Tf, the between-group differences were virtually unchanged — RV: $\Delta X = 93.247$ N·m (95% CI: 54.710–131.784); %MF: $\Delta X = 88.905$ (95%

CI: 34.625–143.185) — and the near-identical CI profiles confirm that both groups progressed at a comparable rate without meaningful amplification of the initial gap. This pattern of stable between-group differences from Ti to Tf is the primary evidence against a differential treatment effect on adductor strength, and represents a more informative clinical conclusion than any comparison of d values, which (d ≈ 0.9–1.3) reflect the pre-existing group separation rather than rehabilitation-induced change.

Abduction: All between-group comparisons are statistically significant ($p < 0.001$), with 95% confidence intervals excluding zero in all cases. As with adduction, the 95% CIs at Ti confirm that the EG held a pre-existing baseline advantage across all variables (RS: ΔX = 1.831, 95% CI: 1.106–2.555; %MF: ΔX = 96.136, 95% CI: 43.549–148.722). At Tf, the magnitude and precision of between-group differences were virtually unchanged (RS: ΔX = 1.889, 95% CI: 1.153–2.625; %MF: ΔX = 97.530, 95% CI: 44.060–151.001). The stability of both point estimates and CI widths from Ti to Tf constitutes the primary evidence that neither group gained a differential advantage through the respective rehabilitation protocol; the observed Tf differences are attributable to baseline non-equivalence rather than differential treatment response. Cohen's d values for between-group comparisons are not reported here as primary indicators; the CI-based analysis above provides a more appropriate and clinically interpretable basis for conclusions about abductor strength outcomes in the context of this exploratory study.

Table 9. Paired t-test: Deficiency

Group	Var.	X̄Ti	X̄Tf	ΔX	SD Δ	t	IC 95% (LL ; UL)	p	d Cohen
GE	KF (Knee Flexion)	15.577	12.731	-2.846	3.233	-4.488	(-4.152 ; -1.54)	<0.001	-0.880
	KE (Knee Extension)	23.769	20.12	-3.65	3.551	-5.24	(-5.084 ; -2.215)	<0.001	-1.028
	ADD (Adductor)	8.808	6.503	-2.305	4.155	-2.828	(-3.983 ; -0.626)	0.009	-0.555
	ABD (Abductor)	11.115	9.66	-1.455	1.332	-5.571	(-1.993 ; -0.917)	<0.001	-1.092
GC	KF (Knee Flexion)	11.977	8.964	-3.013	2.306	-6.665	(-3.945 ; -2.082)	<0.001	-1.307
	KE (Knee Extension)	21.315	17.275	-4.04	2.12	-9.719	(-4.897 ; -3.184)	<0.001	-1.906
	ADD (Adductor)	6.307	5.104	-1.203	0.954	-6.431	(-1.589 ; -0.818)	<0.001	-1.261
	ABD (Abductor)	9.767	8.322	-1.445	1.275	-5.777	(-1.961 ; -0.930)	<0.001	-1.133

EG – experimental group, CG – control group, Δ – difference; Δ – difference; X – arithmetic mean, SD – standard deviation; Ti – initial test, CI – confidence interval, LL – lower limit, UL – upper limit; Tf – final test; t – Student's t-test value, p – probability level.

In GE, statistically significant deficit reductions were observed for KE (ΔX = −3.650%, 95% CI: −5.084 to −2.215), ABD (ΔX = −1.455%, 95% CI: −1.993 to −0.917), and KF (ΔX = −2.846%, 95% CI: −4.152 to −1.540); all three CIs exclude zero, confirming reliable pre-to-post change. ADD in GE showed a smaller, marginally significant reduction (ΔX = −2.305%, 95% CI: −3.983 to −0.626; $p = 0.009$), with the CI approaching zero, indicating less consistent change for this variable. In GC, all deficit reductions were statistically significant ($p < 0.001$) with narrow 95% CIs: KE: ΔX = −4.040% (95% CI: −4.897 to −3.184); KF: ΔX = −3.013% (95% CI: −3.945 to −2.082); ABD: ΔX = −1.445% (95% CI: −1.961 to −0.930); ADD: ΔX = −1.203% (95% CI: −1.589 to −0.818). The narrow CIs in GC reflect high within-group consistency, which also explains the larger Cohen's d magnitudes in GC (e.g., KE: d = −1.906 vs. GE d = −1.028); these d values should not be interpreted as evidence of greater clinical effectiveness, as they are driven by homogeneity of response rather than by the magnitude of the deficit reduction itself.

The clinically decisive benchmark here is not the effect size magnitude but whether residual deficit values reach the 15% reinjury risk threshold: as shown in Table 9, neither group achieved this target at Tf, with KE deficits remaining at 20.12% in GE and 17.275% in GC — both still above the threshold. This finding has direct implications for return-to-sport decision-making, indicating that 16 weeks of either protocol is insufficient to fully restore bilateral symmetry to safe competition levels.

In terms of the absolute magnitude of deficit reductions, the pattern is mixed and should be interpreted with the 95% CIs in mind. For KE, GC achieved a larger absolute reduction (−4.040%, 95% CI: −4.897 to −3.184) than GE (−3.650%, 95% CI: −5.084 to −2.215); the overlapping CIs indicate this difference is not reliable. For ADD, GE achieved a larger but less precise reduction (−2.305%, 95% CI: −3.983 to −0.626) vs. GC (−1.203%, 95% CI: −1.589 to −0.818), with the wide CI in GE suggesting variability in individual response. For KF and ABD, reductions were comparable across groups. The more pronounced KE deficit reduction in GC, despite smaller absolute strength gains, is likely partly attributable to more favorable reference values in that group rather than to superior performance improvement — a clinically important distinction that further cautions against cross-group comparisons of deficit metrics without accounting for normative reference differences. Overall, both groups fell short of the 15% bilateral symmetry threshold required for safe return to competitive sport, reinforcing the need for extended rehabilitation timelines and objective isokinetic reassessment as a mandatory clearance criterion.

Table 10. Independent T-test: Deficit

Comparison	Var.	X̄ GE	X̄ GC	ΔX	t	IC 95% (LL ; UL)	p	d Cohen
GE vs GC · Ti	KF (Knee Flexion)	15.577	11.977	3.6	1.363	(-1.711 ; 8.91)	0.179	0.378
	KE (Knee Extension)	23.769	21.315	2.454	0.824	(-3.526 ; 8.434)	0.414	0.229
	ADD (Adductor)	8.808	6.307	2.5	1.739	(-0.403 ; 5.404)	0.090	0.482
	ABD (Abductor)	11.115	9.767	1.348	1.942	(-0.046 ; 2.743)	0.058	0.539
GE vs GC · Tf	KF (Knee Flexion)	12.731	8.964	3.767	1.82	(-0.397 ; 7.931)	0.075	0.505
	KE (Knee Extension)	20.12	17.275	2.845	1.115	(-2.281 ; 7.97)	0.270	0.309
	ADD (Adductor)	6.503	5.104	1.399	1.501	(-0.476 ; 3.274)	0.140	0.416
	ABD (Abductor)	9.66	8.322	1.338	2.139	(0.082 ; 2.594)	0.037	0.593

EG – experimental group, CG – control group, Δ – difference; Δ – difference; X – arithmetic mean, SD – standard deviation; Ti – initial test, Tf – final test; CI – confidence interval, LL – lower limit, UL – upper limit; t – Student's t-test value, p – probability level.

When analyzing the deficit indices, the independent t-test did not reveal statistically significant between-group differences at Ti for any variable (p = 0.058–0.414), with all 95% CIs including zero (Table 10). This confirms that bilateral deficit levels were comparable between groups at baseline — in contrast to absolute strength, where GE held a pre-existing advantage. At Tf, the same non-significant pattern holds for KF (p = 0.075; 95% CI: −0.397 to 7.931), KE (p = 0.270; 95% CI: −2.281 to 7.970), and ADD (p = 0.140; 95% CI: −0.476 to 3.274), with all CIs crossing zero, confirming no meaningful between-group difference in deficit recovery for these movements. The only exception is ABD at Tf (p = 0.037; 95% CI: 0.082 to 2.594), which is nominally significant but does not survive Bonferroni correction (α = 0.00125), and the CI barely excludes zero, indicating low precision. Clinically, the key finding from this analysis is that neither group achieved meaningfully better bilateral symmetry than the other — and that both groups remained above the 15% reinjury risk threshold at Tf across the primary deficit indicators. This parity in deficit recovery, observed despite GE's absolute strength advantage, underscores the importance of tracking bilateral symmetry as a distinct outcome from absolute strength in post-ACLR rehabilitation and return-to-sport assessment.

4. Discussion

The results of the present study are broadly consistent with both research hypotheses, suggesting that a 16-week combined protocol of physical therapy and adapted functional training is associated with statistically significant improvements in isokinetic parameters among post-ACL senior female athletes, with numerically greater gains than those observed with standard recovery across most absolute strength parameters. These findings should be interpreted as exploratory, however, given the substantial baseline non-equivalence between groups inherent in the quasi-experimental design. These observations align with the growing body of literature documenting the potential benefits of multimodal protocols in post-ACLR rehabilitation. A multimodal post-ACLR rehabilitation program integrating concentric-eccentric training, balance exercises, resistance training, and functional restoration has been reported to be associated with long-term neuromuscular adaptations compared with standard physical therapy; however, intergroup effect size comparisons should not, on their own, be used to establish causal superiority. Our findings are consistent with these observations in the context of a 16-week structured protocol with gradual progression and sport-specificity. A four-month functional training program following ACL reconstruction has demonstrated significant improvements in isokinetic knee strength, dynamic balance, and joint stability compared to conventional recovery, suggesting that integrating a functional component may support recovery of muscle performance, including in the short term [35-37].

Strength gains in the operated limb, for both knee extension and flexion, were greater in the EG than in the CG across most evaluated parameters, based on absolute mean differences. The profile of gains in knee extension showed larger absolute increases in the EG for normalized variables (%RV, RV), reflecting a numerically greater reduction of the deficit relative to normative values; however, these differences should be interpreted cautiously given the pre-existing baseline imbalance between groups. It must be noted that Cohen’s d values alone do not establish clinical superiority: the magnitude of effect sizes in this study is strongly influenced by within-group variance structure and baseline differences, and must be interpreted alongside the 95% confidence intervals and absolute mean differences reported in Tables 3–10. On the non-surgical limb, gains were broadly comparable between groups, and any inference of a systemic transfer effect of the experimental intervention must remain tentative in the absence of formal interaction testing. In athletes with persistent post-ACLR muscle strength deficits, progressive strength training has been shown to produce greater improvements in knee flexor strength compared to low-intensity exercise [38,39]. The addition of isokinetic and functional training components to standard rehabilitation has also been associated with increased knee flexion and extension strength in athletes with ACLR, suggesting that combined interventions may produce greater adaptations than uniform protocols [40,41]; however, between-group comparisons in the present study cannot confirm causality due to baseline group non-equivalence.

The systematic dissociation between higher Cohen’s d values in the CG and smaller absolute gains illustrates a key interpretive limitation of effect size metrics: the high homogeneity of the response in the CG artificially inflates d values without reflecting comparable functional progress. More broadly, Cohen’s d values in this dataset are sensitive to within-group variance structure, group size, and baseline heterogeneity, and should not be used as a direct index of clinical effectiveness or to rank one protocol as superior to another. The 95% confidence intervals reported for each comparison provide a more informative basis for interpreting the precision and clinical relevance of observed differences. The clinically meaningful threshold for absolute strength gains, the %RV relative to sport-specific normative values, and the bilateral deficit index relative to the 15% reinjury risk threshold represent functionally grounded benchmarks that more adequately reflect recovery status than Cohen's d alone. Post-ACLR serial isokinetic assessments using the Biodex System 4 Pro confirm that objective longitudinal monitoring via these indicators is essential to guide rehabilitation progression.

Intergroup comparisons show that the EG began with significantly higher strength values than the CG for most variables, except for absolute maximum strength at knee extension on the surgical limb, which did not reach significance. The stability of Cohen's d values between Ti and Tf across all muscle groups indicates that the between-group difference observed at baseline was largely preserved throughout the intervention, without meaningful amplification. This pattern is consistent with both groups responding to their respective protocols, and does not, by itself, confirm superiority of the experimental intervention; formal interaction testing (Group × Time) would be required to substantiate such a claim. The 95% confidence intervals for between-group comparisons at Tf (Tables 4, 6, 8, 10) provide the most appropriate basis for judging the precision of these estimates. The isokinetic reference values for the quadriceps and hamstrings in female athletes practicing pivot-based sports exhibit considerable interindividual variability, supporting the need to use sport-specific normative values as a standardized reference for interpreting deficits, a procedure systematically applied in the present study via the %RV indicator [42-44].

At the muscle level in the frontal plane, both groups showed significant within-group gains in absolute magnitude for both adductors and abductors. Between-group comparisons showed numerically higher values in the EG across all variables and assessment time points; however, these differences reflect the pre-existing baseline advantage of the EG rather than a demonstrated causal effect of the protocol. The 95% confidence intervals for all adduction and abduction comparisons (Table 8) exclude zero, indicating statistical significance, but the clinical relevance of these differences should be evaluated against meaningful functional thresholds rather than effect size magnitudes alone. The functional condition of the hip muscles, particularly the abductors and adductors, is considered a relevant factor in injury risk among female players, given the essential involvement of these muscle groups in lateral movements, changes of direction, and single-leg balance situations [45,46]. A high percentage of post-ACLR patients fail to reach the hip abductor strength threshold relative to body weight; those with suboptimal values exhibit significantly reduced subjective function and psychological readiness two years post-intervention, highlighting the importance of including frontal plane strength as an explicit domain of assessment and rehabilitation in post-ACLR protocols [47,48].

The bilateral deficit indicator shows a distinct profile compared with absolute strength parameters [49,50]. Although both groups significantly reduced intragroup deficits, intergroup comparisons did not reveal significant differences at any assessment time point, except for abduction at Tf. This finding indicates that the GE's superiority in absolute strength did not translate into significantly better bilateral symmetry, and both groups exhibited a comparable recovery profile. The Tf deficit values remain clinically relevant in the GE, with both exceeding the 15% threshold associated with an increased risk of re-injury, a finding with direct implications for the decision to return to competition. The Delaware-Oslo study demonstrated that returning to sport with greater quadriceps strength symmetry significantly reduces the re-injury rate, and returning nine months or later post-operatively reduces the risk of re-rupture for each additional month of waiting [51,52]. Persistent deficits in knee extension strength may be associated with an increased risk of re-injury even in patients who meet standard symmetry thresholds, highlighting the limitations of the limb symmetry index [53,54]. A limb symmetry index ≥ 80% compared with the contralateral limb remains the most commonly reported functional criterion for return to sport after ACL reconstruction, with isokinetic quadriceps assessment serving as the gold standard for its calculation [55-57]. Therefore, the data from this study support the view that the decision to return to competition should not be based exclusively on time-based criteria but must include bilateral isokinetic assessment and the achievement of normative thresholds [58,59].

Post-ACLR recovery in elite athletes must be based on sport-specific rehabilitation principles, given that poor neuromuscular control during landing and pivoting is a known risk factor for re-injury [60,61]. A systematic review of additional physical therapy interventions used in standard post-ACLR rehabilitation protocols found that most improve pain, range of motion, muscle strength, or knee function, without significant adverse events, supporting, from a methodological perspective, the safety of adding functional components to standard physical therapy, an approach adopted in the present protocol [62-65]. From a Physical and Rehabilitation Medicine perspective, the present findings carry several implications for clinical decision-making in rehabilitation practice. First, the persistence of bilateral deficits exceeding the 15% reinjury risk threshold in both groups at post-intervention assessment underscores the importance of objective isokinetic evaluation as a mandatory component of return-to-sport clearance protocols, rather than relying on time-based criteria alone. Rehabilitation specialists and physiatrists should incorporate standardized isokinetic dynamometry as a primary outcome metric when designing progressive return-to-sport pathways for female athletes following ACLR. Second, the consistent pattern of within-group improvements observed across both protocols—despite their differing composition—highlights the clinical value of structured, criteria-guided progression frameworks, including pain-free execution thresholds and range-of-motion milestones, which align with current evidence-based PRM guidelines and are transferable to a wide range of rehabilitation settings. Third, although causal conclusions cannot be drawn from this exploratory study due to baseline non-equivalence, the observed trend toward larger absolute strength gains in the experimental group warrants consideration when designing individualized rehabilitation plans, particularly regarding the timing and intensity of functional training integration for elite female team-sport athletes. The role of isokinetic assessment extends beyond research into routine PRM practice, providing clinicians with objective, reproducible data to guide progression decisions, identify residual deficits, and establish sport-specific return-to-competition thresholds in a population at high risk of reinjury.

Study Limitations

The main limitations of the study include the small sample size (n = 26 per group), which, although calculated a priori for 80% power, limits the generalizability of the results. The initial non-equivalence of the groups on most strength variables, represents a methodological limitation inherent in the quasi-experimental design. The one-year data collection period introduced potential temporal variability in the assessment conditions. The absence of long-term follow-up prevents assessment of the stability of gains after the protocol concludes, and the exclusive inclusion of senior female handball and basketball players limits the generalizability of the conclusions to other populations or sports. No information regarding graft healing status, surgical technique standardization, or concomitant meniscal/cartilage injuries was systematically collected, which represents an additional limitation to consider when interpreting the results. The study relies exclusively on isokinetic metrics and does not include functional performance tests (e.g., hop tests, movement quality assessments), validated patient-reported outcome measures, psychological readiness assessments (e.g., ACL-RSI), or objective return-to-sport outcome measures, all of which are considered integral components of comprehensive post-ACLR evaluation in current evidence-based practice. The absence of these multidimensional outcomes prevents a full assessment of rehabilitation success and limits the clinical translatability of the findings.

Practical Implications

The present findings are consistent with the value of integrating sport-specific functional training into post-ACLR recovery protocols for elite athletes as a potentially beneficial approach for supporting strength recovery, though the baseline group non-equivalence in this study prevents causal conclusions about superiority over standard recovery. Persistent bilateral deficits above the clinical threshold of 15% at the end of the intervention, present in both groups, suggest that 16 weeks may be insufficient for complete restoration of isokinetic symmetry and that return-to-sport clearance criteria must systematically include objective bilateral isokinetic assessment, rather than relying on time-based criteria alone. In the context of Physical and Rehabilitation Medicine, these findings reinforce the role of isokinetic dynamometry for monitoring rehabilitation progression and informing individualized return-to-sport decisions. Clinicians and rehabilitation specialists are encouraged to apply explicit bilateral strength symmetry thresholds particularly for knee extension on the surgical limb as mandatory criteria before competitive reintegration, complemented by functional performance assessments and patient-reported outcome measures to ensure comprehensive clearance.

5. Conclusions

The present exploratory study suggests that a 16-week combined protocol of physical therapy and adapted functional training is associated with statistically significant improvements in isokinetic muscle strength in senior female athlete's post-ACLR, with numerically greater gains than those observed with standard recovery across most absolute and normalized strength parameters. Due to substantial baseline non-equivalence between groups, however, causal conclusions cannot be drawn, and the findings must be interpreted as hypothesis-generating rather than confirmatory.

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