Association between supervised strength session attendance and isokinetic recovery trajectory in male footballers following ACL reconstruction: a 6-year retrospective cohort study

Anis Chaouachi, [1] **Abdulaziz Farooq,** [1] **Thomas Carruthers,** [1] **Archie Ogden** [1] **Andres Sagarra,** [1] **Christopher Thomas,** [2] **Joao Marques,** [1] **Nuno Nascimento,** [1] **Stefano Nuccio,** [1] **Rod Whiteley,** [1] **Martin Buchheit** [1 3 4 5 6 7]

[1]Aspetar Sports Medicine Hospital, Doha, Qatar
[2]St Mary's University, Twickenham, UK
[3]Type 3.2 Performance, Montvalezan, France
[4]INSEP, Paris, France
[5]Optimo Performance Center, Estepona, Spain
[6]HIIT Science, Revelstoke, Canada
[7]Athletica, Revelstoke, Canada

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Headline

Recovery of quadriceps and hamstring strength is a central determinant of safe return to sport (RTS) after anterior cruciate ligament reconstruction (ACLR), with persistent strength deficits at the time of RTS increasing the risk of graft re-rupture and contralateral injury (Kyritsis et al., 2016; Grindem et al., 2016). Resistance training is universally prescribed during ACL rehabilitation (Buckthorpe & Della Villa, 2020; Welling et al., 2019; Bregenhof et al., 2023), yet most evidence on its effectiveness comes from controlled trials with assigned exposures, while real-world adherence to prescribed strength programs is rarely quantified. One comparable study, in recreational athletes, reported that those attending more supervised physiotherapy visits over six months recovered isokinetic strength better than those attending fewer visits (Czamara et al., 2021), but did not isolate strength sessions specifically nor focus on elite populations. The dose-response relationship between actual strength session attendance and isokinetic strength recovery in elite footballers therefore remains unclear.

Aim

We examined the association between strength session attendance and isokinetic quadriceps and hamstring strength outcomes at 18 and 24 weeks post-ACLR in 55 male footballers progressing through a standardized rehabilitation pathway.

Methods

Design and participants

We conducted a retrospective chart review of de-identified clinical data from the Aspetar ACL rehabilitation program, covering a 6-year period.

The analysis was framed as an adherence study (the prescribed dose was two to three sessions per week; observed variation reflects what athletes actually did, not randomized assignment). Eligible cases were male footballers who had undergone primary unilateral ACLR using a hamstring autograft (semitendinosus alone or semitendinosus + gracilis), with isolated ACL injury or concomitant meniscus repair, meniscectomy, or lateral tenodesis, pre-injury Tegner activity level 8 to 10, and complete isokinetic and attendance data at the relevant timepoints (i.e., from 6 to 12, 18 and 24 weeks post-surgery). Selection was restricted to hamstring-autograft cases for two reasons. First, to ensure a homogeneous cohort, since rehabilitation timelines, donor-site recovery and isokinetic profiles differ between hamstring, patellar tendon and quadriceps tendon grafts. Second, the hamstring autograft was by far the most common graft choice in our retrospective dataset, which made it the only graft category with sufficient sample size for the planned analysis. The hamstring-graft specific recovery pattern is also relevant when interpreting our hamstring outcomes (see Discussion). Fifty-five athletes who provided complete data and met all inclusion criteria were included. The eligible sample was constrained by difficulties retrieving complete strength session logs across the 6-year retrospective period and by the strict inclusion criteria above; we accepted this trade-off to ensure data integrity over a larger but less reliable sample. The study was approved by the Aspetar Institutional Review Board (Ethics Application No. X202501099). Athlete characteristics are presented in Table 1.

Rehabilitation pathway

All athletes completed a standardized criteria-based rehabilitation pathway with prescribed strength training of two to three sessions per week from approximately week 12 onwards. Earlier work, from around week 6, was led primarily by physiotherapists and is not counted as a structured strength session in our analysis; the present study captures only the supervised strength sessions delivered by the strength and conditioning/performance staff, which typically started around week 12. Programs were individualized for each athlete and surgeon, but standardized for structure, with two weekly sessions that each combined a strength-dominant block and an explosive-dominant block within the same session, rather than alternating one focus per session. Each session covered five categories: explosiveness (jumps: countermovement jump [CMJ]/non-countermovement jump [NCMJ], bodyweight [BW] and loaded), quadriceps strengthening, hamstring strengthening, accessory work, and isokinetic work included concentric/concentric knee extension-flexion at 60°/s (Con/Con 60°/s), eccentric (ECC) hamstring and ECC quadriceps work (both performed at 60°/s). Both modalities were strength assessment and training in preparation for the assessment. Programs were structured in 6-week blocks cor-

responding to the rehabilitation phase: the mid-stage block covered weeks 12 to 18, and a late-stage block (referred to internally as SpSp1) covered weeks 19 to 24 and beyond. Sets, repetitions, and loads were progressed within each week (W1 to W6) and across blocks, with involved and uninvolved limbs tracked separately. The general structure of the program is summarized in Table 2.

Table 1. Athlete characteristics (N = 55).

Variable	Value
Age (years), mean ± SD	25.0 ± 6.5
BMI (kg/m^2), mean ± SD	23.3 ± 2.7
Dominant side (left / right)	8 (14.5%) / 47 (85.5%)
Operated side (left / right)	25 (45.5%) / 30 (54.5%)
Graft: semitendinosus only	18 (32.7%)
Graft: semitendinosus + gracilis	29 (52.7%)
Graft: not reported	8 (14.5%)
Meniscus: no procedure	27 (49.1%)
Meniscus: repair	21 (38.2%)
Meniscus: meniscectomy	7 (12.7%)
Lateral tenodesis	11 (20.0%)
Brace restrictions	27 (49.1%)
Weight-bearing restrictions	12 (21.8%)
Tegner score 8 / 9 / 10	12 / 23 / 20

Table 2. General structure of the strength training program (illustrative; exact loads, sets and reps were individualized).

Category	Exercises	Dose
Explosiveness	MVP Shuttle CMJ (DL/SL), Explosive CMJ/NCMJ (DL/SL), Keiser Squat (DL/SL)	3 sets × 3-5 reps
Quadriceps	Safety Bar Squat, Front Squat, SL Smith Squat, SL Leg Press, Leg Extension (CON/ECC), Bulgarian Squat, SL Squat to Box (ECC)	3-4 sets × 8-12 reps
Hamstring	SL/DL RDL, Leg Curl Seated (CON), Leg Curl Prone (ECC), Val Slide ECC, Nordic, SL Leg Curl Standing	3-4 sets × 8-12 reps
Accessory	Adductor, Lateral Lunges, Calf Raise (DL/SL), Hip Thrust (DL/SL)	3-4 sets × 8-12 reps
Isokinetic assessment and training	Con/Con 60°/s, ECC Hamstring, ECC Quadriceps	Periodic check-in and training

CMJ: countermovement jump. NCMJ: non-countermovement jump. DL: double leg. SL: single leg. CON: concentric (muscle action). ECC: eccentric (muscle action). RDL: Romanian deadlift. MVP Shuttle: Horizontal jump device used for double-leg or single-leg countermovement jumps with progressive elastics resistance. Keiser Squat: pneumatic resistance squat machine. Cybex Con/Con 60°/s: concentric/concentric isokinetic test at 60°/s on a Cybex (Humac Norm) dynamometer. SpSp1: institutional name of the late-stage rehabilitation block (weeks 19 to 24+).

Exposure and outcomes

Isokinetic strength testing was performed at 6, 12, 18, and 24 weeks post-surgery on a Humac Norm dynamometer. Strength session attendance was extracted from physiotherapy logs. Data are not reported beyond 24 weeks as after this timepoint an increasing proportion of athletes left Aspetar to complete late-stage rehabilitation closer to their home club or country, leading to systematic loss to follow-up that would have biased any analysis of later timepoints.

The exposure variable was the average number of strength sessions per week attended during the 6-week block preceding each isokinetic test. Thus, the attendance value associated with the 18-week test reflects sessions completed between weeks 12 and 18, and the value associated with the 24-week test reflects sessions completed between weeks 18 and 24. Attendance was categorized as 0, 1, or 2+ sessions per week. We note that 0 sessions per week was not a prescribed condition but reflected athletes who did not complete supervised strength sessions delivered by the strength and conditioning/performance staff during the block. This category captured two distinct situations. The first was non-attendance in the simple sense (the athlete was scheduled but did not show up). The second, and arguably more common, was a deliberate clinical decision to extend the physiotherapy-led phase rather than transition to supervised strength training, because the athlete had not yet met the criteria required to progress (e.g., persisting effusion, range-of-motion deficit, pain, or specific motor-control or graft-healing concerns). The transition to strength work in our pathway is criteria-based, not time-based, so a longer physiotherapy-led phase is part of an individualized program rather than non-adherence in the conventional sense. Outcomes were quadriceps and hamstrings concentric peak torque at 60°/s, hamstrings eccentric peak torque at 60°/s, and corresponding ratios and limb symmetry indices (LSI, ((INV - UNINV)/MAX(INV, UNINV)) x100).

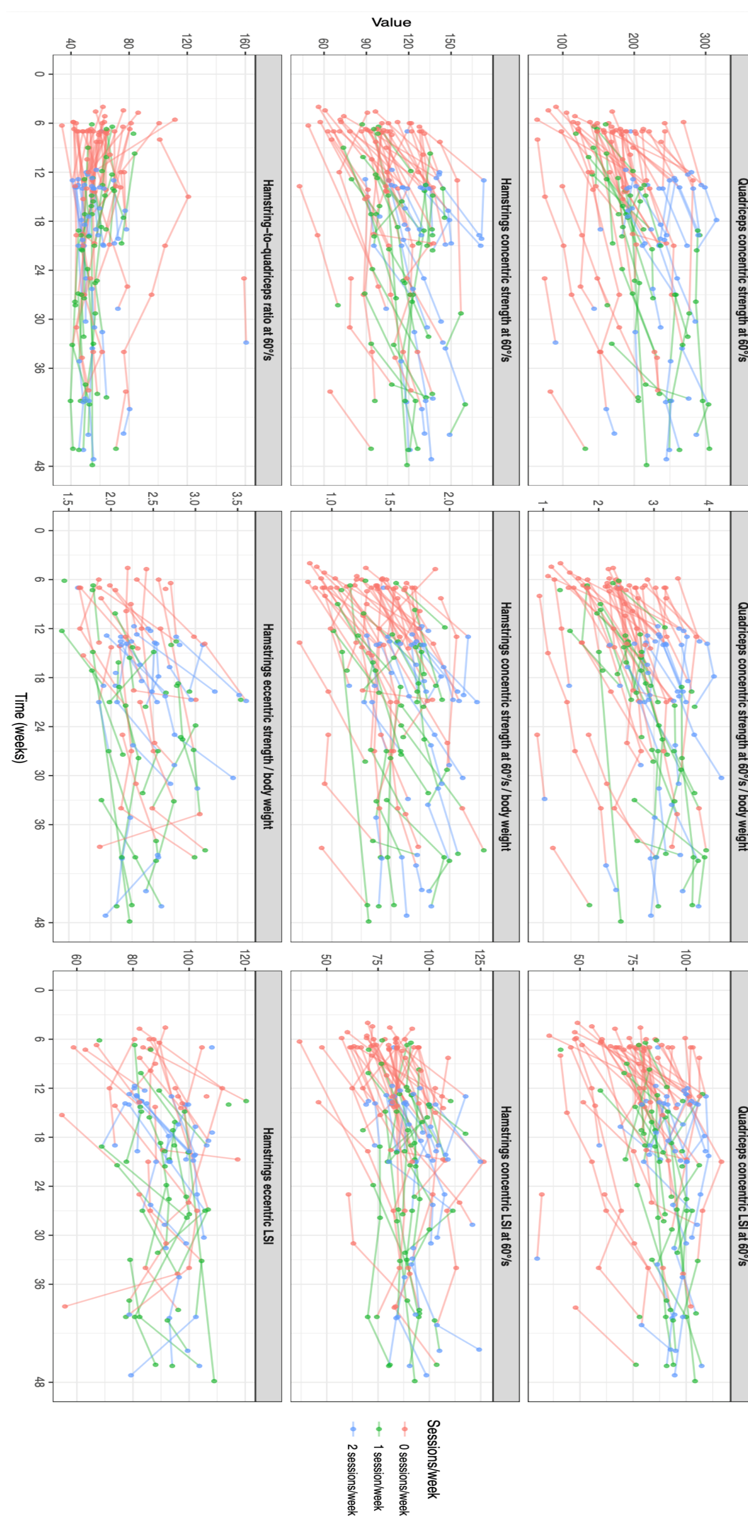

Fig. 1. **Individual athlete trajectories for nine isokinetic outcomes, stratified by strength session attendance during the preceding 6-week block (red: 0 sessions/week; green: 1 session/week; blue: 2+ sessions/week). Each line represents a single athlete; points represent assessment timepoints (weeks post-surgery). Note that the y-axis label "Value" represents different units depending on the panel: panels showing absolute peak torque are in N·m (e.g., Quad CON 60, HS CON 60); panels showing body-weight-normalized peak torque are in N·m·kg^{-1} (e.g., Quad CON 60/BW, HS CON 60/BW, HS ECC/BW; see Methods); and panels showing limb symmetry indices (LSI) are in percent. The 0 sessions/week (red) trajectories are concentrated at later assessment timepoints, reflecting athletes whose preceding 6-week block fell during the transition out of structured strength work.**

Statistical analysis

All analyses were performed using IBM SPSS Statistics, version 21.0. Descriptive statistics were reported as mean ± SD or median and interquartile range for continuous variables, and frequency and percentage for categorical variables.

Paired-samples t-tests were used to compare involved and uninvolved limb strength at each available timepoint. These comparisons were performed at 12, 18, and 24 weeks; 6-week paired comparisons were not conducted because involved-limb data were unavailable. Limb symmetry index was compared between attendance categories, defined as 0, 1, and ≥2 sessions/week, using separate one-way ANOVA at 18 and 24 weeks. Bonferroni-adjusted pairwise comparisons were applied where appropriate.

Linear mixed-effects models were used to examine quadriceps and hamstring concentric strength at 60°/s, with time as the within-athlete factor, attendance category as the between-athlete factor, and athlete as a random effect to account for repeated measures. Models were adjusted for baseline strength, age, time post-surgery, and concomitant meniscus repair status.

Missing data were handled using available-case analysis, and no imputation was performed. Effect sizes were reported as partial eta-squared (η^2p), interpreted as small ≥0.01, medium ≥0.06, and large ≥0.14. All tests were two-sided, with $p < 0.05$ considered statistically significant.

Results

The cohort comprised 55 male footballers, predominantly with right-side dominance and right-leg surgery (Table 1). Concomitant procedures were common: 38% had a meniscus repair, 13% a meniscectomy, and 20% a lateral tenodesis. Group sample sizes for the 0, 1, and 2+ sessions/week comparisons were 15, 12, and 17 at 18 weeks, respectively, and 5, 10, and 15 at 24 weeks, respectively.

Individual trajectories

Individual trajectories of all isokinetic outcomes, stratified by attendance group, are shown in Figure 1. Two patterns are visible. First, athletes in the 2+/week group (blue) tended to start their assessment block earlier in rehabilitation than those in the 0/week group (red), reflecting the natural transition from structured strength work into return-to-running and field-based phases later in the pathway. Second, individual variability within each attendance group was substantial across all outcomes, with overlapping ranges between groups visible in every panel.

Population-level recovery: involved versus uninvolved limb

At the cohort level, both quadriceps and hamstring peak torque on the involved limb increased progressively from 12 to 24 weeks post-surgery (Figure 2). Despite this progression, involved-limb strength remained significantly below the uninvolved limb at every assessed timepoint for all outcomes (all $p < 0.05$; Table 3). At 24 weeks, the involved limb still produced approximately 10% less quadriceps concentric torque (215.4 ± 54.2 vs 239.6 ± 40.7 N·m), 7% less hamstring concentric torque (122.1 ± 26.9 vs 130.9 ± 27.3 N·m), and 9% less hamstring eccentric torque (122.1 ± 26.9 vs 130.9 ± 27.3 N·m) than the uninvolved limb, corresponding to group-mean LSI values of approximately 90–93% across the three outcomes (Figure 3). Absolute (non-normalized) peak torque values are reported in Table 3, and pairwise effect sizes for between-group differences in absolute strength are reported in Table 4.

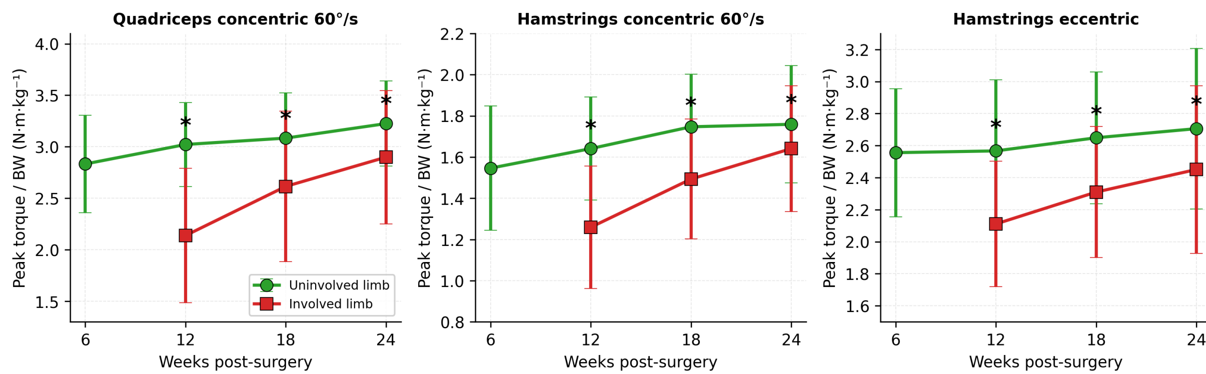

Fig. 2. Group-level body-weight-normalized strength recovery: peak torque per kg body weight (N·m·kg^{-1}) of the involved (red squares) versus uninvolved (green circles) limb at 6, 12, 18 and 24 weeks post-ACLR, pooled across all 55 athletes. Markers represent group means; error bars represent standard deviations. Asterisks indicate significant within-athlete difference between involved and uninvolved limbs at the corresponding timepoint ($p < 0.05$). The 6-week timepoint shows uninvolved-limb data only because most involved-limb isokinetic tests were not yet performed at that stage of rehabilitation.

LSI by adherence group

The clearest dose-response signal emerged for quadriceps concentric LSI at 18 weeks (Figure 3). Athletes attending two or more sessions per week showed substantially higher quadriceps LSI than those attending none (95.6 ± 3.6% vs 78.7 ± 3.8%; mean difference -16.9 percentage points; Bonferroni $p < 0.001$; $d = 1.86$) or one session per week (95.6% vs 78.5 ± 4.3%; mean difference -17.1 percentage points; $p = 0.007$; $d = 1.34$). The gap narrowed by 24 weeks (92.6 ± 3.8% vs 83.8 ± 6.6%; mean difference -8.8 percentage points; $p = 0.94$; $d = 0.80$), with all groups approaching or exceeding the 90% RTS threshold.

For hamstring concentric LSI, between-group differences at 18 weeks were small and inconsistent (Figure 3). The 2+/week group did not show superior LSI outcomes compared to the 0/week group (87.0 ± 3.4% vs 84.0 ± 3.6%; mean difference -3.0 percentage points; d for LSI = -0.21), although the absolute strength comparison was statistically significant (mean

difference -24.2 N·m; p = 0.008; d = -1.21). This apparent inconsistency reflects the fact that the 2+/week group also had higher uninvolved-limb hamstring strength, which cancels in the LSI ratio. At 24 weeks, all three groups exceeded 88% LSI with no meaningful between-group differences (all $d \leq 0.30$). The 1/week group showed a trend for lower hamstring concentric LSI than both other groups at this timepoint, but this is likely not worth commenting on given the small subgroups (n = 5–15) and the absence of any consistent dose-response trend. Hamstring eccentric LSI showed no consistent pattern across attendance categories at either timepoint (all $d \leq 0.20$).

Table 3. Absolute peak torque (N·m, mean ± SD), pooled across athletes (N=55).

Outcome	6 weeks (n=44)	12 weeks N=42	18 weeks N=47	24 weeks N=32
Quad CON 60 uninv.	207.3 ± 38.6	222.8 ± 35.7	230.8 ± 37.4	239.6 ± 40.7
Quad CON 60 inv.	-	157.5 ± 50.6*	195.8 ± 57.4*	215.4 ± 54.2*
HS CON 60 uninv.	113.3 ± 25.3	121.0 ± 21.1	131.0 ± 22.8	130.9 ± 27.3
HS CON 60 inv.	-	92.9 ± 23.8*	112.2 ± 24.7*	122.1 ± 26.9*

*significant within-athlete difference between involved (inv.) and uninvolved (uninv.) limbs ($p < 0.05$). Quad CON 60: quadriceps concentric peak torque at 60°/s. HS CON 60: hamstrings concentric peak torque at 60°/s.
Body-weight-normalized values for these outcomes and for hamstrings eccentric torque are shown in Figure 2. At week 6 involved limb was not assessed.

Table 4. Pairwise effect sizes for between-group differences in absolute strength at 18 and 24 weeks. Negative d values indicate the higher-attendance group had greater strength.

Outcome	Timepoint	Comparison	Mean diff (N·m)	Partial eta-square
Quad CON 60	18w	0 vs 1/wk	6.1	0.007
Quad CON 60	18w	0 vs 2/wk	-46.4	0.299 *
Quad CON 60	18w	1 vs 2/wk	-52.5	0.375 *
Quad CON 60	24w	0 vs 1/wk	-10.5	0.015
Quad CON 60	24w	0 vs 2/wk	-28.5	0.131
Quad CON 60	24w	1 vs 2/wk	-18.0	0.081
HS CON 60	18w	0 vs 1/wk	3.9	0.011
HS CON 60	18w	0 vs 2/wk	-7.0	0.033
HS CON 60	18w	1 vs 2/wk	-10.9	0.083
HS CON 60	24w	0 vs 1/wk	4.9	0.011
HS CON 60	24w	0 vs 2/wk	-7.6	0.036
HS CON 60	24w	1 vs 2/wk	-12.6	0.129

*significant between-group differences in absolute strength ($p < 0.05$).

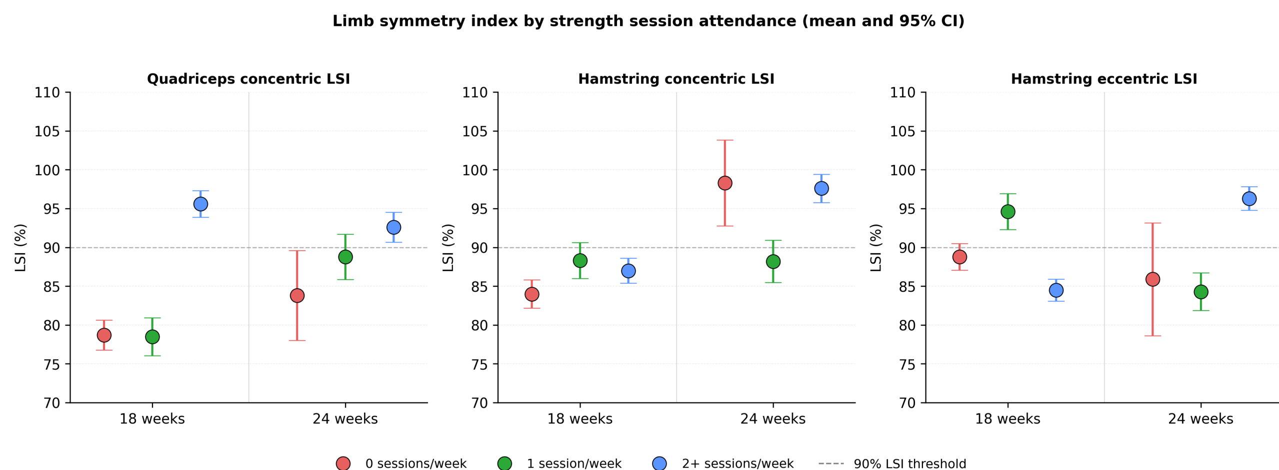

Fig. 3. Limb Symmetry Index (LSI) at 18 and 24 weeks post-ACLR by strength session attendance during the preceding 6-week block. Dots represent group means; error bars represent represent 95% confidence intervals. Dashed line indicates the 90% LSI threshold commonly used as a return-to-sport benchmark. Sample sizes per group: at 18 weeks, n=15 (0/wk), n=12 (1/wk), n=17 (2/wk); at 24 weeks, n=5 (0/wk), n=10 (1/wk), n=15 (2/wk).

Discussion

Among male footballers in standardized post-ACLR rehabilitation, athletes attending two or more strength sessions per week between weeks 12 and 18 reached a quadriceps LSI of 96% by week 18 (large effect vs lower-adherence groups; d = 1.86 and 1.34), while those attending none or one session per week remained at approximately 79%. By week 24 the gap had largely narrowed (residual d = 0.80, no longer statistically significant after correction for multiple comparison). Lower adherence does not appear to permanently impair strength recovery in this population, but it delays the point at which athletes meet a key objective benchmark by several weeks. Earlier work suggested that delaying RTS up to 9 months substantially reduced reinjury risk (Grindem et al., 2016), implying calendar time as the protective variable. More recent Aspetar data (Kotsifaki et al., 2025) show that, once athletes meet objective discharge criteria, time to RTS itself is no longer associated with reinjury risk. Adherence is therefore best framed not as buying calendar time but as compressing the path to criteria-readiness, which matters in competitive football where every week below criteria carries cost.

Our findings align with Czamara et al. (2021), the only directly comparable study, who reported that recreational athletes attending more supervised physiotherapy visits showed greater isokinetic strength recovery. Our quadriceps recovery at 24 weeks (mean 2.90 N·m·kg-¹) exceeds Czamara et al.'s high-adherence (2.56 N·m·kg-¹) and low-adherence (2.25 N·m·kg-¹) groups, and brings our cohort into the lower end of normative ranges for elite male footballers (2.45–3.62 N·m·kg-¹; Asimakidis et al., 2024). Hamstring outcomes compare favourably with the meta-analytic average for hamstring-graft cohorts at 12 months (89.0% LSI; Högberg et al., 2024) and with non-professional data (Eğerci et al., 2025).

For hamstring concentric LSI, between-group differences at 18 weeks did not follow the same dose-response pattern (Figure 3): the 0/wk group showed the lowest LSI (84.0%) but the 1/wk and 2+/wk groups did not differ meaningfully from each other (88.3% vs 87.0%; overlapping 95% CIs). The corresponding comparison on absolute strength was statistically significant (mean difference -24.2 N·m; p = 0.008; d = -1.21), reflecting bilateral strengthening (see Discussion).

Why does the gap close by 24 weeks? Two non-exclusive mechanisms are plausible. First, low-adherence athletes may have increased their attendance after the 18-week assessment, as suggested by the within-athlete attendance variation visible in Figure 1. Second, a ceiling effect approaching the uninvolved-side strength may make further between-group separation harder to detect once all groups are within the 80–95% LSI range. Importantly, this was not an RCT: a given athlete could be in different attendance categories across the two blocks, so the 18- and 24-week analyses should be read as complementary timepoints rather than a longitudinal exposure trajectory.

The hamstring outcomes did not show the same dose-response pattern as the quadriceps. This is not unexpected: in athletes with hamstring graft, the donor muscle undergoes its own recovery driven by graft healing and morphological factors (Welling et al., 2019; Suijkerbuijk et al., 2015) and likely requires specific exercise selection (especially eccentric loading; Palmieri-Smith et al., 2022) rather than total session dose alone.

Högberg et al. (2024), in a meta-analysis of 64 studies and over 8,000 hamstring-autograft patients, found that knee flexor LSI typically reaches the 90% threshold only at two years post-surgery (89.0% at 12 months), and argued that this slow recovery likely reflects under-loading rather than a fixed biological ceiling. Eğerci et al. (2025), in a non-professional cohort, reported that eccentric hamstring LSI declined from 98% pre-op to 70% at 12 months. Together these data suggest hamstring recovery is the rate-limiting outcome after hamstring-graft ACLR and likely requires earlier and more aggressive loading than standard programmes provide.

Our own programme (Table 2) is built around moderate-volume leg curls, Nordic, RDL, and Val Slide ECC, with involved- and uninvolved-limb doses comparable. Hip-dominant high-velocity loading and sprint-pattern eccentric work, which target the donor muscle closer to its competitive demand, are comparatively under-represented. We cannot test from present data whether a more aggressive eccentric and high-velocity prescription on the involved limb would improve outcomes, but plan to address this in a prospective comparison.

Two findings reinforce that the shortfall is a content rather than volume problem. Mendiguchia et al. (2020) reported small to large improvements in sprint performance and biceps femoris long head architecture after six weeks of sprint training, whereas Nordic training and regular soccer practice produced only trivial to small negative changes. Lacome et al. (2020) showed in elite footballers that low-volume eccentric hamstring work (one set per exercise, ten repetitions in total per session) produced similar gains in knee-flexor strength and fascicle length to high-volume work (four sets, forty repetitions), suggesting that exercise quality and distribution may matter more than session count. In hamstring-graft ACLR this is compounded by a graft-healing ceiling that limits how aggressively high-density eccentric and sprint-pattern loading can be prescribed in the mid-stage block, supporting our restriction of the cohort to hamstring-autograft cases.

Finally, the 0 sessions/week trajectories cluster at later timepoints (Figure 1), reflecting athletes transitioning out of structured strength work into running- and field-based phases. This partially confounds attendance category with rehabilitation stage and should be addressed in future work using continuous dose modelling.

Limitations

- Observational design with self-selected exposure (adherence is a behaviour, not an assigned dose).
- Actual exercise dose (sets, repetitions, relative and absolute load etc.) are not reported and need to be investigated
- Sample size was limited by retrospective data availability; selection bias from incomplete records is plausible.
- Small sample in the 0 sessions/week group at 24 weeks (n=5).
- Single-centre, male-only, hamstring-graft-only cohort.
- Exposure windows are non-overlapping (12 to 18 weeks for the 18-week test; 18 to 24 weeks for the 24-week test) so the two timepoints reflect two separate exposure analyses, not a longitudinal trajectory of the same exposure.
- The 24-week follow-up reflects the mid-stage of recovery only; meta-analytic evidence indicates that knee flexor LSI in hamstring-graft cohorts typically reaches ≥90% only at two years (Högberg et al., 2024).
- The 0 sessions/week category partially captures athletes whose assessment block fell during the natural transition out of structured strength work, rather than non-adherence in the strict sense.

Practical applications

- Attending two supervised strength sessions per week between weeks 12 and 18 post-ACLR was associated with earlier achievement of the 90% quadriceps LSI RTS threshold by week 18 (large effect, d = 1.86 vs no attendance).

In contrast, attending one or no sessions per week was not associated with the same response.
- Although athletes with lower attendance appeared to reduce this gap by week 24, delayed achievement of strength criteria may be clinically relevant in competitive football, where each week can influence training progression and reinjury exposure.
- Strength-session attendance should be monitored and discussed as a clinical indicator of rehabilitation progression, rather than treated only as an administrative measure of compliance.
- The 12-to-18 week block may represent a high-leverage window for adherence; during this period, clinicians should prioritize athlete engagement, scheduling support and individualized strength programming.
- Hamstring strength did not show the same dose-response pattern as quadriceps strength, suggesting that hamstring recovery, particularly after hamstring graft ACLR, may require targeted exercise selection and appropriately progressed eccentric loading, rather than greater total volume.
- LSI should not be interpreted in isolation. In our cohort of athletes, higher attendance was associated with strength gains in both limbs, which may have attenuated changes in hamstring LSI. Reporting absolute peak torque alongside LSI provides a clearer interpretation of training response and readiness progression.
- These findings support the clinical value of strength-session adherence as a modifiable factor that may accelerate criteria-readiness, rather than simply extend rehabilitation duration. This interpretation is consistent with recent Aspetar evidence (Kotsifaki et al., 2025) indicating that, once objective discharge criteria are met, calendar time to RTS alone may not independently reduce reinjury risk.

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References

1. Asimakidis, N. D., Mukandi, I. N., Beato, M., Bishop, C., & Turner, A. N. (2024). Assessment of strength and power capacities in elite male soccer: A systematic review of test protocols used in practice and research. Sports Medicine, 54(10), 2607–2644.

2. Bregenhof, B., Aagaard, P., Nissen, N., Creaby, M. W., Thorlund, J. B., Jensen, C., Torfing, T., & Holsgaard-Larsen, A. (2023). The effect of progressive resistance exercise on knee muscle strength and function in participants with persistent hamstring deficit following ACL reconstruction: A randomized controlled trial. Journal of Orthopaedic & Sports Physical Therapy, 53(1), 40–48.

3. Buckthorpe, M., & Della Villa, F. (2020). Optimising the ‘mid-stage’ training and testing process after ACL reconstruction. Sports Medicine, 50(4), 657–678.

4. Cohen, J. (1988). Statistical power analysis for the behavioral sciences (2nd ed.). Lawrence Erlbaum Associates.

5. Czamara, A., Krzemińska, K., Widuchowski, W., & Dragan, S. L. (2021). The muscle strength of the knee joint after ACL reconstruction depends on the number and frequency of supervised physiotherapy visits. International Journal of Environmental Research and Public Health, 18(20), 10588.

6. Egerci, O. F., Arslan, G., Dogruoz, F., Yapar, A., Dikmen, I., & Unal, M. (2025). Significant muscle strength deficits persist one year after ACL reconstruction with hamstring tendon autografts. Sports Traumatology & Arthroscopy, 2(3), 119–127.

7. Grindem, H., Snyder-Mackler, L., Moksnes, H., Engebretsen, L., & Risberg, M. A. (2016). Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: The Delaware-Oslo ACL cohort study. British Journal of Sports Medicine, 50(13), 804–808.

8. Högberg, J., Piussi, R., Lövgren, J., Wernbom, M., Simonsson, R., Samuelsson, K., & Hamrin Senorski, E. (2024). Restoring knee flexor strength symmetry requires 2 years after ACL reconstruction, but does it matter for second ACL injuries? A systematic review and meta-analysis. Sports Medicine - Open, 10(1), 2.

9. Kotsifaki, R., King, E., Bahr, R., & Whiteley, R. (2025). Is 9 months the sweet spot for male athletes to return to sport after anterior cruciate ligament reconstruction? British Journal of Sports Medicine, 59(9), 667–675.

10. Kyritsis, P., Bahr, R., Landreau, P., Miladi, R., & Witvrouw, E. (2016). Likelihood of ACL graft rupture: Not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. British Journal of Sports Medicine, 50(15), 946–951.

11. Lacome, M., Avrillon, S., Cholley, Y., Simpson, B. M., Guilhem, G., & Buchheit, M. (2020). Hamstring eccentric strengthening program: Does training volume matter? International Journal of Sports Physiology and Performance, 15(1), 81–90.

12. Mendiguchia, J., Conceição, F., Edouard, P., Fonseca, M., Pereira, R., Lopes, H., Morin, J.-B., & Jiménez-Reyes, P. (2020). Sprint versus isolated eccentric training: Comparative effects on hamstring architecture and performance in soccer players. PLOS ONE, 15(2), e0228283.

13. Palmieri-Smith, R. M., Brown, S. R., Wojtys, E. M., & Krishnan, C. (2022). Functional resistance training improves thigh muscle strength after ACL reconstruction: A randomized clinical trial. Medicine & Science in Sports & Exercise, 54(10), 1729–1737.

14. Suijkerbuijk, M. A. M., Reijman, M., Lodewijks, S. J. M., Punt, J., & Meuffels, D. E. (2015). Hamstring tendon regeneration after harvesting: A systematic review. American Journal of Sports Medicine, 43(10), 2591–2598.

15. Welling, W., Benjaminse, A., Lemmink, K., Dingenen, B., & Gokeler, A. (2019). Progressive strength training restores quadriceps and hamstring muscle strength within 7 months after ACL reconstruction in amateur male soccer players. Physical Therapy in Sport, 40, 10–18.

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