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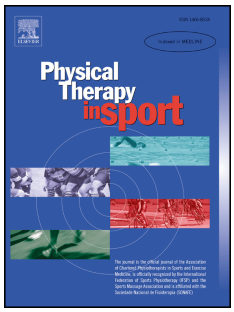

Resistance training with linear periodization is superior to the '3x10 reps protocol' after anterior cruciate ligament reconstruction: a randomized controlled trial

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Resistance training with linear periodization is superior to the '3x10 reps protocol' after anterior cruciate ligament reconstruction: a randomized controlled trial

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Resistance training with linear periodization is superior to the '3x10 reps protocol' after anterior cruciate ligament reconstruction: a randomized controlled trial

ABSTRACT

Objective: To investigate the effects of linear periodization (LP) resistance training after anterior cruciate ligament reconstruction (ACLR).

Setting: Physiotherapy clinic.

Participants: Male recreational athletes who underwent ACLR.

Main outcome measures: Knee extensor and flexor isometric strength, hop tests performance, patient-reported function (International Knee Documentation Committee, IKDC), and psychological readiness (Anterior Cruciate Ligament – Return to Sport after Injury, ACL-RSI).

Results: Twenty-two participants (mean age 27±6 years) were randomized into the LP (n=11) or 3x10 (n=11) groups. The LP group demonstrated greater knee extensor strength gains compared to the 3x10 group (p=0.03): 51% (95%CI, 28 to 73) *vs.* 26% (95%CI, 11 to 40). No statistically significant difference (p=0.11) in knee flexor strength gains was observed between the LP group (45%; 95% CI, 18 to 71) and the 3x10 group (23%; 95% CI, 7 to 39). Six months after ACLR, the LP group exhibited a greater knee extensor limb symmetry index (97±10% *vs.* 85±11%, p<0.01) and higher ACL-RSI scores (68±18 vs. 53±14, p=0.04). No significant between-group differences were found in hop performance or IKDC scores (p>0.05).

Conclusion: A resistance training program incorporating LP is more effective than the traditional '3x10 reps protocol' in enhancing knee extensor strength and psychological readiness during ACLR rehabilitation.

Key Words: ACL; rehabilitation; physiotherapy; strength training.

INTRODUCTION

The anterior cruciate ligament (ACL) is susceptible to injury in athletes across various competitive levels, from non-contact individual sports like gymnastics to field and court-based team sports such as football (soccer), rugby, American football, basketball, and others (Montalvo et al. 2019). Around 80% of athletes return to some kind of sporting activities after an ACL reconstruction (ACLR) surgery, but only 55% return to competitive sports (Ardern et al. 2014). Rehabilitation after ACLR plays a critical role in ensuring a successful return to sport while reducing the risk of reinjury (Grindem et al. 2016; Kyritsis et al. 2016; Kotsifaki et al. 2025). This is a complex process that typically takes 6 to 12 months (Lai et al. 2018), although it is not uncommon for athletes to require longer periods to meet specific criteria to return to sport (Kotsifaki et al. 2025).

Clinical guidelines typically advocate for a comprehensive testing battery assessing strength, functional capacity, and psychological status to guide return-to-sport decision-making after ACLR (van Melick et al 2016; Brinlee et al. 2022; Kotsifaki et al. 2023). Isometric and dynamic strength tests, along with functional assessments such as hop tests, are commonly expressed as the limb symmetry index (LSI), calculated as the ratio between the involved and uninvolved limbs. An LSI of at least 90% is widely used as a benchmark for strength and functional recovery (Burgi et al. 2019). However, most patients do not meet this criterion within six to nine months of ACLR rehabilitation (Welling et al. 2018; Barfod et al. 2019; Raoul et al. 2019). Findings from a recent systematic review of over 34,000 patients indicate that knee extensor strength deficits persist beyond an LSI of 90% even one year after ACLR (Girdwood et al. 2025). This is concerning, as strength is often considered a key factor in determining readiness for activity progression throughout all phases of rehabilitation (Greenberg et al. 2018). Furthermore, athletes who do not pass the return-to-sport testing battery face a higher risk of reinjury (Grindem et al. 2016; Kyritsis et al. 2016; Kotsifaki et al. 2025).

Resistance training has been established as the most effective method for recovering muscle strength during ACLR rehabilitation (Buckthorpe & Della Villa 2020). Periodization involves manipulating training variables over time, such as exercise intensity (i.e., load) and volume, to optimize training adaptations (Kraemer & Ratamess 2004). The *'repetition continuum'*, also known as the *'strength-endurance continuum'*, suggests that the number of reps performed at a given load magnitude leads to specific adaptations (Schoenfeld et al. 2021). A low repetition scheme with heavy loads (i.e., up to 8 reps per set at loads above 80% of 1-repetition maximum [1RM]) optimizes gains in maximum strength, while a high repetition scheme with light loads (i.e., 15 or more reps per set at loads below 60% of 1RM) optimizes improvements in local muscular endurance (Lopez et al. 2021; Schoenfeld et al. 2021).

Considering the advantages of periodized over non-periodized resistance training in healthy individuals (Williams et al. 2017; Moesgaard et al. 2022), it is plausible that strength gains in athletes who underwent ACLR could also be optimized through training periodization. However, clinical trials with ACLR rehabilitation predominantly prescribe resistance exercises with 10 to 20 repetitions per set (Nichols et al. 2021). Some trials have adopted a constant volume throughout the entire training program, such as the classical approach employed in clinical settings consisting of 3 sets of 10 repetitions per exercise (Hughes et al. 2019). This suggests that ACLR patients are often treated within a suboptimal range of the *'repetition continuum'* for maximizing strength development. This may, at least in part, help explain the persistent strength deficits that are consistently reported in this population several months after surgery (Welling et al. 2018; Barfod et al. 2019; Raoul et al. 2019; Girdwood et al. 2025).

Despite the extensive knowledge regarding resistance training periodization for healthy subjects (Williams et al. 2017; Moesgaard et al. 2022), little is known about the effects of periodized training for individuals who underwent ACLR. A previous single-arm pilot study (Welling et al. 2019) implemented ACLR rehabilitation incorporating resistance training with block-based linear periodization and found that, at six months after ACLR, patients exhibited functional outcomes comparable to athletes with similar conditioning levels. However, no randomized controlled trial (RCT) has yet assessed the impact of resistance training periodization during ACLR rehabilitation. Therefore, the present study aims to investigate the effects of linear periodization resistance training in recreational athletes who underwent ACLR.

METHODS

Study Design

This RCT included male recreational athletes who underwent ACLR. All participants followed a standard rehabilitation protocol for the first three months post-surgery. Subsequently, they were randomly assigned to either a linear periodization (LP) resistance training program or the traditional '3x10 reps protocol'. Both groups followed 12-week resistance training programs, with participants completing two weekly sessions that included the same resistance exercises targeting the lower limb muscle groups. The only difference between the groups was the periodization model: block-based linear progression for the LP group versus a fixed-volume protocol for the 3x10 group.

Isometric strength of the knee extensors and flexors served as the primary outcomes, assessed one week before and one week after the resistance training program. Secondary outcomes included hop performance and patient-reported measures, which were evaluated one week after the training period—approximately six months post-ACLR.

The study was conducted in a private physiotherapy clinic in Porto Alegre (Brazil), between March 2022 and June 2023. The study was approved by the Ethics Committee of the Federal University of Health Sciences of Porto Alegre (protocol number: 5.039.703) and a priori registered at *ensaiosclinicos.gov.br* (#U1111-1272-8055). This study was reported according to the Consolidated Standards of Reporting Trials (CONSORT) guidelines.

Deviations from the registered protocol

The following protocol changes from the trial registration should be noted. First, the strength assessment originally planned to use isokinetic dynamometry was replaced by an isometric assessment in a clinical setting, while the ultrasound assessment for analyzing muscle architecture was not conducted. These changes were necessary due to logistical challenges, as the ACLR rehabilitation was conducted in a private physiotherapy clinic while the isokinetic dynamometry and ultrasound equipment were located in a university laboratory. Second, self-reported knee function was initially registered as the primary outcome of this study due to its prominence in most clinical trials involving patients after ACLR. However, considering that muscle strengthening is the primary goal of resistance training in this population, muscle strength outcomes were prioritized and ultimately designated as the primary outcome in the present study. This shift reflects a closer alignment between the study objectives and the mechanisms targeted by the intervention. Additionally, the sample size calculation was revised to be based on the maximal isometric strength outcome.

Participants

This study recruited male recreational athletes aged 18 to 40 years who underwent ACLR. Candidates were excluded if they: (i) underwent ACLR with grafts other than ipsilateral hamstrings (semitendinosus/gracilis); (ii) had graft revisions or meniscal surgery involving more than 50% of the meniscus; (iii) sustained complete medial/lateral collateral ligament or posterolateral corner injuries; (iv) had prior surgeries on the knee, hip, or ankle; (v) were not interested in returning to sports; (vi) used

controlled analgesic medication pre-surgery; (vii) had grade IV condropathy; or (viii) were unable or unwilling to commit to at least six months of post-surgery rehabilitation. Informed consent was obtained prior to the patient's enrollment in the study.

Sample size, randomization, and blinding

Sample size estimation was conducted using G*Power (version 3.1, Heinrich Heine University Düsseldorf, Germany). Isometric strength data collected at three and six months post-ACLR from a prospective cohort of male patients were used to inform the sample size estimation (Welling et al. 2024). The knee extensor and flexor strength data showed effect sizes (Cohen's dz) of 1.72 and 1.03, respectively. With a significance level of 0.05 and a statistical power of 0.80, the minimum required sample size was estimated at 10 participants per group. Accounting for a projected 10% dropout rate, the final recruitment target was set at 11 participants per group.

Participants were randomly assigned to one of two groups using a free online tool (random.org). The allocation sequence was generated in advance by an investigator who was not involved in participant recruitment, assessments, or intervention delivery. This sequence was concealed from all other study personnel. The physiotherapist responsible for delivering the training programs was informed of each participant's group allocation via text message only on the day of their first training session and then relayed this information to the participant at the start of that session. The physiotherapist was not provided with any information about the participant's baseline strength assessment performance. Likewise, the investigator responsible for conducting the assessments did not attend or monitor the training sessions. However, as is common in sports rehabilitation centers, the clinic operated within a single space equipped for both exercise execution and performance assessments. Consequently, complete blinding was not achievable, as the investigator occasionally conducted assessments within the facility concurrently with the training sessions of certain participants.

Interventions

From ACLR to 3th month

The first stage lasted approximately 4-5 weeks post-ACLR and involved patient education on the injury, surgery, and rehabilitation process along with a home-based intervention focused on symptom management, early muscle activation, range of motion (ROM) improvement, and gait recovery. Interventions included: cryotherapy,

compression, patellar mobilization, knee positioning in extension, ankle pumps, quadriceps isometric contractions, wall slides, hamstring stretching, straight leg raises (hip flexion, abduction and adduction), calf raises, sit-to-stand, cycling, and gait training. To progress to second stage, patients needed to meet the following criteria: (i) full knee extension ROM, assessed through the heel-height measurement (Schlegel et al. 2002); (ii) knee flexion ROM >70% of the uninvolved limb, assessed passively with a goniometer; (iii) controlled edema, assessed with the stroke test (Sturgill et al. 2009); (iv) absence of lag sign; and (v) independent gait.

The second stage, typically conducted from week 4-5 to week 12-13 post-ACLR, was focused on basic functional recovery and included two supervised sessions per week with a physiotherapist. In addition to continuing symptom management and increasing knee flexion ROM as needed, the second stage incorporated single-leg balance exercises and lumbopelvic stabilization exercises (front plank, side plank, bridges, deadbug, and bird-dog). Lower limb resistance exercises were also introduced in this stage: bodyweight squat progressing to goblet squat, supported lunge, unilateral seated knee extension (ROM restricted from 90° to 45° of knee flexion), stability ball leg curl, and calf raises. To progress to the third stage, patients needed to meet the following criteria: (i) knee pain rated 3 or less during functional activities, assessed with a 0-10 numeric pain rating scale; (ii) no edema; (iii) knee flexion ROM >90% of the uninvolved limb, assessed passively with a goniometer; and (iv) knee extensor and flexor strength LSI >60%, assessed as detailed next.

From 4th to 6th month

The third stage, typically between weeks 13-14 and 24-25 post-surgery, included progressively more complex single-leg balance and plyometric (jumping) exercises for both groups. During this stage, participants were engaged in a 12-week, twice a week, resistance training program (i.e., 24 training sessions), with specific periodization for the LP group and the 3x10 group. The four resistance exercises were selected for their focus on the muscles typically affected after ACLR and ease of replication in a clinical setting (**Figure 1**). The back squat, lunge, and leg extension exercises were performed from a minimum of 90° knee flexion to near full knee extension, while leg curls were performed through the full ROM. For all exercises, participants were instructed to execute each movement repetition in approximately 4 seconds: 2 seconds for the concentric phase and 2 seconds for the eccentric phase. The physiotherapist monitored exercise ROM and cadence through visual inspection. A one-minute rest interval was observed

between sets. Exercise load was individually managed using the repetitions in reserve method (Lovegrove et al. 2022). After each set, participants reported the number of additional repetitions they felt capable of performing with that load. The load was increased if the participant reported being able to perform more than two additional repetitions. Conversely, the load was decreased if the participant was unable to complete the predetermined number of repetitions due to muscle fatigue or knee discomfort. The first training session was used to find the appropriate load for all four exercises using a trial-and-error approach. The loads applied in each exercise across the 24 training sessions were recorded to monitor participants' progression throughout the program.

Participants in the 3x10 group performed a fixed training volume of 3 sets of 10 repetitions per exercise with progressive load throughout the 12-week resistance training program (**Figure 1**). In contrast, participants in the LP group followed a linear periodization, organized into three four-week blocks, featuring a progressive reduction in repetitions per set accompanied by a corresponding increase in load: 3 sets of 15 reps in the first block, 3 sets of 10 reps in the second block, and 3 sets of 5 reps in the third block (**Figure 1**). Therefore, the groups performed an equalized volume of repetitions across the 12-week resistance training program, totaling 720 repetitions per exercise.

Group	Traininig week	Sessions per week	Exercises per session	Sets per exercise	Reps per set	Total sets/week	Total reps/week
3x10	1-4	2	4	3	10	24	240
	5-8	2	4	3	10	24	240
	9-12	2	4	3	10	24	240
LP	1-4	2	4	3	15	24	360
	5-8	2	4	3	10	24	240
	9-12	2	4	3	5	24	120

FIGURE 1. *Top:* Resistance training programs for the linear periodization (LP) and 3×10 groups. *Bottom:* Exercises prescribed for both groups: (A) squat, (B) lunge, (C) leg extension, and (D) leg curl.

Outcome measures

Muscle strength

The maximum isometric strength of the knee extensor and flexor muscles was the only outcome measured both before and after the resistance training program. Assessments were conducted by a single researcher in a clinical setting using a handheld dynamometer (Medeor, MedTech, Brazil). These isometric tests demonstrated a high level of test-retest reproducibility, with intraclass correlation coefficients (ICC) of 0.98 for knee extensors (Almeida et al. 2019) and 0.92 for knee flexors (Goossens et al. 2017). For knee extensor strength assessment, the participant was seated on an examination table with the knee at 90° flexion, while the evaluator sat facing them. A strap stabilized the knee and supported the dynamometer, positioned on the anterior aspect of the ankle joint. The participant was secured to the table with straps to prevent compensatory movements. For knee flexor strength assessment, the participant lay prone on the table with 30° of knee flexion, and the evaluator stood at their feet, placing the dynamometer on the heel of the tested limb, again using a strap for stabilization. The participant was instructed to perform a 5-second maximal isometric contraction in each trial. A one-minute rest interval was provided between trials. The highest value among three valid trials was recorded as the final isometric strength.

Changes between the three-month post-surgery values and those collected post-training (six-month post-surgery) were considered the primary outcomes od this study. Additionally, the LSI was used for statistical analysis.

Hop performance

Given the risks associated with performing single leg hop tests three months post-surgery, these assessments were conducted only after the completion of the resistance training program (i.e., six months post-surgery). Four hop tests were conducted: (i) single hop for distance; (ii) triple hop for distance; (iii) medial rotation hop for distance; and (iv) vertical jump (single leg countermovement jump). All hop tests were performed according to previous recommendations, and present high level of test-retest reproducibility (ICC's greater than 0.93) (Dingenen et al. 2019). For the horizontal jump tests, a 6-meter line was marked on the ground, with a tape measure placed alongside to record the results. Participants completed three familiarization pre-tests and then performed three attempts for each hop test, with all attempts recorded. Both limbs were assessed, and there were no restrictions on arm movement during the tests. A rest period of 30 to 60 seconds was allowed between attempts. Each test began with the hallux of the tested

limb positioned at the starting line, and the final distance was measured at the rearfoot. Participants were instructed to maintain their final landing position for 2 seconds. Loss of balance, additional jumps during landing, or touching the ground with the contralateral limb were considered unsuccessful attempts. For the vertical jump test, participants stood on one leg with their hands on their hips. After maintaining stability in this position for at least 3 seconds, they were instructed to perform a countermovement jump as high as possible. Hop height was assessed using the My Jump app (version 3.2.2), with the camera positioned 1.5 meters above the ground and 3 meters from the participant. Hop height was calculated based on the flight time, defined as the duration between takeoff and landing (Whiteley et al. 2023). The post-training LSI was used for statistical analysis of hop performance.

Self-reported functional status

Functional status perceived by participants was assessed after the completion of the resistance training program using the Brazilian Portuguese version of the International Knee Documentation Committee (IKDC) questionnaire (Metsavaht et al. 2010). This questionnaire is a standardized tool used to assess knee function and health in individuals with various knee conditions. It evaluates three main areas: symptoms (such as pain, stiffness, and swelling), sports and recreational activities, and knee function in daily life. Higher scores (ranging from 0 to 100) indicate better functional status, with cutoff scores of 85 to 90 points commonly used to define pass or fail for this criterion (Gokeler et al. 2017).

Psychological readiness to return to sport

Psychological readiness was assessed using Brazilian Portuguese version of the ACL-Return to Sport after Injury (ACL-RSI) (Silva et al. 2018). By assessing three dimensions -emotions, confidence in performance, and risk appraisal- the ACL-RSI provides insights into a patient's mental readiness and potential barriers to returning to pre-injury levels of physical activity. The questionnaire consists of 12 items, with scores ranging from 0 to 100, where higher scores indicate greater confidence in returning to sport. A cutoff score of 56 points is commonly used to define pass or fail for this criterion (Gokeler et al. 2017).

Statistical analysis

Demographic characteristics were compared between groups using independent t-tests or a Fisher's exact test. Analyses were conducted on an intention-to-treat basis,

with all participants analyzed in the groups to which they were originally assigned, regardless of adherence to the intervention. Knee extensor and flexor strength data were analyzed using mixed linear models, with two groups (LP and 3x10) and two time points (pre- and post-training). Within-group changes were evaluated using effect sizes (ES), calculated using Cohen's d and interpreted as "trivial" (ES < 0.2), "small" (ES ≥ 0.2), "moderate" (ES ≥ 0.5), "large" (ES ≥ 0.8), and very large (ES ≥ 1.2). Between-group comparisons were conducted using independent t-tests for the percent change in knee extensor and flexor strength from pre- to post-training, as well as for secondary outcomes assessed only at post-training (i.e., hop test, IKDC, and ACL-RSI). Missing values in post-training strength and hop test data were addressed using multiple imputation. There were no missing data for IKDC or ACL-RSI. All analyses were conducted using SPSS version 18.0 (SPSS Inc., Chicago, IL, USA), with statistical significance set at $\alpha \leq 0.05$.

RESULTS

Thirty-two potentially eligible participants were screened from March 2022 to June 2023. Six volunteers did not meet the inclusion criteria. Four volunteers initiated the standard protocol but dropped out before randomization. Finally, 22 participants were randomized and initiated the resistance training programs (**Figure 2**). LP and 3x10 groups were similar for demographic characteristics and strength levels at 3 months post-ACLR (**Table 1**). One participant in the LP group and two participants in the 3x10 group were lost at follow-up; they lacked training compliance but agreed to complete the IKDC and ACL-RSI questionnaires six months after ACLR. Those participants retained in the study had a training adherence exceeding 90%: 10 participants in the LP group and nine in the 3x10 group.

Pre- and post-training knee extensor strength measures revealed a significant main effect of time and a significant group-by-time interaction (**Figure 3-A**). Within-group analyses showed effect sizes of 1.73 (95% CI: 0.60 to 2.83) for the LP group and 0.82 (95% CI: –0.56 to 2.15) for the 3x10 group. Percent improvement in knee extensor strength was significantly greater in the LP group compared to the 3x10 group: 50.67% (95% CI: 27.94 to 73.40) vs. 25.83% (95% CI: 11.48 to 40.18) (**Figure 3-B**).

For knee flexor strength, a significant main effect of time was observed, but no significant group-by-time interaction was found (**Figure 3-C**). Within-group analyses showed effect sizes of 1.05 (95% CI: 0.13 to 1.63) for the LP group and 0.96 (95% CI: 0.25 to 1.50) for the 3x10 group. No statistically significant between-group difference was

observed in percent changes in knee flexor strength from pre- to post-training: the LP group improved by 44.98% (95% CI: 18.47 to 71.49) and the 3x10 group by 22.89% (95% CI: 6.83 to 38.95) (**Figure 3-D**).

The uninvolved limbs also showed a significant increase in knee extensor and flexor strength over time (main effect of time of $p<0.001$ for both), with no significant group-by-time interaction. At the post-training evaluation, knee extensor strength values were 798.81 (95% CI: 728.98 to 868.64) in the LP group and 796.16 (95% CI: 724.66 to 867.66) in the 3x10 group. Knee flexor strength values were 383.17 (95% CI: 307.77 to 458.57) and 364.90 (95% CI: 272.44 to 457.46) for the LP and 3x10 groups, respectively.

Following the 12-week resistance training programs, approximately six months post-ACLR, the LP group demonstrated a higher limb symmetry index (LSI) for knee extensor strength and a greater IKDC score (**Table 2**). No significant between-group differences were observed in knee flexor strength LSI, hop performance, or ACL-RSI score (**Table 2**).

The load progression across the 24 training sessions for each group is illustrated in **Figure 4**. The 3x10 group followed a consistent progression pattern, whereas the LP group showed marked increases in load during the 5th and 9th weeks (or sessions 9 and 17), corresponding to transitions to blocks with lower repetitions per set.

Four participants (two in the LP group and two in the 3x10 group) experienced transient episodes of acute knee joint pain (i.e., <4 on numeric pain rating scale) in the following days after a training session. Loading and range of motion were adjusted in the following sessions, and therapeutic strategies were used to ease the symptoms allowing training to resume after 1 week. All four participants managed to keep within the 80% threshold of acceptable adherence.

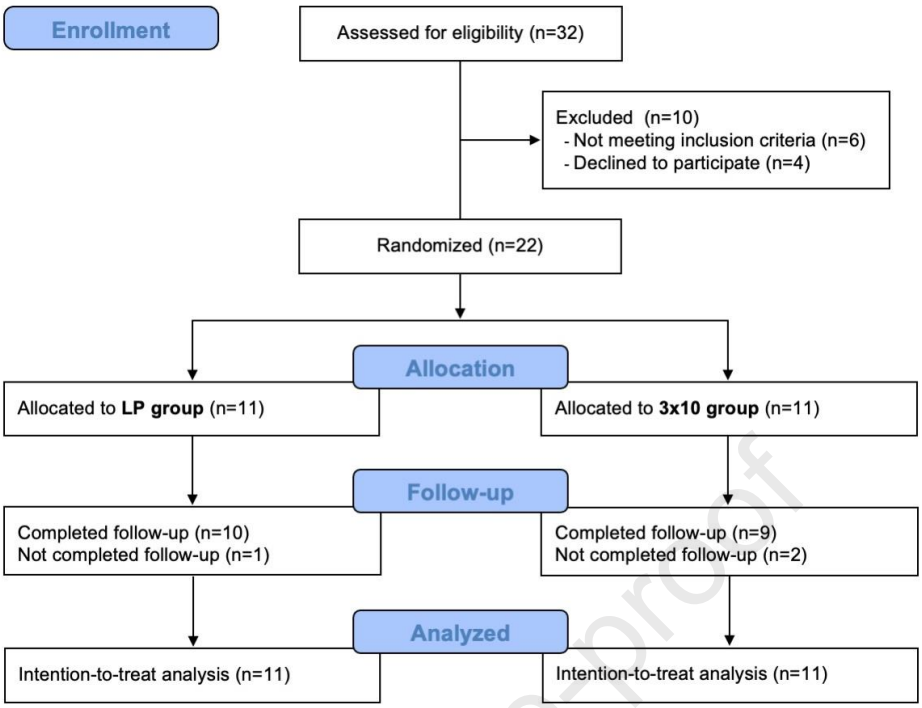

FIGURE 2. Flowchart of the study.

TABLE 1. Demographics and strength profile at three months post-surgery in the linear periodization (LP) and 3x10 groups. Results presented as mean and standard deviation.

	LP group	3x10 group	p-value
Age (years)	28.18 (6.26)	28.09 (5.70)	0.972
Body mass (kg)	83.55 (8.25)	78.09 (8.37)	0.104
Height (cm)	177.27 (8.30)	175.91 (5.11)	0.647
Body mass index (kg/m²)	26.61 (2.39)	25.21 (2.14)	0.161
KE strength			
Involved limb (N)	530.93 (151.15)	537.70 (146.28)	0.916
Uninvolved limb (N)	657.35 (93.53)	698.77 (96.74)	0.319
LSI (%)	79.74 (15.38)	75.95 (11.67)	0.532
KF strength			
Involved limb (N/kg)	246.37 (74.98)	254.20 (71.10)	0.804
Uninvolved limb (N/kg)	284.96 (79.11)	300.40 (75.16)	0.644
LSI (%)	86.27 (9.53)	85.58 (16.23)	0.905
ACLR limb	8 D, 3 ND	7 D, 4 ND	1.000

ACLR, anterior cruciate ligament reconstruction; D, dominant limb; KE, knee extensor; KF, knee flexor; LSI, Limb symmetry index; ND, non-dominant limb.

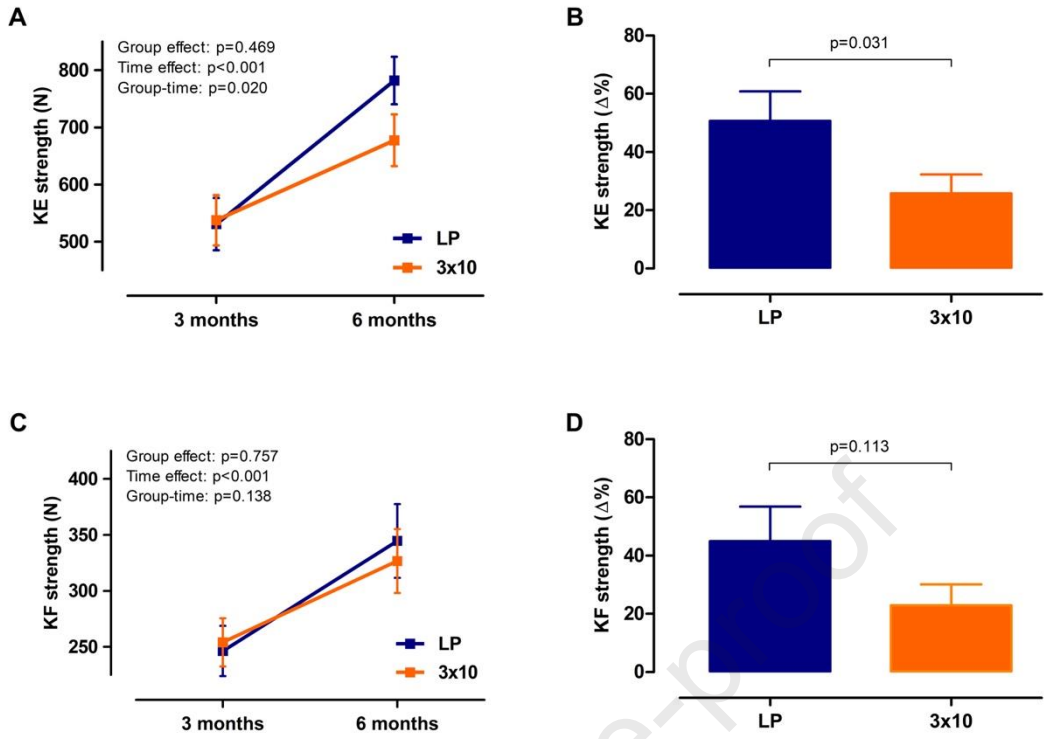

FIGURE 3. Knee extensor (KE, panels A and B) and knee flexor (KF, panels C and D) strength in the linear periodization (LP) and the 3x10 groups. Results presented as mean and standard error mean.

TABLE 2. Outcomes measured post-training (six months three months post-surgery) in the linear periodization (LP) and the 3x10 groups. Results presented as mean and standard deviation.

	LP group	3x10 group	p-value
LSI (%)			
KE strength	97.11 (9.78)	84.66 (10.94)	**0.005**
KF strength	92.80 (18.04)	89.22 (22.39)	0.686
Single-leg hop test	89.69 (5.94)	91.68 (6.24)	0.464
Triple hop test	90.35 (6.50)	93.46 (9.12)	0.373
Medial rotation hop test	89.76 (7.40)	93.61 (8.23)	0.260
Vertical jump test	75.35 (21.29)	81.70 (24.71)	0.521
IKDC (score)	81.29 (13.13)	78.79 (13.02)	0.658
ACL-RSI (score)	67.87 (18.04)	52.64 (14.22)	**0.040**

ACL-RSI, Anterior Cruciate Ligament - Return to Sport after Injury; IKDC, International Knee Documentation Committee; KE, knee extensor; KF, knee flexor; LSI, limb symmetry index.

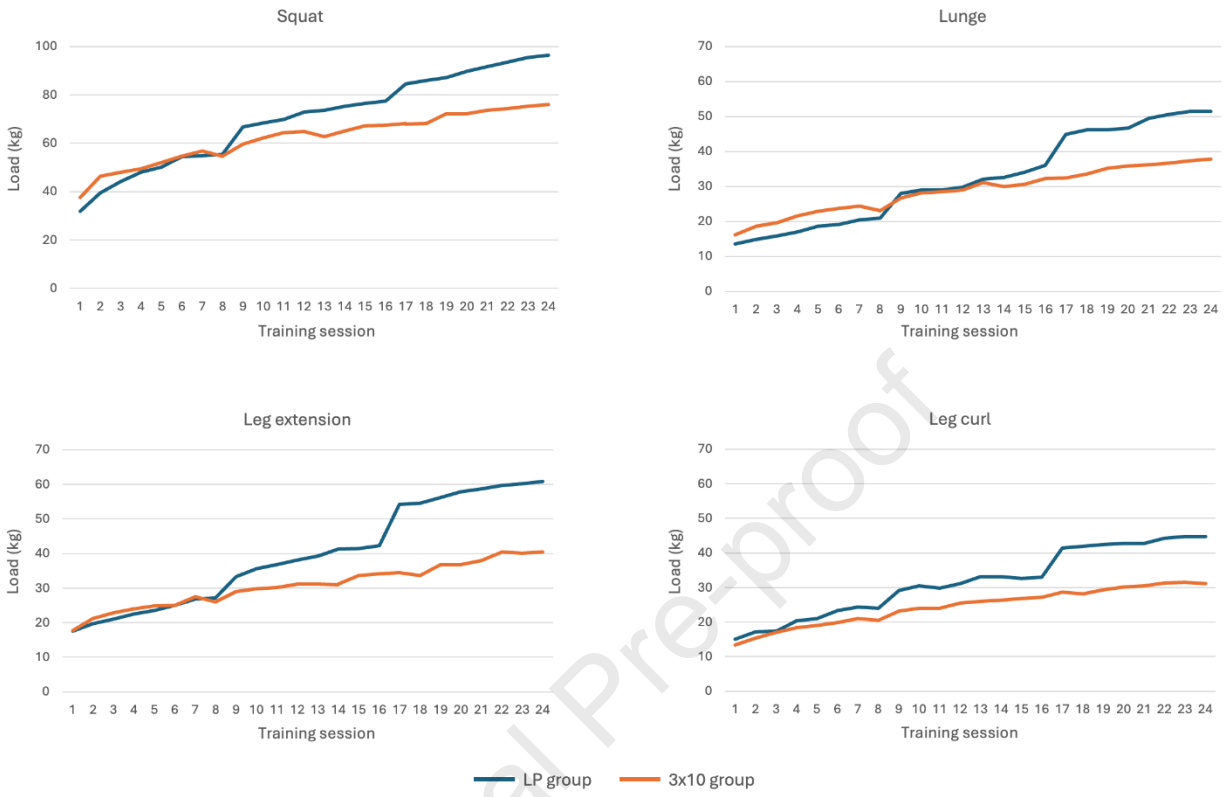

FIGURE 4. Mean exercise loads used by the linear periodization (LP) and the 3x10 groups across the 24 resistance training sessions.

DISCUSSION

The current study introduces to the field of ACLR rehabilitation a topic that has been extensively investigated in the context of resistance training for healthy individuals (Williams et al. 2017; Moesgaard et al. 2022). This RCT employed resistance training following either a linear periodization or the traditional '3x10 reps protocol' to restore isometric maximum strength, hop performance, self-perceived functional status, and psychological readiness to return to sport in recreational athletes who underwent ACLR. The main findings indicate that linear periodization was more effective in enhancing knee extensor strength, resulting in a higher strength LSI at six months post-ACLR. Additionally, participants in the LP group demonstrated greater IKDC scores at this timepoint.

In the current study, the LP group exhibited mean percentage strength gains nearly twice as large as those observed in the 3x10 group, with a statistically significant difference for knee extensors. Strength profiles at three months post-ACLR were similar between groups, suggesting that the greater improvement observed in the LP group was not attributable to baseline differences.These findings suggest that the resistance training program itself was a key driver of the observed strength gains. Since strengthening the thigh muscles is a cornerstone of ACLR rehabilitation (van Melick et al. 2016; Brinlee et al. 2022; Kotsifaki et al. 2023), these findings support the adoption of linear periodization resistance training by clinicians. However, the reasons why linear periodization did not optimize knee flexor strength gains compared to the '3x10 reps protocol' remain unclear.

Given that the contralateral limb often undergoes reduced workload during ACLR rehabilitation—potentially resulting in strength loss and consequently unreliable LSI values (Wellsandt et al. 2017)—it is noteworthy that the training programs in the present study not only counteracted this detrimental effect but also enhanced strength in the uninvolved limb. Previous research indicates that patients with a strength LSI below 90% are nearly three times more likely to sustain a subsequent knee injury compared to those with an LSI above 90% (Grindem et al. 2016). In the present study, at six months post-ACLR, the LP group achieved mean knee extensor LSI values of 97%, surpassing the 90% cutoff, while the 3x10 group had mean values of only 85%. These results further support previous recommendations (Buckthorpe & Della Villa 2020; Nichols et al. 2021) that ACLR patients benefit from engaging in periodized resistance training.

This study stands out from conventional post-ACLR rehabilitation trials by systematically recording the load used by each patient in each training session. The load progression curves in **Figure 4** offer valuable insights into training responses. Notably, starting with 15 reps per set in the LP group did not result in lower loads compared to the group starting with 10 reps. Between sessions 9 and 16, both groups performed 10 reps per set, yet the LP group sustained higher loads in three of the four exercises. Finally, in the last training block (sessions 17 to 24), the LP group trained within the *'repetition continuum'* zone consistently shown to be most effective for maximizing strength—characterized by heavy loads and low repetitions (Lopez et al. 2021; Schoenfeld et al. 2021). It is plausible that the third training block in the LP group was instrumental in producing greater strength gains compared to the 3x10 group. However, the contribution of the first two blocks should not be overlooked, as they likely prepared LP participants both biologically (e.g., movement coordination, muscle-tendon structure and function) and psychologically (e.g., confidence) to safely tolerate the high-load exercises introduced in the final block.

At six months post-ACLR, both groups achieved mean interlimb symmetry values close to or above 90% in horizontal hop tests, but not in the vertical jump. Worse performance in vertical jump was expected, as the knee contributes approximately one-third to vertical jump height but only about one-eighth to horizontal hop distance (Kotsifaki et al. 2021). Our findings align with those of Kotsifaki et al. (2022), who reported that athletes cleared to return to sport after ACLR achieved 97% symmetry in horizontal hop distance but only 83% in vertical jump height. Moreover, the greater strength gains observed with linear periodization did not appear to translate into improved hop test performance. This is likely due, at least in part, to the principle of specificity, which states that training adaptations are specific to the exercises performed (Kraemer & Ratamess 2004). Since both groups followed the same plyometric intervention, a comparable progression in hop performance between groups was a plausible outcome. Therefore, incorporating lower limb power training and specific single-leg hop exercises appears advisable for improving interlimb symmetry in hop tests. Training aimed at improving hop performance is typically reserved for the later phases of ACLR rehabilitation, with achieving a minimum strength recovery threshold (i.e., 80–90% LSI) being a key milestone for progressing to advanced neuromuscular training focused on restoring explosive capacity (Buckthorpe 2019). Therefore, although the linear periodization resistance training prescribed in this study did not produce direct effects on hop performance, it is reasonable to assume that the additional strength gains achieved by the LP group serve as a more effective preparatory step for the subsequent power development phase in ACLR rehabilitation.

LP and 3x10 groups showed comparable levels of self-reported functional status at six months post-ACLR. The mean IKDC scores were below the typical cutoff of 85–90 points (Gokeler et al. 2017); however, it should be noted that athletes tend to average around 87 points even up to five years post-ACLR (McAleese et al. 2025). The gap observed in this study between strength gains and patients' self-perceived recovery further underscores the need for comprehensive interventions that address the multifaceted biopsychosocial factors involved. Interestingly, although participants did not perceive their functional status as different from their peers, those who underwent linear periodization resistance training reported greater psychological readiness to return to sport. The LP group had a mean ACL-RSI score of approximately 68 points, above the 56-point cutoff (Gokeler et al. 2017), while the 3x10 group scored only around 53 points. This is a noteworthy finding, as fear of reinjury is the most commonly reported barrier preventing athletes from returning to sport (Nwachukwu et al. 2019). While the association between strength and psychological readiness remains debated (Dombrowski et al. 2024), enhanced strength recovery may have contributed to the higher ACL-RSI scores observed in the LP group (Sugarman et al. 2022). Furthermore, it is reasonable to hypothesize that enabling athletes to work with heavier loads during rehabilitation (see **Figure 4**) may

positively influence psychological traits relevant to the return-to-sport process, such as self-efficacy, catastrophizing, and kinesiophobia (Christino et al. 2015).

This study has limitations that should be acknowledged. Firstly, logistical constraints restricting access to the university campus laboratory prevented the inclusion of isokinetic dynamometry and ultrasound assessments, as originally outlined in the trial registration. The assessment of isokinetic torque was replaced by isometric strength testing using a handheld dynamometer. Although more examiner-dependent than isokinetic dynamometry, isometric testing with a handheld dynamometer is reliable (Goossens et al. 2017; Almeida et al. 2019) and has been widely used in both research and clinical settings. Specifically in patients who have undergone ACLR, handheld dynamometer testing has shown to be a valid measure when compared to the gold standard of isokinetic dynamometry (Almeida et al. 2019). Due to the absence of ultrasound, the present study did not examine the effects of resistance training programs on muscle architecture. While not a clinically adopted outcome to assess recovery status after ACLR, the analysis of muscle architecture adaptations could have provided additional insights into the mechanisms underlying strength gains. As a second limitation, the study included only adult male recreational athletes, as the partnering physiotherapy clinic had treated few female patients and professional athletes in previous years. Consequently, caution should be exercised when generalizing the findings to ACLR populations with different profiles. Lastly, the study followed participants only during the first six months of ACLR rehabilitation. The lack of a longer follow-up prevented the assessment of potential effects of the resistance training programs on outcomes of interest for this population, such as return-to-sport rates, time to meet all discharge criteria, and the incidence of re-injuries.

CONCLUSION

In male recreational athletes who underwent ACLR, a 12-week program of supervised resistance training using a linear periodization model proved to be more effective than the traditional ‘3x10 reps protocol’ in enhancing knee extensor strength, as well as psychological readiness to return to sport. These findings suggest that linear periodization should be encouraged in rehabilitation protocols for patients recovering from ACLR.

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Highlights

- Linear periodization resulted in greater knee extensor strength gains than the ‘3x10 reps protocol’.
- Linear periodization group showed higher psychological readiness to return to sport.
- No between-group differences were found in hop tests or self-reported function

Ethical statement

The study was approved by the Ethics in Research Committee of the Federal University of Health Sciences of Porto Alegre, Porto Alegre, RS, Brazil (approval number: 5.039.703) and a priori registered at *ensaiosclinicos.gov.br* (#U1111-1272-8055).

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Declaration of interest

Authors declared no conflict of interest.