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Effectiveness of a sport-specific exercise programme for overhead athletes with unilateral subacromial shoulder pain: a study protocol of a randomised controlled trial

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ABSTRACT

Subacromial shoulder pain is one of the most common musculoskeletal conditions affecting overhead athletes, particularly those engaged in high-intensity training modalities such as CrossFit. The prevalence of shoulder injuries in this population continues to rise due to increased participation, repetitive overhead movements, and biomechanical stress on the rotator cuff and scapular stabilisers. While various rehabilitation approaches exist, no consensus exists on the most effective exercise intervention for improving shoulder function and pain outcomes in athletes with subacromial shoulder pain. Current rehabilitation protocols for overhead athletes lack specificity, failing to address the sport-specific demands and movement patterns that may contribute to persistent pain and dysfunction. This study compares the effectiveness of a sport-specific exercise programme versus a scapular stability programme in improving clinical and functional outcomes in CrossFit athletes with subacromial shoulder pain.

This study follows a randomised controlled trial (RCT) design, adhering to Consolidated Standards of Reporting Trials and Standard Protocol Items: Recommendations for Interventional Trials guidelines for intervention-based trials. Outcome assessments will include validated patient-reported outcome measures, objective strength and mobility tests, and biomechanical performance metrics. Participants will be recruited from sports clinics and CrossFit training centres across Madrid, ensuring a representative sample of athletes experiencing shoulder pain.

INTRODUCTION

Subacromial shoulder pain (SSP) is common among athletes engaged in overhead sports, particularly in disciplines such as CrossFit, which involve repetitive, high-intensity movements.[1] These activities place excessive stress on the shoulder complex, often leading to microtrauma, inflammation and impingement of the subacromial structures.[2 3] The prevalence of shoulder injuries in CrossFit athletes is estimated to be 20.7%, with exercises

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Subacromial shoulder pain is one of the most common conditions affecting overhead athletes, with high prevalence rates in sports requiring repetitive overhead movements, including weightlifting, CrossFit and swimming.
⇒ Conventional rehabilitation programmes for shoulder pain often focus on general strengthening and mobility exercises, lacking specificity to sport-related movement demands.
⇒ Scapular stability and rotator cuff strength are key components in preventing and managing shoulder pain, yet the most effective training approach for CrossFit athletes remains unclear.

WHAT THIS STUDY ADDS

⇒ This study will compare a sport-specific exercise intervention versus a scapular stability programme, providing high-quality evidence of their effectiveness in treating subacromial shoulder pain in athletes.
⇒ The research will assess pain, functional improvements, range of motion, strength gains and biomechanical adaptations using validated patient-reported outcome measures, strength testing and force-velocity profiling.
⇒ The findings will contribute to developing tailored rehabilitation strategies, ensuring athletes receive optimal treatment approaches based on their sport-specific demands.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ The results of this study will guide clinicians and sports rehabilitation specialists in selecting the most appropriate exercise-based interventions for overhead athletes with shoulder pain.
⇒ Researchers will benefit from objective data on strength, mobility and workload progression, facilitating future injury prevention and performance optimisation investigations.
⇒ The study may influence rehabilitation guidelines and policy recommendations, promoting evidence-based, sport-specific treatment approaches for subacromial shoulder pain in athletic populations.

like the clean and jerk and shoulder press posing significant risks.[1] The mechanics of these movements require high levels of stability, mobility and neuromuscular control, which, if compromised, can predispose athletes to overuse injuries.[1] The repetitive overhead lifting and rapid force generation in CrossFit training can result in mechanical compression of the rotator cuff tendons and the subacromial bursa, leading to chronic irritation and eventual dysfunction.

Additionally, improper lifting techniques, inadequate warm-up, muscular imbalances and fatigue contribute to the onset and progression of subacromial pain.[4] Over time, athletes may develop movement compensations, further exacerbating the dysfunction and increasing the likelihood of secondary injuries.[5] Such injuries can severely impact an athlete's performance, limit their ability to train effectively and sometimes necessitate prolonged rest or medical intervention.[6] The inability to perform key movements due to persistent shoulder pain may lead to frustration, reduced participation in training and diminished overall athletic potential.[4] Addressing these issues through targeted rehabilitation programmes is essential for ensuring long-term athletic performance and injury prevention.

The aetiology of SSP is multifactorial,[7] involving reduced shoulder mobility, imbalances in rotator cuff strength and excessive training loads.[8] While conventional rehabilitation protocols focus on generalised strengthening and mobility exercises, a lack of individualised programming tailored to the unique biomechanical demands of CrossFit athletes persists.[6]

Study objectives

The primary objective of this study is to compare the effectiveness of a sport-specific exercise programme versus a scapular stability exercise programme in improving shoulder function in CrossFit athletes with unilateral SSP at 6 and 12 weeks, assessed using the Shoulder Pain and Disability Index (SPADI) and functional performance tests. The secondary objectives include evaluating the impact of both exercise programmes on isometric shoulder muscle strength, measured using a handheld dynamometer (ActiveForce2) for external and internal rotators at 90° of abduction. Another key outcome is assessing changes in the range of motion (ROM), including active external and internal rotation, measured with a digital goniometer in a standardised supine position. The study will also analyse modifications in force-velocity profiles, evaluating maximum strength (F0), velocity (V0) and power output using a linear encoder (Vitruve system) during overhead pressing movements. Finally, the study will examine the relationship between training load variations and shoulder pain levels, with acute-to-chronic workload ratio (ACWR) assessed via session Rating of Perceived Exertion (sRPE) logs and pain intensity measured on a Numerical Pain Rating Scale (NPRS, 0–10 scale) before and after training sessions.

We hypothesised that the sport-specific exercise programme will improve shoulder function, muscle strength, ROM and force-velocity characteristics compared with the scapular stability exercise programme. Additionally, athletes in the sport-specific group are expected to experience a more significant reduction in pain levels and better adaptation to training loads, leading to superior performance outcomes.

METHODS

Study design

This RCT follows the Consolidated Standards of Reporting Trials[9] guidelines for the transparent and standardised reporting of clinical trials. The study design also adheres to the Standard Protocol Items: Recommendations for Interventional Trials[10] guidelines to ensure methodological rigour in trial protocols. In addition, the selection and reporting of outcome measures align with the Consensus-based Standards for the Selection of Health Measurement Instruments[11] checklist for evaluating assessment tools' reliability, validity and measurement properties.

Sample size calculation

The sample size was determined based on previous studies investigating exercise interventions for shoulder dysfunction in overhead athletes. Using data from Hotta *et al*,[12] which examined changes in the internal rotation ROM in individuals with SSP, an effect size of 0.25 was estimated. The calculation was performed using G*Power V.3.1.9.2 software, considering a two-way repeated-measures analysis of variance (ANOVA) design with an alpha level of 0.05, a statistical power of 80% (β=0.20), and three time points (baseline, 6 weeks and 12 weeks). The analysis determined that 40 participants (20 per group) would be required to detect statistically significant differences between the sport-specific and scapular stability exercise programmes. To account for potential dropouts and non-compliance, an additional 20% contingency was applied, increasing the total sample size to 48 participants (24 per group). This ensures sufficient statistical power to detect meaningful differences in shoulder function, strength and pain outcomes over the intervention period.

Participants

Participants will be recruited from CrossFit training centres, sports performance facilities and rehabilitation clinics in Madrid, Spain. Recruitment will be done through direct collaboration with CrossFit coaches, physiotherapy clinics specialising in sports injuries, and online outreach via social media platforms and athlete forums. Flyers containing QR codes linked to an online screening questionnaire will be distributed at CrossFit boxes and rehabilitation centres.

Eligible participants will undergo an initial screening process, including a clinical history review, physical examination and functional shoulder assessment conducted by trained physiotherapists. To confirm eligibility, SSP

will be diagnosed based on clinical orthopaedic tests such as Neer, Hawkins, Jobe, Apprehension and Repositioning tests.[13 14] Athletes meeting the inclusion criteria will receive detailed study information and provide written informed consent before participating.

Participants will be excluded if they have a history of shoulder surgery or fractures affecting the scapula, clavicle or humerus. Those with structural shoulder pathologies such as full-thickness rotator cuff tears, advanced osteoarthritis or adhesive capsulitis will not be eligible. Individuals with neuromuscular or systemic conditions, including neurological disorders like brachial plexopathy or radiculopathy and inflammatory diseases such as rheumatoid arthritis or ankylosing spondylitis will also be excluded. Participants undergoing active shoulder treatments, including physical therapy, manual therapy or corticosteroid injections within the past 3 months, will not be eligible. The use of pain medication such as nonsteroideal anti-inflamatory drugs (NSAIDs), corticosteroids or opioids within 1 week before baseline assessments will also be an exclusion criterion. Individuals engaging in high physical activity outside CrossFit, including other overhead sports or structured strength training programmes, will not be included to ensure a homogeneous sample. Those with less than 6 months of consistent CrossFit training experience with at least 3 weekly sessions will be excluded. Participants who cannot commit to scheduled evaluations, maintain adherence to the intervention or complete follow-ups will not be eligible. Pregnancy or being within 6 months post partum will also result in exclusion due to potential hormonal and biomechanical influences on joint stability. Lastly, individuals presenting serious medical conditions such as unexplained weight loss, severe night pain, systemic infection or suspected malignancy will be excluded to prioritise medical evaluation and ensure participant safety.

The intervention sessions will take place in sports science laboratories at the European University of Madrid and affiliated CrossFit training centres equipped for supervised strength and rehabilitation programmes. Outcome assessments will be conducted at baseline, 6 weeks and 12 weeks postintervention, with trained evaluators blinded to group allocation to minimise bias.

Randomisation and allocation

Participants will be randomly assigned in a 1:1 ratio to either the sport-specific or the scapular stability exercise group. The randomisation sequence will be generated using a computer-based random number generator to ensure unbiased allocation.

A sealed, opaque and sequentially numbered envelope system will be used to maintain allocation concealment. An independent researcher who is not involved in the recruitment or assessment process will oversee the randomisation procedure and distribute assignments to participants accordingly.

Blinding will be applied to the outcome assessors, who will be unaware of the participant's group allocation to minimise detection bias. Due to the nature of the intervention, participants and physiotherapists administering the exercise programmes cannot be blinded. However, all efforts will be made to standardise assessments and limit potential bias in outcome evaluations.

Intervention groups

Scapular stability exercise programme

The standardised scapular stability intervention consists of four therapeutic exercises to enhance scapular control and shoulder complex strength. The programme includes external rotation exercises, horizontal abduction in side-lying and prone positions, and prone shoulder extension with dumbbells. Participants will complete 18 unsupervised sessions over 6 weeks, integrating these exercises into their warm-up routine at their regular CrossFit training facility. Each session will include three sets of 10 repetitions per exercise, with 60 s of rest between exercises and 90 s between sets, performed thrice weekly.

Sport-specific multimodal exercise programme

The sport-specific intervention follows the CERT (Consensus on Exercise Reporting Template) checklist[15] and is tailored to improve mobility, strength and stability in sport-relevant movement patterns. This programme comprises seven exercises incorporating PVC pipes, barbells and resistance bands, emphasising glenohumeral mobility and activating the rotator cuff and periscapular muscles. Each exercise will be performed twice weekly during the warm-up routine at the athletes' usual CrossFit training centre. Participants will complete two sets of eight repetitions per exercise, with 60 s of rest between exercises and 90 s between sets, over 18 sessions across 6 weeks.

To ensure appropriate resistance progression, initial band resistance will be selected based on repetition maximum criteria, allowing athletes to perform 8–12 repetitions per set before reaching fatigue.[16] An individualised progression algorithm based on pain response will be implemented (table 1). This programme aligns with the Bern Consensus,[4] which recommends exercises be performed in sport-specific positions, incorporating multiple joints with minimal equipment, competitive elements and integration into warm-up and resistance training sessions for at least 10–5 min per session, with 5 min dedicated to shoulder-specific activities.

General considerations

No additional manual therapy or complementary interventions will be applied to either group. Before beginning the programme, both groups will receive guidance from a physiotherapist specialising in therapeutic exercise, providing education on pain response, movement control and postural awareness. To support adherence, participants will receive exercise demonstration videos, available as online supplemental file 1 for

Table 1 Exercise description for both groups

Exercise programme	Sets×repetitions (rest)	Scapular stability programme	Sets×repetitions (rest)
Overhead squat (PVC pipe)	2×8 (1')	Prone horizontal abduction	3×10 (1')
Overhead squat (barbell)	2×8 (1')	Side-lying horizontal abduction	3×10 (1')
Y-Wall press	2×8 (1')	Side-lying shoulder external rotation	3×10 (1')
Overhead squat (resistance band)	2×8 (1')	Prone shoulder extension	3×10 (1')
Scapular push-ups	2×8 (1')		
Wall slides (resistance band)	2×8 (1')		
Gymnastic bear crawl (10 m)	1×10 m (1')	–	–

the stability group and online supplemental file 2 for the sport-specific group.

Motivational strategies will include weekly follow-up calls, reinforcement of the importance of therapeutic exercise in shoulder impingement management, instructional videos, motivational messages after training sessions and mid-intervention performance reports to enhance compliance and engagement.

Following CERT recommendations,[15] both intervention groups will implement strategies to enhance motivation, adherence and participant follow-up. Participants will receive weekly follow-up calls to address concerns, reinforce compliance and provide motivation and guidance. Additionally, educational reinforcement will be provided regarding the importance of therapeutic exercise in shoulder impingement management. Adherence will be monitored through exercise logs, training reminders and mid-intervention progress evaluations to ensure consistency in participation.

Outcome measures

The primary outcome of this study is shoulder function, assessed using the SPADI, which evaluates pain intensity and functional limitations associated with SSP. The SPADI consists of 13 items divided into pain (5 items) and disability (8 items) subscales, each rated on a Numerical Rating Scale (0–10), with higher scores indicating greater impairment. The total score is expressed as a percentage (0%–100%), with higher scores reflecting worse shoulder function.[17]

Secondary outcomes will include assessments of pain intensity, ROM, muscle strength, force-velocity profile and training load variations. Pain intensity will be measured using the NPRS, where participants rate their pain on a scale of 0 (no pain) to 10 (worst pain imaginable) before and after training sessions.[18]

ROM will be evaluated using a digital goniometer, measuring active external and internal rotation in a supine position with 90° shoulder abduction and 90° elbow flexion, ensuring standardised scapular stabilisation.[19]

Muscle strength will be assessed with a traction dynamometer, measuring maximal voluntary isometric contraction (MVIC) of the external and internal rotators at 90° of abduction in neutral and 90° external rotation positions.[19]

The assessment of the force-velocity profile will follow the methodology of García-Ramos *et al*[20] and Samozino *et al*,[21] using a linear regression model to estimate the individual force-velocity relationship during a seated one-arm overhead press with a barbell. A linear encoder (Vitruve system) will record bar displacement, velocity and power output across five sets of single repetitions at progressive loads ranging from 30% to 80% of one-repetition maximum (1RM).[22]

Training load variations will be monitored using the ACWR, calculated based on sRPE and training duration (minutes). To estimate the total workload, participants will report postsession effort ratings on a 0–10 scale, multiplied by session duration.

Adherence to the programme will be determined by the ratio of completed sessions to the total number of prescribed sessions, calculated as (completed sessions/scheduled sessions)×100. A score of 0% indicates no adherence, while a score of 100% reflects full adherence. The scapular stability and sport-specific multimodal programmes consist of three sessions per week for 6 weeks, totalling 18 sessions.[23]

Table 2 shows a full description of each outcome measure.

Statistical analysis

All statistical analyses will be conducted using IBM SPSS Statistics (V.29.0, IBM). A two-tailed significance level of 0.05 will be used for all comparisons, with 95% CIs reported where applicable.

Baseline characteristics of participants, including age, sex, training history and baseline outcome measures, will be summarised using means and SDs (mean±SD) for normally distributed continuous variables and medians and IQRs for non-normally distributed variables. Categorical variables will be presented as frequencies and percentages.

The Kolmogorov-Smirnov and Shapiro-Wilk tests will assess data normality for continuous variables. Homogeneity of variances will be tested using Levene's test, and where assumptions of normality

Table 2 Detailed description of primary and secondary outcome measures, assessment protocols and data collection points

Outcome measure	Measurement tool	Details of the measurement	Completed by
Primary outcome			
Shoulder function	Shoulder Pain and Disability Index[17]	Self-reported questionnaire with 13 items assessing pain intensity (five items) and functional limitation (eight items) over the past week. Each item is rated on a numerical scale (0–10), with higher scores indicating greater impairment. The total score is calculated as a percentage (0%–100%), with higher values indicating worse shoulder function. Evaluation at baseline, 6 weeks and 12 weeks.	Participants
Secondary outcomes			
Pain intensity	Numerical Pain Rating Scale[18]	Subjective pain assessment using an 11-point numerical scale (0=no pain, 10=worst pain imaginable). Participants will rate pain intensity before and after each training session to track pain fluctuations across the intervention. Recorded at each session and summarised at 6 and 12 weeks.	Participants
Range of motion	Digital Goniometer[19]	Measured in a supine position with the scapula stabilised, shoulder abducted at 90° and elbow flexed at 90°. External and internal rotation angles are recorded three times per side, with the mean value used for analysis. The assessor ensures consistent positioning and elimination of compensatory movements. Evaluation at baseline, 6 weeks and 12 weeks.	Evaluators
Muscle strength	Traction Dynamometer[19]	Measures the external and internal rotators' maximal voluntary isometric contraction. The test is performed in a seated position, with the shoulder abducted at 90° and the elbow flexed at 90°. Resistance is applied at the distal forearm, and participants perform three maximal contractions (5 s each) with 30 s of rest between trials. The mean value is used for analysis. Assessment at baseline, 6 weeks and 12 weeks.	Evaluators

Continued

Table 2 Continued

Outcome measure	Measurement tool	Details of the measurement	Completed by
Force-velocity profile	Linear Encoder (Vitruve system)[22]	The force-velocity relationship will be derived using Samozino's equations,[21] where maximum theoretical force (F0) and velocity (V0) will be determined through linear extrapolation, the force-velocity slope will be calculated as the linear regression coefficient, and theoretical maximal power will be obtained as F0×V0/4, representing the optimal trade-off between force and velocity. The individual optimal force-velocity profile will be estimated to determine whether participants have a force or velocity deficit, guiding personalised strength interventions. To ensure reliability, each test will be performed twice per session, with a 90 s rest between repetitions and a 2 min rest between load increments, using the best repetition for analysis.[24] Assessment at baseline, 6 weeks and 12 weeks.	Evaluators
Training load variations	Acute-to-chronic workload ratio (ACWR)	The session Rating of Perceived Exertion and training duration (minutes) was calculated. After each session, participants will rate their effort using a 0–10 Borg scale multiplied by session duration to estimate internal workload. The ACWR is calculated weekly (acute workload divided by chronic workload) to monitor the progression and risk of overuse injuries. Data were collected weekly and analysed at 6 and 12 weeks.	Participant

or homogeneity are violated, non-parametric alternatives will be used.

The effect of the intervention on shoulder function (SPADI scores) over time will be assessed using a two-way repeated-measures ANOVA (group×time interaction), with within-group (baseline, 6 weeks and 12 weeks) and between-group (sport-specific vs scapular stability programme) comparisons. Post hoc Bonferroni corrections will be applied for multiple comparisons. If assumptions of sphericity are violated (Mauchly's test), the Greenhouse-Geisser correction will be used.

Pain intensity (NPRS scores), muscle strength (MVIC values) and ROM (external and internal rotation angles) will be analysed using two-way repeated-measures ANOVA, similar to the primary outcome. Force-velocity characteristics (F0, V0, Sfv) will be analysed using mixed-model ANOVA, adjusting baseline values.

Training load variations (ACWR values) will be examined using generalised estimating equations to account for within-subject variability across weekly measures.

For significant findings, post hoc paired t-tests (or Wilcoxon signed-rank tests for non-parametric data) will be conducted to compare differences at each time point. Between-group differences will be analysed using independent t-tests (or Mann-Whitney U tests for non-parametric data). Effect sizes will be calculated using Cohen's d (small: 0.2, medium: 0.5, large: 0.8) for pairwise comparisons and partial eta squared (η^2p) for ANOVA results (small: <0.02, medium: 0.03–0.08, large: >0.09).

Spearman or Pearson correlation coefficients will be used to explore the relationships between training load variations (ACWR) and pain levels (NPRS scores). χ^2 or Fisher's exact tests will assess simple associations between categorical variables such as adherence rates and intervention effectiveness. Additionally, binary logistic regression will be performed to examine the influence of variables such as intervention group, baseline pain levels, training load variations and participant characteristics on the likelihood of adherence and functional improvement. Results will be reported as ORs with 95% CIs to quantify the strength of associations between predictors and outcomes.

Monitoring

Data monitoring

A data monitoring committee will not be established for this study, as the intervention involves non-invasive exercise-based interventions with a low risk of adverse events. Instead, the study will implement periodic internal reviews conducted by the research team to monitor participant safety, adherence and protocol compliance. Data will be reviewed at baseline, 6 and 12 weeks, with any unexpected findings reported to the ethics committee.

Interim analysis and stopping guidelines

No formal interim analyses are planned due to the study's short intervention period and non-invasive nature. However, if significant adverse effects are reported, the principal investigators will conduct a midpoint evaluation to determine if modifications are needed. Any decision to terminate the trial early will be made by the research team in consultation with the Hospital Clínico San Carlos Ethics Committee.

Adverse events

All adverse events and unintended effects related to the intervention will be systematically recorded. Participants will be instructed to self-report any pain exacerbation, discomfort or limitations experienced during or after the exercise sessions. Reports will be collected at each training session and formal assessments (6 and 12 weeks). If a participant experiences serious adverse events, such as persistent pain-preventing daily activities, they will be referred for a medical evaluation, and their participation may be suspended. Any unanticipated adverse events will be reported to the ethics committee and addressed following institutional guidelines.

Auditing

The study will be internally audited by the research team every 4 weeks to assess adherence to protocol, data integrity and participant compliance. This process will include random verification of collected data, adherence logs and documentation reviews.

Protocol amendments

Any significant modifications to the protocol (eg, changes in eligibility criteria, outcome measures or statistical analysis methods) will be submitted for approval to the ethics committee. All protocol updates will be communicated to investigators, trial registries and relevant regulatory bodies, and modifications will be reflected in publications and trial reports.

Consent and data collection

Informed consent will be obtained from all participants before a trained investigator enrols. The process will include verbal explanations and written documentation detailing the study purpose, procedures, potential risks and voluntary participation rights. Participants will have the opportunity to ask questions before signing the consent form.

There are no plans for ancillary studies involving biological specimen collection; therefore, no additional consent provisions apply.

Confidentiality

All personal data will be anonymised and stored in a password-protected electronic database. To maintain confidentiality, participants will be assigned a unique coded identifier (eg, EXER_01, CTRL_01). Data access will be restricted to the principal investigators and designated research staff. At the end of the study, personal data will be securely archived for 5 years before being permanently deleted.

Access to data

Only principal investigators and designated research staff will have access to the final dataset. No contractual agreements limit data sharing, and data will be made available on request for academic purposes following ethics committee approval.

Ancillary and post-trial care

Since the study involves exercise-based interventions, no post-trial medical care requirements exist. However, participants reporting persistent pain or functional limitations will be referred to a medical specialist for further evaluation. No compensation for participants experiencing adverse effects is planned, as the study does not involve high-risk interventions.

Dissemination policy

Communication of results

Study findings will be disseminated through scientific publications, conference presentations and publicly accessible trial registries. Results will be shared with participants, healthcare professionals and the research community through open-access journal articles and institutional reports.

Authorship and data sharing

Authorship eligibility will follow the International Committee of Medical Journal Editors (ICMJE) guidelines, requiring substantial contributions to study design, data collection, analysis and manuscript drafting. No professional writers will be used.

The full study protocol, anonymised dataset and statistical analysis code will be made available in public data repositories after publication, ensuring transparency and reproducibility of findings.

DISCUSSION

This protocol describes an RCT designed to compare the effectiveness of a sport-specific exercise programme versus a scapular stability programme in CrossFit athletes with unilateral SSP. The study aims to establish this population's most clinically effective approach for improving shoulder function, pain reduction, strength and training adaptations.

This protocol will also be used for a randomised trial registered in Australia (ACTRN12624000798561p). The trial findings will be disseminated at international conferences, published in peer-reviewed journals and shared with participants via personalised reports. The study results will be publicly available through open-access platforms and institutional websites.

The main strengths of this trial include its randomised design, sport-specific population and comprehensive outcome measures, allowing for a robust evaluation of intervention effectiveness. Furthermore, the study incorporates a standardised progression model, adherence tracking strategies and real-world implementation within athletes' regular training environments, enhancing its external validity and clinical relevance. The use of blinded outcome assessments, objective performance measures and a detailed statistical framework further strengthens the study's methodological rigour.

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Competing interests None declared.

Patient and public involvement Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

Patient consent for publication Not applicable.

Ethics approval This study has been approved by the Hospital Clínico San Carlos Ethics Committee (Approval ID: 24/421-EC-X_Tesis) and complies with the ethical principles outlined in the Declaration of Helsinki and the General Data Protection Regulation for research involving human participants. All participants provided informed consent before enrolment.

Provenance and peer review Not commissioned; internally peer reviewed.

Data availability statement Data sharing not applicable as no datasets generated and/or analysed for this study. No data are available.

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