RESEARCH ARTICLE

Effects of progressive eccentric training on pain relief and functional recovery in boxing athletes with patellar tendinopathy: A randomized controlled trial

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Patellar tendinopathy is a common overuse injury among boxing athletes, affecting performance and training capacity. Conventional treatment approaches show limited long-term efficacy. This study investigated the effectiveness of a 12-week progressive eccentric training program compared to conventional physical therapy for pain relief and functional recovery in boxing athletes with patellar tendinopathy. Forty competitive boxing athletes aged 24.8 ± 4.0 years old with diagnosed patellar tendinopathy were randomly allocated to either a progressive eccentric training group (n = 20) or a conventional physical therapy group (n = 20). The intervention group performed a 12-week structured eccentric training program, while the control group received standard physical therapy treatment including ultrasound therapy and traditional strengthening exercises. Outcomes were assessed at baseline, 6 weeks, and 12 weeks including pain intensity using visual analog scale (VAS), functional status using Victorian Institute of Sport Assessment-Patella (VISA-P), knee extensor strength using isokinetic dynamometry at 60°/s and 180°/s, tendon morphology using ultrasound imaging, and jump performance with single-leg hop, triple hop, counter-movement jump. The results showed that the intervention group demonstrated significantly greater improvements in VAS (mean difference: -3.4 points, 95% CI: -4.1 to -2.7, *P* < 0.001) and VISA-P scores (mean difference: 15.4 points, 95% CI: 11.8 to 19.0, *P* < 0.001) at the end of 12 weeks. Significant differences between two groups were observed in knee extensor strength and jump performance measures. The intervention demonstrated a high adherence rate of 94.8% with only minor, self-limiting adverse events reported in the initial weeks. This 12-week progressive eccentric training program was more effective than conventional physical therapy in improving pain and function in boxing athletes with patellar tendinopathy. These findings suggested that progressive eccentric training should be considered as a primary intervention for patellar tendinopathy in combat sport athletes.

Keywords: patellar tendinopathy; eccentric exercise; boxing; sports rehabilitation; pain management; athletic performance.

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Introduction

Patellar tendinopathy commonly known as jumper's knee represents a significant challenge in combat sports, particularly affecting boxing athletes who rely heavily on explosive lower limb movements. This chronic degenerative condition of the patellar tendon not only impacts athletic performance but also poses a substantial threat to career longevity in competitive boxing. Recent epidemiological studies have indicated that patellar tendinopathy affects approximately 14 - 16% of elite combat sports athletes with boxers showing a notably higher prevalence rate of up to 23% [1]. The pathophysiology of patellar tendinopathy in boxing athletes presents unique characteristics due to sport’s specific biomechanical demands. The repetitive nature of boxing movements including rapid directional changes, explosive punching mechanics, and constant weight transfers places exceptional stress on the patellar tendon. Research has demonstrated that these movements generate forces of up to 6 - 8 times body weight through the knee extensor mechanism, potentially contributing to tendon degeneration over time [2]. Traditional therapeutic approaches for patellar tendinopathy have shown variable efficacy with many athletes experiencing persistent symptoms despite conventional interventions. In addition to rest, nonsteroidal anti-inflammatory drugs (NSAIDs) and standard strength training have historically been treatment options. However, recent evidence suggests that these conservative treatments have limited long-term efficacy [3]. This therapeutic challenge has led to increased interest in progressive loading protocols, particularly eccentric training, which has shown promising results in treating various tendinopathies [4]. Eccentric training characterized by muscle lengthening under tension has emerged as a potentially effective intervention for tendinopathy. Recent systematic reviews have highlighted the physiological benefits of eccentric loading including enhanced collagen synthesis, improved tendon mechanical properties, and normalized neovascularization patterns [5]. However, despite the unique demands and limitations of the sport of boxing, the specific application of progressive eccentric training protocols in boxers with patellar tendinopathy remains underexplored [6].

Evidence supporting eccentric training is growing and has led to a variety of programs, but standardization remains a challenge. Recent research has demonstrated that progressive loading programs carefully tailored to individual athlete capabilities and sport-specific requirements may yield superior outcomes compared to standardized approaches [7]. The integration of progressive eccentric training into the rehabilitation of boxing athletes requires careful consideration of training volume, intensity progression, and sport-specific movement patterns [8]. Pain modulation and functional recovery represent critical outcomes in patellar tendinopathy rehabilitation, particularly in combat sports where performance demands are high. Recent studies have suggested that progressive eccentric training may influence pain perception through multiple mechanisms including mechanical desensitization and improved neuromuscular control [9]. Furthermore, evidence indicates that appropriate loading protocols may enhance tendon remodeling and functional adaptation, potentially leading to improved athletic performance [10]. Monitoring and assessing treatment outcomes in patellar tendinopathy present another significant challenge, particularly in high-performance athletics. While various outcome measures exist including the Visual Analogue Scale (VAS) for pain and the Victorian Institute of Sport Assessment for Patellar Tendinopathy (VISA-P), their application in a combat sport setting requires careful consideration of the functional demands of the specific sport. [11]. Recent research has emphasized the importance of incorporating both subjective and objective measures to comprehensively evaluate treatment efficacy [12].

The current research shows a notable gap in understanding the specific effects of progressive eccentric training on patellar tendinopathy in boxing athletes. While eccentric training has shown promise in treating tendinopathy in various athletic populations, research specifically addressing its application and efficacy in boxing is limited [13]. Given the unique biomechanical demands and training constraints in boxing, there is a clear need for targeted research examining the effects of progressive eccentric training on this specific athletic population. This study investigated the effects of progressive eccentric training on pain relief and functional recovery in boxing athletes with patellar tendinopathy through a randomized controlled trial design by using a comprehensive assessment approach including pain scales, functional questionnaires, strength measurements, and imaging techniques. The findings of this study would significantly contribute to the development of evidence-based rehabilitation protocols specific to combat sports athletes, potentially improving clinical practice and athletic performance outcomes in this specialized population.

Materials and methods

Participants and grouping

This randomized controlled trial was conducted at the Sports Medicine Center of Criminal Investigation Police University of China (Shenyang, Liaoning, China) between March 2024 and December 2024. Between March and December 2023, 67 boxers from regional boxing associations, sports medicine clinics, and boxing training centers aged 18 - 35 years old with a clinical diagnosis of patellar tendinopathy were assessed for eligibility of participation. Among them, 40 participants met the inclusion criteria, being active boxers with at least three years of competition experience, training at least 12 h per week, having a VISA-P score below 80, a VAS-reported pain rating greater than 3 during sport-specific activities, having participated in at least one regional-level competition in the past 12 months, and maintaining a stable training program throughout the study period. Exclusion criteria included previous knee surgery, concurrent knee disease including patellofemoral pain syndrome, meniscal injury, and ligament instability, systemic inflammation, corticosteroid injections within the past six months, and participation in a structured rehabilitation program for patellar tendinopathy within the past three months. Further exclusion criteria included a body mass index greater than 30 kg/m^2, a history of patellar dislocation, neurological disease affecting lower limb function, and any cardiovascular disease that would preclude participation in sports. The diagnosis was made through comprehensive three-step verification including initial screening by sports medicine physicians, confirmatory examination by an independent orthopedic specialist, and diagnostic ultrasound imaging. Clinical diagnosis included the presence of anterior knee pain localized to the patellar tendon during loading activities for at least three months accompanied by tenderness on palpation of the proximal patellar tendon and positive findings on both single leg decline squat and palpation tests. The diagnostic ultrasound examination was performed using standardized protocols with a high-frequency (12 - 18 MHz) linear transducer. The imaging diagnostic criteria included tendon thickening larger than 4 mm through anterior-posterior measurement), presence of hypoechoic regions, and altered fibrillar pattern. Power Doppler assessment was further conducted to evaluate neovascularization with findings being graded on a modified Öhberg scale. All 40 participants were allocated to either the intervention group (n = 20) or the control group (n = 20) using a computer-generated randomization sequence with block stratification for age and symptom duration through R (version 4.1.2) (https://www.r-project.org/) with a block size of four to ensure balanced group sizes throughout recruitment. The group assignment was concealed using sequentially numbered, opaque, sealed envelopes prepared by an independent statistician and opened by a research assistant who was not involved in participant assessment or intervention delivery. All procedures of this study was approved by the Ethics Committee of Criminal Investigation Police University of China (Shenyang, Liaoning, China) and was designed and reported following the Consolidated Standards of Reporting Trials (CONSORT) guidelines for clinical trials. All participants were informed of the study procedures, potential risks, and benefits, and provided written informed consent.

Intervention protocols

(1) Progressive eccentric training group

Participants in the intervention group underwent a 12-week progressive eccentric training program while maintaining their regular boxing training schedule. The program consisted of three supervised sessions per week, each lasting approximately 45 minutes with a minimum interval of 48 hours between sessions to allow adequate recovery. Training was conducted under the guidance of experienced physical therapists who had received standardized training in the protocol implementation including 20 hours of theoretical education and practical workshops. The eccentric training program was meticulously structured across four phases. Phase one that covered weeks 1 - 3 emphasized movement control and proper technique using body weight exercises, which focused on developing appropriate motor patterns during declined single-leg squats (25° decline board), step-downs, and modified Nordic hamstring exercises. Exercise volume began with 3 sets of 10 repetitions with a 4-second eccentric phase and 2-second concentric phase. A 60 second rest period between sets was strictly maintained. Phase two that covered weeks 4 - 6 introduced external loading using weight machines and free weights. The exercise protocol expanded to include leg press with eccentric emphasis (4-second lowering phase), weighted decline squats, and eccentric leg extensions. Loading was initiated at 40% of pre-determined one-repetition maximum (1RM) and progressed based on individual tolerance and weekly pain monitoring. Phase three that covered weeks 7 - 9 incorporated sport-specific movement patterns and increased loading intensity. Exercises included plyometric movements with eccentric emphasis, sport-specific footwork patterns with resistance, and combined movement sequences mimicking boxing-specific demands. Loading increased to 60 - 70% 1RM for appropriate exercises. Phase four that covered weeks 10 - 12 focused on power development and sport-specific performance enhancement, which incorporated complex training methods, combining heavy resistance exercises with explosive movements, while maintaining eccentric emphasis. Exercise intensity reached 70 - 85% 1RM for strength components with power exercises performed at body weight or with light external loads.

(2) Control group

The participants in control group continued their regular boxing training and received a standardized conventional physical therapy program administered by licensed physical therapists with a minimum of five years of sports rehabilitation experience. Each session lasted 45 minutes and followed a structured protocol including therapeutic ultrasound application, transverse friction massage, and traditional strengthening exercises. Therapeutic ultrasound application was conducted using a BTL-4000 professional calibrated device (BTL Industries Ltd., Boston, MA, USA) with standardized parameters of 1 MHz frequency, 1.5 W/cm² intensity, 1:4 ratio pulsed mode, and 10 minutes duration. The treatment area covered the painful region of the patellar tendon with a 50% overlap technique using ultrasound coupling gel. This treatment was only applied to the control group. Transverse friction massage was performed for 10 minutes following a standardized protocol, which was applied perpendicular to the tendon fibers with moderate pressure, focusing on the most symptomatic areas identified during assessment. Massage intensity was modulated based on individual tolerance and tissue response. This treatment was only applied to the control group. Traditional strengthening exercises included straight leg raises, short-arc quadriceps exercises, and closed-chain exercises such as wall slides and mini-squats. Exercise progression followed a standardized protocol based on participant tolerance and symptom response. Sets and repetitions were matched to the intervention group's volume to control for total exercise exposure.

Outcome measurements

VAS was used for pain intensity assessment during a single leg decline squat test followed a rigorous standardization protocol. Participants performed the test on a 25° decline board under consistent lighting and temperature conditions. Pain was recorded at the lowest point of the squat position, maintained for 3 seconds. Three trials were conducted with 30-second rest intervals, and the average score was recorded. The VISA-P questionnaire was administered in a quiet, private room under the supervision of a trained research assistant. Participants completed the questionnaire independently with standardized instructions provided. The questionnaire was administered at consistent times of day (±2 hours) for each assessment period to control diurnal variation in symptoms. Biodex System 4 Pro (Biodex Medical Systems, Inc., Shirley, NY, USA) was used for knee extensor strength assessment following a standardized protocol. Participants underwent a familiarization session one week prior to baseline testing. The testing position was standardized with hip flexion at 85° and stabilization straps across the chest, pelvis, and tested thigh. Gravity correction was performed prior to each test. The isokinetic strength was tested at 60°/s with five maximal concentric contractions following three submaximal practice repetitions. Peak torque, average power, and total work were recorded. The participants were then tested at 180°/s with fifteen maximal contractions to assess muscular endurance and power output at higher velocities. Work fatigue index and peak torque were calculated. Ultrasound images were obtained using a Samsung RS85 system (Samsung Medison Co., Ltd., Seoul, South Korea) with a 3-12 MHz linear array transducer in both longitudinal and transverse planes, while the participants were in a standardized supine position with 30° knee flexion. Power Doppler was conducted with the standardized settings of 500 Hz pulse repetition frequency and just below random noise. Three images were captured in each plane with measurements performed by two independent sonographers blinded to group allocation. Jump performance assessment included single leg hop tests that three variants (single hop for distance, triple hop, and timed 6-meter hop) were performed following a standardized warm-up. Three trials of each test were recorded with one-minute rest intervals. Counter-movement jumps were performed on an AMTI OR6-7 force platform (Advanced Mechanical Technology, Inc., Watertown, MA, USA) sampling at 1,000 Hz. Participants performed three maximal efforts with hands on hips and 45-second rest intervals. Peak force, power output, and jump height were calculated using custom LabVIEW software (https://www.ni.com/en-us/shop/labview.html).

Data collection and analysis

All assessments were conducted by physical therapists with a minimum of five-year experience in sports rehabilitation, who underwent specific training in the study protocols. Testing sessions were scheduled at consistent times (±2 hours) to minimize diurnal variation. Room temperature (20 - 22°C) and humidity (45 - 55%) were controlled during all testing sessions. All participants maintained detailed training diaries throughout the study period, recording their boxing training volume, intensity, and any additional physical activity. Dietary intake was monitored using three-day food records during each assessment period. Compliance with the intervention protocols was tracked using dedicated log sheets and verified by supervising physical therapists. The sample size was determined using G*Power (version 3.1.9.7) (https://www.psychologie.hhu.de/arbeitsgruppen/allgemeine-psychologie-und-arbeitspsychologie/gpower) based on anticipated changes in VISA-P scores from previous studies and pilot testing data. SPSS (version 27.0) (IBM, Armonk, NY, USA) was employed for data analysis. The initial data screening included assessment of outliers and normality testing using the Shapiro-Wilk test. Baseline comparisons between groups were conducted using independent t-tests for normally distributed continuous variables and Mann-Whitney U tests for non-normally distributed data. Categorical variables were analyzed using chi-square tests or Fisher's exact test when expected cell counts were less than five. A mixed-model ANOVA was applied with time (baseline, 6 weeks, 12 weeks) as the within-subjects factor and group as the betweensubjects factor. The assumption of sphericity was assessed using Mauchly's test with Greenhouse-Geisser corrections applied when violated. Interaction effects were examined using simple main effects analysis with Bonferroni-adjusted pairwise comparisons. To account for potential confounding variables, an analysis of covariance (ANCOVA) was conducted with baseline scores, age, body mass index, and symptom duration as covariates. Missing data were addressed using multiple imputation techniques with 20 imputations including all outcome variables and demographic characteristics in the imputation model. Effect sizes were calculated using partial eta-squared (η^2p) for ANOVA effects and Cohen's d for pairwise comparisons with 95% confidence intervals computed for all effect sizes. Minimal clinically important differences were established from previous literature reviews for each outcome measurement with treatment success defined as achieving changes exceeding these thresholds. Bonferroni corrections were applied for multiple comparisons. Results were reported following CONSORT guidelines including point estimates and measures of variability for all outcomes. *P* value less than 0.05 was defined as a statistically significant difference. Additional regression analyses were performed to identify potential predictors of treatment response with multicollinearity assessed using variance inflation factors and appropriate residual analyses conducted to verify regression assumptions.

Results

Baseline measurements

All outcome measures demonstrated normal distribution, and no significant outlier was identified. Missing data was minimal (< 5%) and was handled using multiple imputations. The baseline demographic and clinical characteristics showed that the intervention group (n=20) had a mean age of 24.5 ± 3.8 years old, height of 175.8 ± 6.4 cm, body mass of 71.3 ± 8.4 kg, BMI of 23.1 ± 2.1 kg/m², boxing experience of 6.8 ± 2.4 years, training hours per week of 14.2 ± 2.8, symptom duration of 8.2 ± 3.1 months, baseline VAS score of 6.8 ± 1.2, and baseline VISA-P score of 58.4 ± 12.3. The control group (n = 20) had a mean age of 25.1 ± 4.2 years old, height of 174.9 ± 6.8 cm, body mass of 70.8 ± 7.9 kg, BMI of 23.3 ± 2.3 kg/m², boxing experience of 6.5 ± 2.6 years, training hours per week of 13.9 ± 3.1, symptom duration of 7.9 ± 3.4 months, baseline VAS score of 6.7 ± 1.3, and baseline VISA-P score of 59.1 ± 11.8. There were no statistically significant differences in all baseline measures (*P* > 0.05).

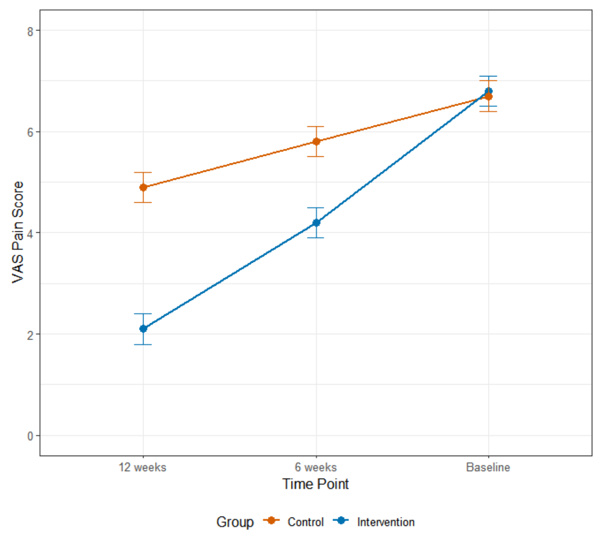

Figure 1. Changes in pain intensity.

Pain Intensity and VISA-P scores

The results demonstrated significant time × group interactions for both pain intensity (F = 45.6, *P* < 0.001, η^2p = 0.45) and VISA-P scores (F = 52.3, *P* < 0.001, η^2p = 0.52). Mauchly's test indicated no violation of sphericity for either measure (*P* > 0.05). The intervention group demonstrated significantly greater pain reduction than that in the control group at both 6 weeks (mean difference: -2.1 points, 95% CI: -2.8 to -1.4, *P* < 0.001, Cohen's d = 1.2) and 12 weeks (mean difference: -3.4 points, 95% CI: -4.1 to -2.7, *P* < 0.001, Cohen's d = 1.8). After adjusting for baseline scores, age, BMI, and symptom duration through ANCOVA, these between-group differences remained significant (adjusted *P* < 0.001). Similar improvements were observed in VISA-P scores with the intervention group

Table 1. Changes in measurements over time.

Outcome measure	Group	Baseline	6 weeks	12 weeks	Effect size (η^2p)	Between-group difference at 12 weeks (95% CI)
VAS Pain Score	Intervention	6.8 ± 1.2	4.2 ± 1.1	2.1 ± 0.9	0.45	-3.4 (-4.1 to -2.7)*
	Control	6.7 ± 1.3	5.8 ± 1.2	4.9 ± 1.1		
VISA-P Score	Intervention	58.4 ± 12.3	76.5 ± 11.2	89.6 ± 8.4	0.52	15.4 (11.8 to 19.0)*
	Control	59.1 ± 11.8	68.3 ± 10.8	74.9 ± 9.6		
Peak Torque 60°/s (Nm)	Intervention	185.3 ± 28.4	201.6 ± 26.8	228.4 ± 25.3	0.39	32.6 (24.3 to 40.9)*
	Control	183.8 ± 29.1	190.4 ± 27.5	195.8 ± 26.7		

Notes: Values were presented as mean ± SD. VAS: Visual Analog Scale. VISA-P: Victorian Institute of Sport Assessment-Patella. η^2p: partial eta-squared. *: $P < 0.001$.

Table 2. Changes in jump performance measures.

Performance measure	Group	Baseline	12 Weeks	Mean change (95% CI)	Effect size (η^2p)
Single Hop Distance (cm)	Intervention	142.3 ± 18.6	168.5 ± 16.8	26.2 (22.4 to 30.0)*	0.40
	Control	143.1 ± 18.2	152.4 ± 17.5	9.3 (6.1 to 12.5)	
Triple Hop Distance (cm)	Intervention	428.6 ± 45.3	486.2 ± 42.8	57.6 (51.2 to 64.0)*	0.39
	Control	425.8 ± 46.1	448.3 ± 44.2	22.5 (17.8 to 27.2)	
CMJ Height (cm)	Intervention	32.4 ± 4.8	38.6 ± 4.2	6.2 (5.1 to 7.3)*	0.38
	Control	31.9 ± 4.6	34.2 ± 4.4	2.3 (1.5 to 3.1)	

Notes: Values were presented as mean ± SD. CMJ: Counter-Movement Jump. η^2p: partial eta-squared. *: $P < 0.001$.

showing superior outcomes throughout the study period. At 12 weeks, the intervention group demonstrated a mean improvement of 31.2 points (95% CI: 27.8 to 34.6) compared to 15.8 points (95% CI: 12.4 to 19.2) in the control group ($P < 0.001$, Cohen's d = 1.6) (Figure 1). ANCOVA results confirmed these findings after controlling for potential confounding variables.

Knee extensor strength

Mixed-model ANOVA revealed significant time × group interactions for both peak torque at 60°/s (F = 38.4, $P < 0.001$, $\eta^2p = 0.39$) and total work at 180°/s (F = 42.7, $P < 0.001$, $\eta^2p = 0.42$). The intervention group demonstrated significantly greater improvements in peak torque than that in the control group at 12 weeks (mean difference: 32.6 Nm, 95% CI: 24.3 to 40.9, $P < 0.001$, Cohen's d = 1.4) (Table 1).

Tendon structure and neovascularization

Significant improvements in tendon morphology were observed in both groups with superior outcomes in the intervention group. Mixed-model ANOVA showed significant time × group interactions for both tendon thickness (F = 35.2, $P < 0.001$, $\eta^2p = 0.37$) and neovascularization score (F = 33.8, $P < 0.001$, $\eta^2p = 0.36$) (Figure 2).

Jump performance

Analysis of functional performance revealed significant time × group interactions for all jump tests including single leg hop (F = 40.2, $P < 0.001$, $\eta^2p = 0.40$), triple hop (F = 38.9, $P < 0.001$, $\eta^2p = 0.39$), and CMJ height (F = 36.4, $P < 0.001$, $\eta^2p = 0.38$) (Table 2).

Predictors of treatment response

Multiple regression analysis identified several significant predictors of treatment response. Baseline pain intensity ($\beta = 0.45$, $P < 0.01$), symptom duration ($\beta = -0.38$, $P < 0.01$), and initial VISA-P score ($\beta = 0.32$, $P < 0.01$) were significant predictors of improvement in the pain intensity. No significant multicollinearity was observed among predictor variables (all VIF < 2.0).

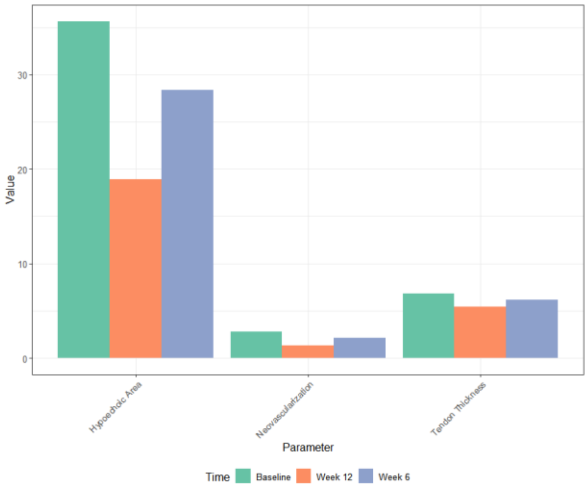

Figure 2. Changes in tendon parameters.

Clinical significance

The improvements in both pain and VISA-P scores exceeded the established minimal clinically important differences (MCID) in 85% of intervention group participants compared to 45% in the control group (risk ratio = 1.89, 95% CI: 1.45 to 2.46, *P* < 0.001). The number needed to treat to achieve one additional positive outcome (exceeding MCID) was 2.5 (95% CI: 1.8 to 3.4).

Treatment adherence and adverse events

Adherence to the intervention protocol was high in both groups with participants completing 94.8% (SD = 3.2%) of scheduled sessions in the intervention group and 92.6% (SD = 3.8%) in the control group. No serious adverse events were reported during the study period. Minor muscle soreness was reported by 7 participants (35%) in the intervention group and 5 participants (25%) in the control group during the first two weeks of the program, resolving spontaneously without interruption to the intervention protocol.

Discussion

This study investigated the effects of progressive eccentric training on pain relief and functional recovery in boxing athletes with patellar tendinopathy. The results demonstrated that a 12-week progressive eccentric training program was significantly more effective than conventional physical therapy in improving pain, functional performance, and tendon structural characteristics.

Pain reduction and clinical significance

The intervention group showed substantially greater improvements in both pain reduction and VISA-P scores than that in the control group. The mean reduction in VAS pain scores (3.4 points) and improvement in VISA-P scores (31.2 points) exceeded the minimal clinically important differences established in previous research [14]. The results of pain reduction aligned with recent systematic reviews [15], which reported effect sizes ranging from 0.8 to 1.3 for eccentric training in tendinopathy management. The large effect sizes observed in this study for both pain ($\eta^2 p$ = 0.45) and function ($\eta^2 p$ = 0.52) suggested that progressive eccentric training had a robust therapeutic impact. These results extended beyond previous findings by specifically addressing the unique demands of boxing athletes [16]. The superior outcomes in the intervention group might be attributed to several physiological and biomechanical mechanisms. The progressive nature of the eccentric protocol likely facilitated optimal tendon loading and adaptation as supported by recent mechanobiological research [17]. The sport-specific movement patterns incorporated into the later phases of the program might have enhanced neuromuscular control and functional transfer of training effects, consistent with motor learning principles in sports rehabilitation [18]. The systematic progression of load and intensity might have addressed the specific demands placed on the patellar tendon during boxing-related activities, particularly the high-velocity, explosive movements characteristic of the sport [19].

Strength and performance improvements

The significant improvements in knee extensor strength and jump performance in the intervention group highlighted the broader functional benefits of progressive eccentric training. The enhancement in peak torque at 60°/s (mean difference: 32.6 Nm) suggested improved maximal strength capacity, while the gains in high-velocity strength (180°/s) indicated enhanced power production capabilities. These adaptations aligned with recent research on velocity-specific strength adaptations in athletes and were particularly relevant for boxing performance, where rapid force development was crucial [20]. The substantial improvements in jump performance metrics demonstrated the transfer of strength gains to functional performance. The intervention group's superior improvements in single leg hop distance (26.2 cm), triple hop distance (57.6 cm), and countermovement jump height (6.2 cm) exceeded those reported in previous studies of tendinopathy rehabilitation [21, 22]. These functional gains were especially noteworthy given that boxing success depended heavily on lower limb power and reactive strength for footwork and punching mechanics [23].

Structural adaptations and tissue response

The ultrasound findings revealed significant improvements in tendon morphology and neovascularization patterns in the intervention group. The reduction in tendon thickness and improvement in structural integrity suggested positive tissue remodeling in response to the progressive loading protocol. These structural adaptations supported current understanding of mechanotransduction in tendon tissue and aligned with recent research on load-induced tendon adaptation [24, 25]. The observed changes in tendon architecture might represent a key mechanism underlying the sustained improvement in symptoms and function. The significant decrease in neovascularization scores (mean reduction: 1.5 points on modified Öhberg scale) was particularly relevant as abnormal vascularity had been strongly associated with symptom severity in tendinopathy [26]. Recent research suggested that controlled loading through eccentric exercise might normalize tendon vasculature by modulating angiogenic factors and inflammatory mediators [27]. The gradual modification of vascular patterns observed in this study provided clinical evidence supporting these mechanistic findings.

Clinical applications and implementation strategies

The high adherence rates (94.8%) and minimal adverse events observed in this study suggested that progressive eccentric training was both feasible and well-tolerated by boxing athletes. The structured progression of exercises and integration of sport-specific movements likely contributed to program compliance while maintaining training specificity [28]. The identification of baseline pain intensity (β = 0.45) and symptom duration (β = -0.38) as significant predictors of treatment response provided clinicians with valuable information for patient selection and prognosis estimation [29]. The implementation of this protocol required careful consideration of several factors. The timing of eccentric training sessions relative to regular boxing training was crucial as demonstrated by recent research on training periodization in combat sports [30]. The results suggested that scheduling eccentric training sessions with at least 48 hours between high-intensity boxing sessions optimized recovery and adaptation while minimizing interference with sport-specific training.

Study limitations and future directions

Several limitations should be considered when interpreting these results. The relatively short follow-up period (12 weeks) did not allow for assessment of long-term outcomes or recurrence rates, which were particularly relevant given the chronic nature of tendinopathy. While the study population represented competitive boxing athletes, the findings might not generalize to elite-level competitors or other combat sports, where training loads and performance demands might differ significantly. In addition, the single-center design and specific geographical location might limit external validity. While many potential confounding variables were controlled, factors such as nutritional status and sleep quality, which might influence tissue healing and adaptation, were not systematically monitored. Further, the lack of biomechanical analysis of boxing-specific movements limited the understanding of how improvements in strength and function were translated to sport performance. Future research should address these limitations through multi-center trials with longer follow-up periods and the inclusion of elite athletes. Investigation of the optimal timing and progression of eccentric loading relative to competition schedules would provide valuable practical guidance. Additionally, studies incorporating biomechanical analysis of boxing-specific movements and examination of tissue adaptation mechanisms through advanced imaging and biological markers would enhance the understanding of the therapeutic mechanisms.

References

1. Choi E, Han M, Jun H. 2024. Comparative analysis on injury incidence and characteristics in men's collegiate athletes between combat and ball sports. Exerc Sci. 33(3):323-330.
2. Dinu D, Louis J. 2020. Biomechanical analysis of the cross, hook, and uppercut in junior *vs*. elite boxers: Implications for training and talent identification. Front Sports Act Living. 2:598861.
3. Núñez-Martínez P, Hernández-Guillen D. 2021. Management of patellar tendinopathy through monitoring, load control, and therapeutic exercise: A systematic review. J Sport Rehabil. 31(3):337-350.
4. Breda SJ, Oei EHG, Zwerver J, Visser E, Waarsing E, Krestin GP, *et al*. 2021. Effectiveness of progressive tendon-loading exercise therapy in patients with patellar tendinopathy: A randomized clinical trial. Br J Sports Med. 55(9):501-509.
5. Beyer R, Kongsgaard M, Hougs Kjær B, Øhlenschlæger T, Kjær M, Magnusson SP. 2015. Heavy slow resistance versus eccentric training as treatment for Achilles tendinopathy: A randomized controlled trial. Am J Sports Med. 43(7):1704-1711.
6. Wilson JJ, Best TM. 2005. Common overuse tendon problems: A review and recommendations for treatment. Am Fam Physician. 72(5):811-818.
7. Gravare Silbernagel K, Vicenzino BT, Rathleff MS, Thorborg K. 2019. Isometric exercise for acute pain relief: Is it relevant in tendinopathy management? Br J Sports Med. 53(21):1330-1331.
8. Agergaard AS, Svensson RB, Malmgaard-Clausen NM, Couppé C, Hjortshoej MH, Doessing S, *et al*. 2021. Clinical outcomes, structure, and function improve with both heavy and moderate loads in the treatment of patellar tendinopathy: A randomized clinical trial. Am J Sports Med. 49(4):982-993.
9. Solomons L. 2022. Nervous system sensitization in musculoskeletal pain syndromes [D]. University of British Columbia. Vancouver, BC, Canada.
10. McMahon G. 2022. No strain, no gain? The role of strain and load magnitude in human tendon responses and adaptation to loading. J Strength Cond Res. 36(10):2950-2956.
11. Visentini PJ, Khan KM, Cook JL, Kiss ZS, Harcourt PR, Wark JD. 1998. The VISA score: An index of severity of symptoms in patients with jumper's knee (patellar tendinosis). Victorian Institute of Sport Tendon Study Group. J Sci Med Sport. 1(1):22-28.
12. van der Vlist AC, Winters M, Weir A, Ardern CL, Welton NJ, Caldwell DM, *et al*. 2021. Which treatment is most effective for patients with Achilles tendinopathy? A living systematic review with network meta-analysis of 29 randomized controlled trials. Br J Sports Med. 55(5):249-256.
13. Lu J, Li H, Zhang Z, Xu R, Wang J, Jin H. 2023. Platelet-rich plasma in the pathologic processes of tendinopathy: A review of basic science studies. Front Bioeng Biotechnol. 11:1187974.
14. Agergaard AS, Svensson RB, Malmgaard-Clausen NM, Magnusson SP. 2024. Clinical outcomes and tendon structure at 3- to 4-year follow-up after exercise-based treatment of patellar tendinopathy: A prospective study. Orthop J Sports Med. 12(10):23259671241280192.
15. Rosen AB, Wellsandt E, Nicola M, Tao MA. 2022. Clinical management of patellar tendinopathy. J Athl Train. 57(7):621-631.
16. Lazarczuk SL, Maniar N, Opar DA, Duhig SJ, Shield A, Barrett RS, *et al*. 2022. Mechanical, material and morphological adaptations of healthy lower limb tendons to mechanical loading: A systematic review and meta-analysis. Sports Med. 52(10):2405-2429.
17. Zouhal H, Boullosa D, Ramirez-Campillo R, Ali A, Granacher U. 2021. Editorial: Acute: Chronic workload ratio: Is there scientific evidence? Front Physiol. 12:669687.
18. Kharazi M, Bohm S, Theodorakis C, Mersmann F, Arampatzis A. 2021. Quantifying mechanical loading and elastic strain energy of the human Achilles tendon during walking and running. Sci Rep. 11(1):5830.
19. Esculier JF, Maggs K, Maggs E, Dubois B. 2020. A contemporary approach to patellofemoral pain in runners. J Athl Train. 55(12):1206-1214.
20. Bourantanis A, Katsos K, Samolis A, Vlachodimitropoulos D, Troupis G, Sakelliadis EI, *et al*. 2024. Forensic investigation into head trauma in combat sports, blunt force homicides, and traditional martial arts. Forensic Sci Int. 365:112269.
21. Suchomel TJ, Wagle JP, Douglas J, Taber CB, Harden M, Haff GG, *et al*. 2019. Implementing eccentric resistance training-part 2: Practical recommendations. J Funct Morphol Kinesiol. 4(3):55.
22. Visnes H, Bache-Mathiesen LK, Yamaguchi T, Gilhuus HP, Algaard KRH, Hisdal E, *et al*. 2024. Long-term prognosis of patellar tendinopathy (jumper's knee) in young, elite volleyball players: Tendon changes 11 years after baseline. Am J Sports Med. 52(13):3314-3323.

23. Rodrigues R, Daiana Klein K, Dalcero Pompeo K, Aurélio Vaz M. 2022. Are there neuromuscular differences on proximal and distal joints in patellofemoral pain people? A systematic review and meta-analysis. J Electromyogr Kinesiol. 64:102657.
24. Turner AN, Comfort P, McMahon J, Bishop C, Chavda S, Read P, *et al*. 2021. Developing powerful athletes part 2: Practical applications. Strength Cond J. 43(1):23-31.
25. González FA, Garuz AT, Morales JC, Soler BC. 2022. Physiology and mechanobiology of tendon and muscle tissue. Rev Esp Artrosc Cir Articul. 29(1):3-12.
26. Williamson PM, Freedman BR, Kwok N, Beeram I, Pennings J, Johnson J, *et al*. 2021. Tendinopathy and tendon material response to load: What we can learn from small animal studies. Acta Biomater. 134:43-56.
27. van Oosten CCM, van der Vlist AC, van Veldhoven PLJ, van Oosterom RF, Verhaar JAN, de Vos RJ. 2022. Do high-volume injections affect the ultrasonographic neovascularization in chronic Achilles tendinopathy? A randomized placebo-controlled clinical trial. Clin J Sport Med. 32(5):451-457.
28. de Vos RJ, Gravare Silbernagel K, Malliaras P, Visser TS, Alfredson H, Akker-Scheek IVD, *et al*. 2024. ICON 2023: International Scientific Tendinopathy Symposium Consensus - the core outcome set for Achilles tendinopathy (COS-AT) using a systematic review and a Delphi study of professional participants and patients. Br J Sports Med. 58(20):1175-1186.
29. Jaén-Carrillo D, Roche-Seruendo LE, Felton L, Cartón-Llorente A, García-Pinillos F. 2021. Stiffness in running: a narrative integrative review. Strength Cond J. 43(2):104-115.
30. Lystad RP, Alevras A, Rudy I, Soligard T, Engebretsen L. 2021. Injury incidence, severity and profile in Olympic combat sports: A comparative analysis of 7712 athlete exposures from three consecutive Olympic Games. Br J Sports Med. 55(19):1077-1083.