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Research article

Acute Impact of Cold Compression Therapy Across Diverse Age Groups and Physical Conditioning Status: A Randomized Crossover Study

Robert Trybulski [1,2], Adrian Kużdżał [3], Gracjan Olaniszyn [1,4], Ana Filipa Silva [5], Filipe Manuel Clemente [6,7,8]✉ and Wang Hsing-Kuo [9,10]

[1] Faculty of Medicine, Katowice Business University, Katowice, Poland; [2] Provita Medical Centre, Żory, Poland; [3] Institute of Physiotherapy, Faculty of Health Sciences and Psychology, Collegium Medicum, University of Rzeszów, Poland; [4] Olaniszyn Physiotherapy Centre, Poland; [5] Faculty of Sport Sciences and Physical Education, University of Coimbra, Coimbra, Portugal; [6] Sport Physical Activity and Health Research & Innovation Center, Portugal; [7] Applied Research Institute (i2A), Polytechnic University of Coimbra, Portugal; [8] Department of Biomechanics and Sport Engineering, Gdansk University of Physical Education and Sport, Poland; [9] School and Graduate Institute of Physical Therapy, National Taiwan University, Taipei; [10] Center of Physical Therapy, National Taiwan University Hospital, Taipei

Abstract

To test whether a pneumatic cold-compression system (CC) improves recovery of maximal voluntary contraction (MVC) at 48 h (T4) versus Sham after a standardized hamstring fatigue protocol. Secondary aims were to compare muscle stiffness, microvascular perfusion, pressure pain threshold (PPT), blood lactate, perceived recovery (TQR), and harms across subgroups. This multicenter, randomized, participant- and assessor-blinded, sham-controlled, two-period crossover trial enrolled 80 participants. After fatigue testing, participants received CC (3 °C, 75 mmHg, 10 min twice daily for 3 days) or Sham (15 °C, 15 mmHg). Outcomes were assessed at baseline (T0), post-fatigue (T1), immediately post-first intervention (T2), 24 h (T3), and 48 h (T4). Continuous outcomes were analyzed using mixed-way ANOVA with Population as the between-subject factor and Condition and Time as within-subject factors, followed by Bonferroni-adjusted pairwise comparisons. Paired Cohen's dz was reported for key within-participant contrasts. TQR was analyzed using rank-based factorial ANOVA, and Borg CR10 scores using ordinal logistic regression. Across populations, MVC was higher under CC than Sham from T2 to T4, with the largest between-condition difference at T4 (all $p < .001$). Muscle stiffness was lower under CC from T2 to T4 (all $p < .001$). Microvascular perfusion and pressure pain threshold were higher under CC at T2 - T4 overall (all $p < .001$), with earlier between-condition differences in MMA athletes and young adults and delayed differences in older adults. Blood lactate was lower under CC only immediately after the first intervention session (T2; $p < .001$). TQR was higher under CC at T2 - T4 in MMA athletes, at T2 - T3 in older adults, and at T3 only in young adults. No adverse events were reported. CC accelerated recovery after hamstring fatigue, improving strength, stiffness, perfusion, pain thresholds, lactate, and perceived recovery across populations, with earlier benefits in athletes and young adults and delayed but comparable improvements in older adults. Registration: ISRCTN49499065.

Key words: Cryotherapy, Compression, Muscle Fatigue, Recovery of Function, Sports Medicine.

Introduction

Hamstring muscles are prime contributors to hip extension, knee flexion, and pelvic control during gait and sprinting, making them central determinants of locomotor performance and injury risk in sport (Mann and Hagy, 1980). Hamstring injuries remain highly prevalent across field-based team sports and impose a substantial burden on health and performance (Maniar et al., 2023). These injuries frequently cause time-loss and exhibit important recurrence rates, emphasizing the need for robust prevention and recovery strategies (Diemer et al., 2021). Fatigue-induced alterations in muscle mechanical properties—particularly increases in stiffness—are implicated in heightened susceptibility to strain, linking neuromuscular fatigue to hamstring injury mechanisms (Lettner et al., 2024). At the same time, fatigue reduces maximal voluntary contraction, elevates blood lactate, disrupts microvascular perfusion, and lowers pressure pain thresholds, all of which influence recovery dynamics and injury risk. Objective quantification of muscle tone and stiffness using handheld myotonometry shows acceptable reliability (Davidson et al., 2017), while complementary measures of strength, perfusion, metabolic status, and pain sensitivity provide a more comprehensive picture of fatigue and readiness.

Within sports medicine, structured recovery is integral to sustaining adaptation and reducing cumulative load effects, with practitioners drawing on a toolbox that spans thermal, mechanical, and active modalities to accelerate the restoration of function (Dupuy et al., 2018). Contemporary evidence syntheses suggest that cooling-based strategies can benefit soreness and neuromuscular recovery (while contrast water therapy may better address some biochemical markers), highlighting that modality choice must be contextualized to the aimed outcomes (Chen et al., 2024). Theoretically, cold exposure reduces tissue temperature and modulates blood flow and inflammatory responses, providing a physiological rationale for its use after fatiguing exercise (Allan et al., 2022). When cooling is combined with intermittent compression, randomized data indicate superior reductions in swelling and pain and faster functional gains versus cryotherapy alone in postoperative knee cohorts, suggesting potential synergy between thermal and mechanical inputs (Quesnot et al., 2024). However, narrative syntheses of cold plus (predominantly static) compression report that the effects of combined treatment, while clearly superior to no intervention, do not appear to be directly additive relative to cold or compression alone, with only marginal gains and substantial methodological heterogeneity across trials, thereby tempering strong claims of synergy and underscoring the importance

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of protocol-specific interpretation (Block, 2010). In athletic contexts, contemporary cryo-compression applied post-training has been shown to acutely improve performance-related measures in elite academy footballers, indicating translational value for sport recovery (Alexander et al., 2022). At the same time, caution is warranted because repeated cold-water immersion can blunt anabolic signaling and satellite-cell responses, implying possible trade-offs if used chronically around resistance training (Roberts et al., 2015). Meta-analytic work further emphasizes heterogeneity in protocols, populations, and endpoints, leaving uncertainty about optimal cooling prescriptions across use-cases (Hohenauer et al., 2015).

The need to fit recovery can be amplified by aging biology, as older adults experience motor-unit remodeling with reduced strength/power and increased fatigability that can reshape recovery kinetics and tissue tolerance (Hunter et al., 2016). Conversely, elite athletes operate at high training loads where rapid load changes elevate illness and injury risk without careful management, making efficient, evidence-based recovery a performance and health priority (Soligard et al., 2016). Despite these clear population differences, the literature lacks multicenter randomized comparisons testing whether cryo-compression efficacy differs across older adults, young adults, and elite performers, even as reviews highlight age-associated differences in recovery from exercise-induced muscle damage (Li et al., 2024). Evidence in combat-sport athletes is beginning to show that pressure-based cooling and contrast protocols can acutely modulate perfusion, muscle tone, and perceived regeneration, yet hamstring-specific outcomes and cross-population generalizability remain insufficiently defined (Trybulski et al., 2024b). Accordingly, the present multicenter study will use a standardized hamstring-focused fatiguing stimulus and test whether cryo-compression, compared with sham, enhances microvascular perfusion, normalizes stiffness, elevates pressure-pain thresholds, and expedites strength recovery across age and training-status strata, building on the established centrality of eccentric hamstring loading in performance and injury prevention paradigms (van der Horst et al., 2015). By coupling these aims with validated viscoelastic assessments to capture tissue-level adaptations, this work seeks to deliver population-specific guidance for recovery practice in sport and rehabilitation.

Therefore, the objective of this multicenter randomized crossover trial was to investigate how age and training status modulate the physiological and perceptual recovery of the hamstring muscles following a standardized fatigue protocol, and to determine the effectiveness of pneumatic cold compression system therapy (CC) compared with a sham procedure across three distinct populations: elite mixed martial arts athletes, young adults, and adults over 50 years of age. Specifically, the study aimed to analyze acute and short-term recovery trajectories in terms of systemic metabolic response, measured by blood lactate clearance; local microvascular adaptations, captured through tissue perfusion; mechanical properties of the hamstrings, including stiffness and tone; sensory response, assessed by pressure pain threshold; and functional restoration, evaluated by maximal voluntary contraction of knee flexors. Complementary outcomes included subjective perception of exertion and global recovery quality. By integrating objective biomechanical, physiological, and perceptual indices across repeated time points, the study sought to delineate both within-group and between-group differences, thereby clarifying whether cryo-compression provides uniform or population-specific benefits in recovery dynamics.

Methods

Patient and public involvement

Patients or members of the public were not involved in the design, conduct, reporting, or dissemination plans of this study. The selection of study populations (elite mixed martial arts athletes, healthy young adults, and healthy adults over 50 years) was based solely on methodological and scientific considerations described in the Introduction.

Study design

This investigation was conducted as a multicenter, randomized, participant- and assessor-blinded, sham-controlled, two-period crossover clinical trial with a superiority framework. Three independent research centers in Poland participated: The Provita Medical Center in Żory, responsible for elite mixed martial arts athletes; the Upper Silesian Academy in Katowice, responsible for young adults; and the Medical Center in Racibórz, responsible for adults over 50 years of age.

Each participant completed two study periods, separated by a washout interval of 14 days to minimize carryover effects. In one period, participants received the active intervention consisting of pneumatic cold-compression system therapy, while in the other period they received the sham comparator, with the sequence randomized in a 1:1 ratio. At the beginning of each study period, participants performed a standardized fatigue protocol based on the Nordic Hamstring Exercise to volitional exhaustion, after which the allocated intervention was initiated. The intervention phase comprised six treatment sessions, scheduled twice daily in the morning between 8:00 and 11:00 and in the evening between 17:00 and 20:00, over the course of three consecutive days.

Outcome assessments were performed at five predefined time points. Baseline values were recorded before the fatigue protocol (T0), immediately after the completion of the fatigue protocol (T1), immediately following the first intervention session (T2), twenty-four hours after the fatigue protocol (T3), and forty-eight hours after the fatigue protocol (T4). This structure allowed the evaluation of both acute and short-term recovery dynamics, while ensuring that each participant served as their own control, thereby improving statistical efficiency and minimizing the influence of interindividual variability.

Trial setting, registration, and ethics

The trial was conducted between June and September 2025 under controlled laboratory conditions, with room temperature maintained between 20 - 22 °C and relative humidity kept stable across centers. The study was prospectively registered in the International Standard Randomised Controlled Trial Number (ISRCTN) registry under the number ISRCTN49499065(https://www.isrctn.com/ISRCTN49499065; Date: 3 / 06 / 2025), prior to participant enrollment.

The protocol and statistical analysis plan were reviewed and approved by the Ethical Committee for Scientific Research of Physiotherapists at the Polish Society of Physiotherapy on June 11, 2025 (Ref. No.: Resolution 1.06.2025). The trial was conducted in accordance with the Declaration of Helsinki and applicable national regulations. Written informed consent was obtained from all participants prior to any study procedures.

Eligibility criteria

Eligibility criteria were defined separately for each study population. For the elite mixed martial arts (MMA) group, inclusion required a minimum of 5 years of continuous training with at least 5 weekly sessions, participation in at least three professional fights, and classification within grade I or II according to the McKay framework (McKay et al., 2022). For the young adult group, participants were required to be healthy, aged 20 - 24 years, and free from recent musculoskeletal injury. For the 50+ group, eligibility required good general health, age over 50 years, and the ability to perform the prescribed fatigue and recovery protocols. Across all groups, exclusion criteria were: (i) musculoskeletal injury or surgery of the thigh in the preceding 6 months; (ii) presence of chronic cardiovascular, metabolic, or neurological disease; (iii) uncontrolled hypertension, defined as resting blood pressure >140/90 mmHg; and (iv) consumption of ergogenic aids or stimulants (including caffeine, energy drinks, or cola-type beverages) within 12 hours before each experimental session.

Centers were required to have access to standardized laboratory equipment for biomechanical and physiological measurements and to controlled environmental testing conditions. All interventionists received standardized training in the use of the pneumatic cold-compression system and in delivering sham protocols. Importantly, personnel responsible for interventions were distinct from those conducting outcome assessments, to preserve blinding.

Intervention and Comparator

Experimental intervention (pneumatic cold compression therapy- CC)

Cold compression was delivered using a multi-modality pneumatic cold-compression unit (Med4 Elite, Game Ready/Avanos Medical, USA). The Med4 Elite is an AC-powered, software-controlled device designed for professional clinical use, providing iceless cold therapy, thermotherapy, rapid contrast (alternating heat and cold), and intermittent pneumatic compression for up to two patients simultaneously. Treatment parameters (therapy mode, total treatment time, and minimum/maximum treatment temperature) are set on an integrated touchscreen in either °C or °F, and maintained by an internal refrigeration and heat-exchange system rather than ice. The system delivers cold and compression through dual-chamber “Active Temperature Exchange” (ATX®) wraps, which incorporate separate channels for circulating fluid and air and are anatomically contoured to provide circumferential coverage of the limb. Intermittent pneumatic compression is generated within the air chamber at pre-set levels (low, medium-low, medium, high), corresponding to approximate peak cuff pressures from about 5 up to 75 mmHg in cold-therapy and compression-only modes. In the present study, only the cold-therapy mode combined with intermittent pneumatic compression was used, with the cold module set to 3 °C and the compression level set to “high” (nominal peak pressure 75 mmHg), applied via full-thigh wraps to the exercised limb for each treatment session.

Participants were positioned supine with both thighs enveloped by wraps ensuring full sleeve-to-skin contact (no clothing between wrap and skin). The controller was set to cold at 3 °C and intermittent compression targeting 75 mmHg (high mode) for 10 min per session, delivered twice daily (08:00 - 11:00 and 17:00 - 20:00) over three consecutive days (total 6 sessions, 60 min cumulative exposure). Within each 10-min exposure, the device’s automated duty cycle applied rhythmic inflation/deflation to maintain the high-mode pressure profile (engineer-fixed cycle timing), providing a dynamic mechanothermal stimulus while participants remained relaxed. The choice of 3 °C with high-mode compression is aligned with contemporary sport-science trials using pneumatic cold-compression system that explicitly applied 3 °C and 75 mmHg and reported acute improvements in perfusion and muscle mechanical properties, supporting these settings as therapeutically active for skeletal muscle recovery (Trybulski et al., 2024a).

In hamstring-focused work with pneumatic cold-compression system, high intermittent pressure spanning 5 - 75 mmHg has been used together with a target cooling of ~10 °C after fatiguing exercise, further validating the upper end of the compression range for lower-limb musculature in athletic cohorts (Alexander et al., 2021). Additionally, randomized crossover evaluations of commercial cryo-compression devices show that dosing aimed to achieve skin temperatures of ~10 - 15 °C is considered the therapeutic target window; using a cold set-point near 3 °C at the cuff typically yields skin temperatures in that window because of tissue/liner thermal gradients, justifying our temperature selection on safety and efficacy grounds (Belsey et al., 2024). Finally, a randomized study on optimal pneumatic cold-compression system exposure in elite combat-sport athletes indicates that 10 minutes of cryo-compression is sufficient to elicit measurable, favorable changes in perfusion, pain threshold, stiffness, and strength—supporting our 10-min session length for an acute-recovery protocol (Trybulski et al., 2024d).

Comparator (sham cryo-compression)

Sham sessions matched the active protocol for participant position, wrap type, session timing, and total exposure but used milder settings designed to mimic sensation without producing meaningful mechanophysiological change: controller temperature 15 °C and compression 15 mmHg in intermittent mode. These low-cooling/low-pressure parameters are consistent with sham conditions used in pneumatic cold-compression system trials (e.g., sham temp 15 - 36 °C with 15 - 25 mmHg), which have been shown to preserve blinding while minimizing physiological effects relative to active dosing (Trybulski et al., 2024c).

Treatment delivery, fidelity and safety considerations

At each site, interventions (active and sham) were delivered by physiotherapists with ≥5 years of clinical experience who completed centralized hands-on training with the

Med4 Elite and trial SOPs before enrollment began; treating therapists were not involved in outcome assessment. Session-level fidelity checklists documented device model/serial number, wrap size, side(s) treated, set temperature, compression mode, start/stop times, and any deviations; device parameters were verified prior to each session. The controller's compression modes follow manufacturer-defined pressure ranges (e.g., high = 5 - 75 mmHg) and automated inflation/deflation cycles, ensuring reproducible dosing across centers; these specifications were used to standardize settings and were not user-editable beyond the chosen mode. Prior to each session, skin integrity and sensation were checked; sessions were discontinued for excessive cold pain, numbness, abnormal skin changes, or cardiovascular instability (Khoshnevis et al., 2015). Any such occurrences were recorded as prespecified adverse events, which are summarized in the 'Harms' section.

Fatigue protocol

To induce a standardized and reproducible state of hamstring fatigue, participants performed the Nordic Hamstring Exercise (NHE) on a dedicated kneeling apparatus with the ankles secured under padded rollers, the hips held in full extension, the trunk aligned with the thighs, and the arms crossed on the chest; from this position, they leaned forward under eccentric control until they could no longer resist the descent and then used their hands to prevent a fall, a technique consistent with canonical descriptions of the NHE in training and research (Mjølsnes et al., 2004).

The protocol comprised three sets performed to volitional exhaustion with two minutes of seated rest between sets, and exhaustion was operationalized as the inability to maintain a controlled eccentric lowering for two consecutive repetitions despite standardized encouragement from the assessor, which reflects common practice in experiments using repeated NHE exposures to elicit acute fatigue (Magdalena et al., 2024). To improve interpretability of the fatigue stimulus across populations, the immediate decline in MVC from T0 to T1 was expressed as a relative fatigue index. Mean MVC decreased by approximately 25.1% and 25.7% in MMA athletes, 30.6% and 30.2% in young adults, and 35.2% and 34.8% in older adults during the CC and Sham periods, respectively, indicating similar fatigue induction across crossover periods within each population, but greater relative fatigue in older adults than in MMA athletes.

One week before experimental testing, all participants completed a familiarization session in which they received standardized instruction and performed supervised practice repetitions to minimize learning effects and ensure consistent technique during data collection, an approach aligned with reliability work showing improved measurement quality when NHE execution is standardized and rehearsed before testing (Lee et al., 2018). The choice of the NHE as the fatiguing stimulus was based on evidence that this exercise produces high eccentric demand in the knee flexors, is widely adopted in both research and applied sport, and has causal evidence for reducing hamstring injury incidence in randomized controlled trials, which underscores its ecological validity for lower-limb performance and recovery studies (van der Horst et al., 2015). Beyond its preventive efficacy, repeated-set NHE exposures reliably provoke acute alterations in the hamstring's mechanical and morphological properties and are associated with soreness responses characteristic of exercise-induced muscle damage, thereby providing a sensitive model to study early recovery kinetics over the subsequent 24 - 48 hours (Behan et al., 2023; Magdalena et al., 2024).

Outcomes

All outcome assessments were scheduled around this stimulus at five predefined timepoints to capture both the immediate effects of fatigue and short-term recovery: baseline before NHE (T0), immediately post-NHE (T1), immediately after the first intervention session (T2), twenty-four hours post-NHE (T3), and forty-eight hours post-NHE (T4), with assessors trained to monitor technique and discontinue the set if hip flexion, compensatory trunk movements, or undue discomfort compromised safe execution, consistent with safety practices in eccentric hamstring testing.

Muscle function

The primary outcome was maximal voluntary contraction of the knee flexors (MVC), recorded bilaterally with a handheld dynamometer (Kinvent K-Force) while participants lay prone with the hip extended and knee at 30° flexion; two five-second maximal isometric trials were performed per leg with 60 seconds of rest between attempts, and the highest value was retained for analysis. MVC was expressed in Newtons (N). Handheld dynamometry provides reliable and valid estimates of knee flexor strength in healthy populations and has been recommended for both clinical and research applications (Mentiplay et al., 2015).

Metabolic response

Systemic metabolic recovery was quantified by capillary blood lactate concentration ($mmol\cdot L^{-1}$) using a portable analyzer (Lactate Scout+, EKF Diagnostics, Leipzig, Germany), which has been validated for accuracy and reliability in exercise physiology research (Tanner et al., 2010). Two measurements were obtained per timepoint, with a third performed if the first two differed by more than 0.2 $mmol\cdot L^{-1}$; the mean of the two closest values was retained. Blood lactate was expressed as concentration in $mmol\cdot L^{-1}$.

Microvascular perfusion

Local circulatory function was assessed by laser Doppler flowmetry (PeriFlux 6000, Perimed, Sweden). The probe was affixed over the biceps femoris at a standardized midpoint between the ischial tuberosity and fibular head. Following a five-minute resting familiarization period in the testing position, perfusion was recorded continuously for two minutes at each timepoint. The outcome was expressed as mean perfusion units (PU). Laser Doppler flowmetry is an established technique for quantifying human microvascular function with reproducible results (Roustit and Cracowski, 2013).

Muscle mechanical properties

Hamstring muscle stiffness was measured using the MyotonPRO (Myoton AS, Estonia). The device probe was applied perpendicularly to the biceps femoris, and three consecutive mechanical impulses were delivered at one-second intervals. The mean of the three readings was extracted for analysis. Stiffness was expressed in Newtons per meter (N/m). Myotonometry has been validated as a reliable method for characterizing muscle viscoelastic properties (Chen et al., 2019).

Sensory response

Pain sensitivity was measured by the pressure pain threshold (PPT) using a digital algometer (Wagner Instruments, Greenwich, CT, USA). The probe was applied to the biceps femoris with steadily increasing force until the participant reported the first sensation of discomfort, and three trials were averaged. PPT was expressed in kilopascals (kPa). Digital pressure algometry has been shown to provide reliable PPT measures for musculoskeletal tissues (Park et al., 2011).

Subjective perception

Recovery perceptions were assessed with the Total Quality of Recovery (TQR) scale, which ranges from 6 (very poor recovery) to 20 (very good recovery). Perceived exertion was simultaneously measured with the Borg CR10 scale, which ranges from 0 (no exertion) to 10 (maximal exertion). Both were administered once at each timepoint without repetition, and the scores were recorded as absolute values. The TQR scale has been validated as a monitoring tool for athlete recovery (Kenttä and Hassmén, 1998), while the Borg CR10 scale has extensive validation as a perceptual index of exertion (Borg, 1990).

Harms

Harms were prespecified as excessive pain, abnormal skin reactions, cold-induced numbness or paresthesia, or cardiovascular instability. The skin was inspected immediately before and after each cryo-compression session, and participants were systematically queried for unusual sensations at each timepoint.

Sample size

The a priori sample size calculation focused on the primary endpoint, defined as the within-participant difference between CC and Sham in change of hamstring maximal voluntary contraction (MVC) from baseline to 48 h after the fatiguing task (ΔMVC T4 - T0) in the two-period, two-sequence crossover. For planning, we approximated the analysis by a paired t-test on the within-participant treatment difference at T4, which is a standard approach for crossover trials with a single primary post-treatment time point. Published crossover studies of lower-limb cryo-compression (Julious et al., 1999) report small-to-moderate recovery benefits on MVC at 24 - 48 h (standardized within-participant effect sizes ≈0.3 - 0.6).37 To be conservative with respect to heterogeneity across our three populations, we assumed a small standardized effect size of $dz = 0.30$ for ΔMVC at T4, with a two-sided $\alpha = 0.05$ and 90% power. Under these assumptions, approximately 117 participants completing both periods are required (Julious et al., 1999).

Due to pragmatic considerations related to multicenter logistics and recruitment timelines, enrollment was capped at 80 participants (40 elite MMA athletes, 20 young adults, 20 older adults), all of whom completed both periods. With this achieved sample, the observed within-participant effect size for ΔMVC at T4 ($dz = 1.0$) yielded post hoc power >99% for the primary comparison at $\alpha = 0.05$, indicating that the study remained well powered for the effect actually observed.

Randomization

The random allocation sequence was generated prior to recruitment by an independent statistician not otherwise involved in participant enrollment, intervention delivery, or outcome assessment. Randomisation was computer-based, using a reproducible pseudo-random number generator (R statistical software, version 4.3).

The trial used stratified block randomisation with variable block sizes of 4 and 6 to ensure balanced allocation within each study population (elite mixed martial arts athletes, young adults, and adults over 50 years) and by sex. Participants were randomized in a 1:1 ratio to one of two treatment sequences: (i) pneumatic cold-compression system followed by sham, or (ii) sham followed by pneumatic cold-compression system. Stratification minimized the risk of imbalances in demographic and training-related characteristics across the crossover sequences.

Allocation concealment was maintained using sequentially numbered, opaque, sealed envelopes prepared at the coordinating center. Envelopes were identical in appearance, tamper-proof, and opened only after baseline testing and enrollment were complete. The envelopes contained the treatment sequence assignment for each participant and were kept in a secure location accessible only to the local trial coordinator. Neither participants nor outcome assessors had access to the allocation sequence at any time.

Blinding

Outcome assessors, data-entry personnel, and statisticians were blinded to treatment allocation throughout the study. Because the active and sham interventions were delivered using the same device, wrap, positioning, session timing, and therapist contact, participant blinding was attempted. However, the active condition (3 °C with high intermittent compression up to 75 mmHg) and the sham condition (15 °C with minimal intermittent compression of 15 mmHg) differed in sensory intensity, and no formal blinding assessment was performed. Therefore, the success of participant blinding could not be verified and should be considered uncertain. Only the physiotherapists delivering the intervention were aware of allocation, and they had no role in recruitment, randomisation, or outcome assessment.

Statistical analysis

Continuous outcomes (maximal voluntary contraction [MVC], muscle stiffness, microvascular perfusion, pressure pain threshold [PPT], and blood lactate) were analyzed using three-way mixed ANOVA, with Population (MMA athletes, young adults, and older adults) as the between-subject factor and Condition (CC vs Sham) and Time (T0 - T4) as within-subject factors. Descriptive data are presented as mean ± SD. For each model, residuals were inspected graphically (Q-Q plots, histograms, and residuals-versus-fitted plots), Shapiro-Wilk tests were used to assess approximate normality, and sphericity for repeated factors was examined using Mauchly's test; when sphericity was violated, Greenhouse–Geisser corrections were applied. Omnibus effects are reported as F statistics with corrected degrees of freedom where appropriate, associated p values, and partial eta squared (ηp^2). Significant main effects and interaction terms were explored using Bonferroni-adjusted post hoc comparisons.

To provide the detailed contrasts reported in the Results and Supplementary Material, paired CC versus Sham comparisons at each time point and within-condition temporal contrasts were additionally summarized for continuous outcomes using paired t-tests, with Bonferroni-adjusted p values and Cohen's dz. Between-population comparisons of treatment response was performed on subject-level CC–Sham difference scores using one-way ANOVA, reported with eta squared (η^2). Because TQR and Borg CR10 are ordinal outcomes, inferential analyses for these variables were conducted using nonparametric procedures. Longitudinal TQR patterns were examined with aligned rank-transform factorial ANOVA using the same Population × Condition × Time structure, and follow-up paired CC versus Sham comparisons were tested with Wilcoxon signed-rank tests. For ordinal outcomes, between-population comparisons of CC–Sham difference scores were examined with Kruskal–Wallis tests. Effect sizes are reported as matched rank-biserial correlations for paired ordinal contrasts and epsilon squared (ε^2) for Kruskal–Wallis models. Although TQR and Borg were analyzed nonparametrically, observed mean ± SD values are also presented descriptively in the supplementary tables for consistency across outcomes. All tests were two-sided, performed in SPSS (Version 28), and statistical significance was set at $p < .05$. Because TQR is an ordinal outcome, it was analyzed using an aligned rank transform (ART) factorial model implemented in R (ARTool package), with Population as the between-subject factor and Condition and Time as within-subject factors.

Results

Participant flow and recruitment

Among the 120 individuals screened/recruited, 80 were randomized into the crossover trial, with equal distribution to the two intervention sequences: Sequence A (CC to Sham, n = 40) and Sequence B (Sham to CC, n = 40). All participants received the intended interventions in both periods and were included in the analyses of the primary outcome. No participants were lost to follow-up, discontinued the interventions, or were excluded from the final analyses. Thus, the per-protocol and intention-to-treat samples were identical. The full trajectory of participants through screening, allocation, and analysis is displayed in the CONSORT flow diagram (Figure 1).

Of the randomized participants, 40 were elite mixed martial arts (MMA) athletes, 20 were healthy young adults, and 20 were healthy, physically active older adults. Within each subgroup, allocation was balanced between the two crossover sequences (MMA: 20/20; Young: 10/10; Older: 10/10). All participants completed both intervention phases and were analysed for the primary outcome, resulting in complete paired data across conditions for MVC at baseline and 48 h. There were no losses, withdrawals, or exclusions after randomisation. All randomized participants were retained through both intervention arms, with no adverse events or protocol deviations reported that required exclusion.

At baseline, MMA athletes (n = 40) had a mean age of 27.2 ± 3.5 years, height of 179.2 ± 7.6 cm, weight of 76.3 ± 10.2 kg, body mass index (BMI) of 23.7 ± 2.6 kg/m², and training experience of 11.0 ± 2.8 years. The healthy young adults (n = 20) had a mean age of 21.8 ± 1.6 years, height of 171.3 ± 8.0 cm, weight of 68.0 ± 10.6 kg, BMI of 23.1 ± 2.4 kg/m², and training experience of 2.5 ± 1.4 years. The healthy, physically active older adults (n = 20) presented with a mean age of 55.6 ± 3.8 years, height of 171.8 ± 7.8 cm, weight of 77.3 ± 12.0 kg, BMI of 26.1 ± 3.2 kg/m², and training experience of 7.3 ± 2.6 years. For the overall cohort of 80 participants, the mean age was 33.0 ± 13.7 years, height 175.4 ± 8.6 cm, weight 74.5 ± 11.3 kg, BMI 24.2 ± 2.9 kg/m², and training experience 8.0 ± 4.3 years.

Because of the large amount of statistical data, descriptive tables for all outcomes, conditions, and populations are provided in Supplementary Material 1.

Fatigue induction and recovery status

The Nordic hamstring protocol induced a marked immediate reduction in maximal voluntary contraction (MVC) in all three populations (Table 1). Averaged across crossover periods, MVC fell from T0 to T1 by 25.3% in MMA athletes, 30.4% in young adults, and 35.0% in older adults, indicating that the relative fatigue burden was greatest in the older group. Despite the consistently more favorable trajectory under pneumatic cold compression (CC), recovery at 48 h remained incomplete in every population. At T4, MVC under CC had returned to 96.1% of baseline in MMA athletes, 76.3% in young adults, and 69.1% in older adults, compared with 87.7%, 61.1%, and 46.2% under sham, respectively (Table 1). Hamstring stiffness also remained above baseline at T4 under both conditions, although the residual elevation was smaller with CC in every population (Table 1).

Primary outcome: maximal voluntary contraction

MVC trajectories are shown in Figure 2. No between-condition difference was present at baseline or immediately after the fatigue protocol. From T2 onward, MVC was higher under CC than under sham, with paired between-condition effects of dz = 0.76 at T2, dz = 0.97 at T3, and dz = 1.02 at T4; the largest pooled mean difference was observed at T4 (+95.4 N, $p < .001$). There was also a strong main effect of population on overall MVC level across the repeated series, $F_{(2,\ 77)} = 129.26$, $p < .001$, $\eta p^2 = .771$, with MMA athletes highest, young adults intermediate, and older adults lowest overall. The onset of benefit differed by population: the CC advantage was evident from T2 in MMA athletes and young adults, whereas in older adults it became significant at T3 (Table 2). Because the population-dependent time course was significant, this omnibus between-population effect should be interpreted alongside the population-specific contrasts in Table 2. By 48 h, the absolute mean MVC remained below baseline in all populations, but the residual deficit was materially smaller with CC than with sham, particularly in older adults (30.9% vs 53.8% below baseline) and young adults (23.7% vs 38.9% below baseline) (Table 1; Figure 2). To improve clinical interpretability, MVC values were also expressed relative to baseline. Under CC, MVC at T4 recovered to 96.1% of baseline in MMA athletes, 76.5% in young adults, and 69.0% in older adults, compared with 87.7%, 60.9%, and 46.4%, respectively, under Sham. Thus, although CC significantly improved MVC recovery relative to Sham, complete recovery to baseline was not achieved within 48 h in young and older adults, with the largest residual deficit observed in older adults.

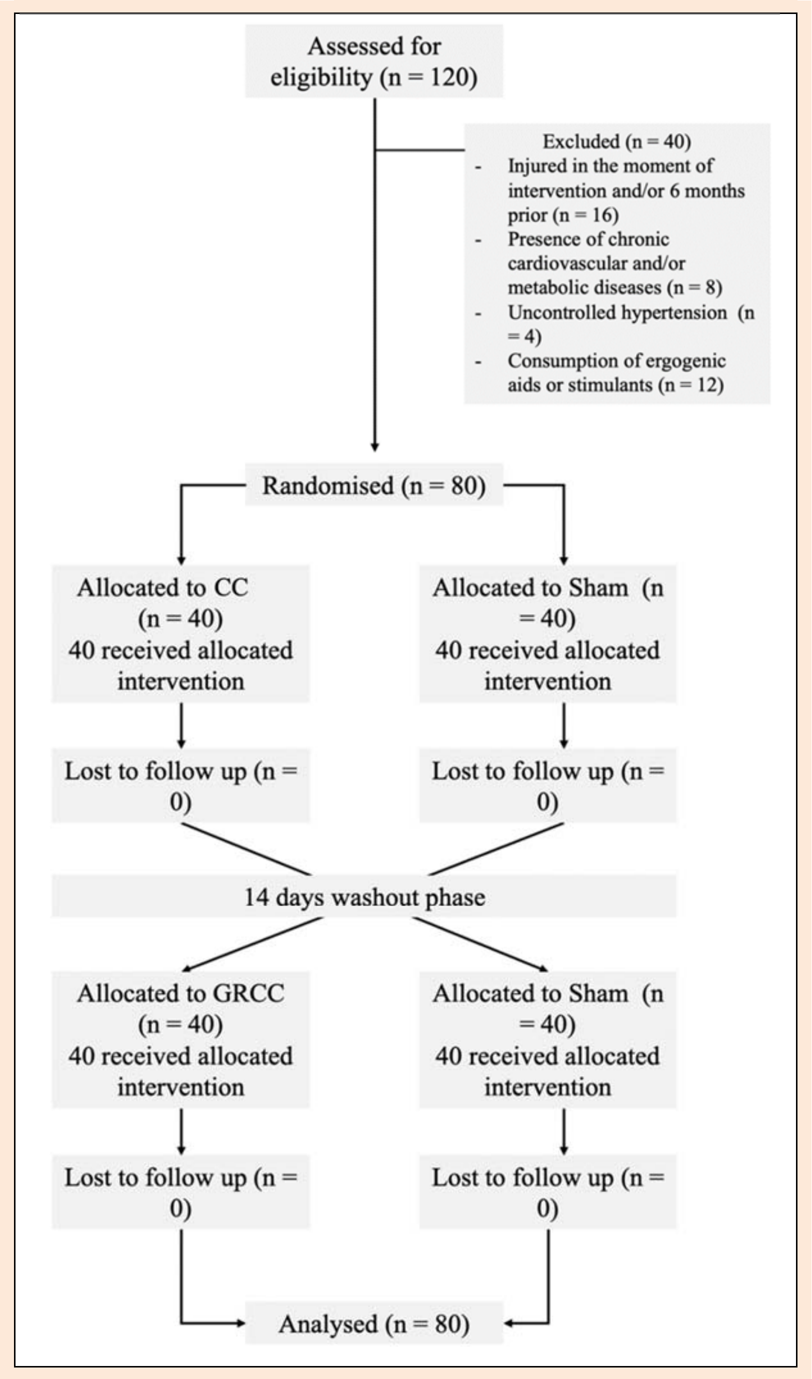

Figure 1. Flow diagram. CC: pneumatic cold-compression system therapy.

Table 1. Relative fatigue immediately after the Nordic hamstring protocol and recovery status at 48 h.

Population	Mean MVC decline at T1 vs T0	MVC at T4 under CC (% of baseline)	MVC at T4 under sham (% of baseline)	Stiffness at T4 under CC (% of baseline)	Stiffness at T4 under sham (% of baseline)
MMA athletes	25.3%	96.1%	87.7%	118.0%	150.6%
Young adults	30.4%	76.3%	61.1%	118.0%	161.0%
Older adults	35.0%	69.1%	46.2%	132.1%	162.5%

Values >100% for stiffness indicate residual stiffness above baseline; MVC: maximal voluntary contraction.

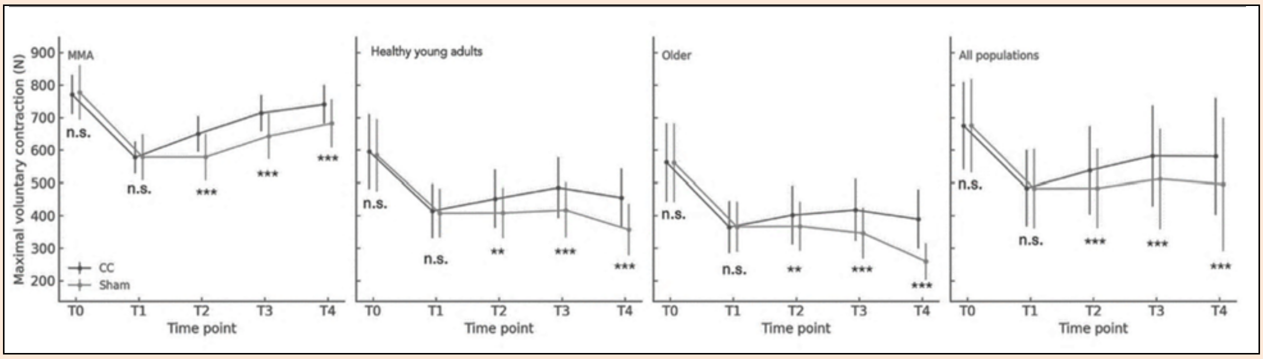

Figure 2. Recovery of maximal voluntary contraction (MVC) across time points (T0 = baseline, T1 = post-fatigue, T2 = immediately after first intervention, T3 = 24 h, T4 = 48 h). CC: pneumatic cold compression. Between-conditions (CC vs. sham) differences per time point are indicated by asterisks (**$p < 0.010$; ***$p < 0.001$). n.s.: no significant. MMA, n = 40; young healthy adults, n = 20; Older, n = 20.

Primary outcome: maximal voluntary contraction

MVC trajectories are shown in Figure 2. No between-condition difference was present at baseline or immediately after the fatigue protocol. From T2 onward, MVC was higher under CC than under sham, with paired between-condition effects of $dz = 0.76$ at T2, $dz = 0.97$ at T3, and $dz = 1.02$ at T4; the largest pooled mean difference was observed at T4 (+95.4 N, $p < .001$). There was also a strong main effect of population on overall MVC level across the repeated series, $F_{(2, 77)} = 129.26$, $p < .001$, $\eta p^2 = .771$, with MMA athletes highest, young adults intermediate, and older adults lowest overall. The onset of benefit differed by population: the CC advantage was evident from T2 in MMA athletes and young adults, whereas in older adults it became significant at T3 (Table 2). Because the population-dependent time course was significant, this omnibus between-population effect should be interpreted alongside the population-specific contrasts in Table 2. By 48 h, the absolute mean MVC remained below baseline in all populations, but the residual deficit was materially smaller with CC than with sham, particularly in older adults (30.9% vs 53.8% below baseline) and young adults (23.7% vs 38.9% below baseline) (Table 1; Figure 2). To improve clinical interpretability, MVC values were also expressed relative to baseline. Under CC, MVC at T4 recovered to 96.1% of baseline in MMA athletes, 76.5% in young adults, and 69.0% in older adults, compared with 87.7%, 60.9%, and 46.4%, respectively, under Sham. Thus, although CC significantly improved MVC recovery relative to Sham, complete recovery to baseline was not achieved within 48 h in young and older adults, with the largest residual deficit observed in older adults.

Table 2. Borg CR10 ratings immediately after the fatigue protocol (T1).

Population	CC, mean ± SD	Sham, mean ± SD
MMA athletes	4.92 ± 0.89	4.83 ± 0.84
Young adults	6.10 ± 0.91	6.25 ± 0.91
Older adults	6.55 ± 1.10	6.20 ± 1.11

Secondary Outcomes

Muscle stiffness

Muscle stiffness trajectories are presented in Figure 3. No between-condition difference was observed at T0 or T1. From T2 onward, stiffness was lower under CC than under sham, with paired between-condition effects of $dz = -3.54$ at T2, $dz = -2.29$ at T3, and $dz = -2.50$ at T4; the pooled mean differences were -21.7 N/m at T2, -9.0 N/m at T3, and -26.3 N/m at T4 (all $p < .001$). There was also a main effect of population on overall stiffness across the repeated series, $F_{(2, 77)} = 37.69$, $p < .001$, $\eta p^2 = .495$, indicating lower overall stiffness in older adults than in MMA athletes and young adults, whereas MMA athletes and young adults were similar overall. However, full mechanical normalization was not achieved by 48 h under either condition. At T4, stiffness under CC remained 18.0% above baseline in MMA athletes and young adults and 32.1% above baseline in older adults, compared with 50.6%, 61.0%, and 62.5% above baseline under sham, respectively (Table 1; Figure 3). Although muscle stiffness was lower under CC than Sham from T2 to T4, stiffness values remained above baseline at T4 in both conditions, indicating incomplete mechanical recovery within 48 h.

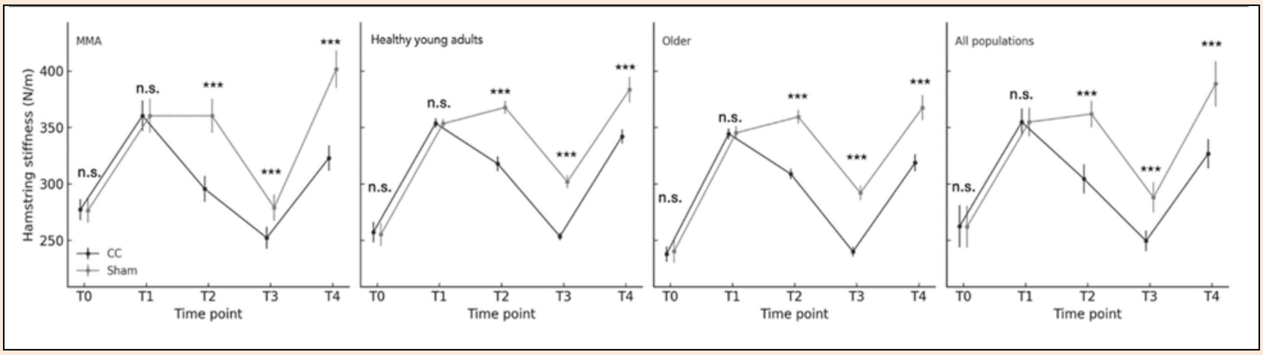

Figure 3. Recovery of hamstring muscle stiffness across time points (T0–T4) in MMA athletes. CC: pneumatic cold compression. Between-conditions (CC vs. sham) differences per time point are indicated by asterisks (***$p < 0.001$). n.s.: no significant. MMA, n = 40; young healthy adults, n = 20; Older, n = 20.

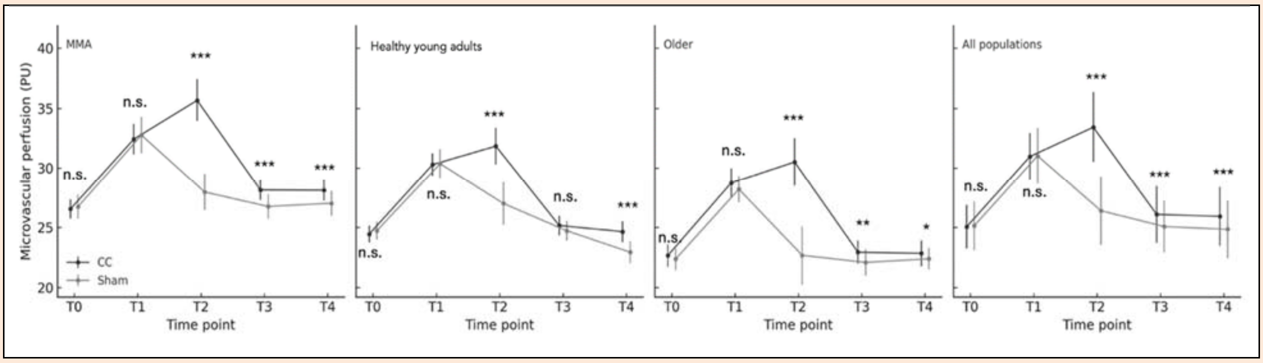

Figure 4. Microvascular perfusion expressed as perfusion units (PU) across time points (T0 - T4). CC: pneumatic cold compression. Between-conditions (CC vs. sham) differences per time point are indicated by asterisks (* $p < 0.05$; ** $p < 0.010$; *** $p < 0.001$) ns: no significant. MMA, n = 40; young healthy adults, n = 20; Older, n = 20.

Microvascular perfusion

Perfusion trajectories are shown in Figure 4. No condition difference was detected at T0 or T1. At T2, which represents the immediate response to the first treatment session rather than a later recovery endpoint, perfusion was higher under CC than under sham; this advantage persisted at T3 and T4. The pooled between-condition differences were +6.807 PU at T2, +0.897 PU at T3, and +1.093 PU at T4, with corresponding paired effects of dz = 2.14, 0.83, and 0.82 (all $p < .001$). There was also a main effect of population on overall perfusion across the repeated series, $F_{(2, 77)} = 280.91$, $p < .001$, $\eta p^2 = .879$, with MMA athletes highest, young adults intermediate, and older adults lowest overall. Population-specific onset again differed, with earlier separation in MMA athletes and young adults (T2) and delayed separation in older adults (T3).

Pressure pain threshold

Pressure pain threshold (PPT) trajectories are shown in Figure 5. No between-condition difference was observed at T0 or T1. From T2 onward, PPT was higher under CC than under sham overall, with pooled mean differences of +3.408 N/cm² at T2, +3.296 N/cm² at T3, and +15.018 N/cm² at T4, corresponding to paired effects of dz = 0.55, 0.46, and 1.88, respectively (all $p < .001$). There was also a main effect of population on overall PPT across the repeated series, $F_{(2, 77)} = 313.80$, $p < .001$, $\eta p^2 = .891$, with MMA athletes highest, young adults intermediate, and older adults lowest overall. The earliest statistically significant separation occurred in MMA athletes at T2; in young adults, the between-condition difference first appeared at T2 and became most pronounced at T4; and in older adults, the effect emerged at T3.

Blood lactate

Lactate trajectories are shown in Figure 6. The between-condition effect was confined to the immediate post-session assessment. At T2, lactate was lower under CC than under sham (pooled mean difference -1.125 mmol/L, $p < 0.001$; dz = -3.49), whereas no between-condition difference was present at T0, T1, T3, or T4. There was also a main effect of population on overall lactate across the repeated series, $F_{(2, 77)} = 151.90$, $p < 0.001$, $\eta p^2 = .798$, with older adults highest, young adults intermediate, and MMA athletes lowest overall. Consistent with the non-significant population-by-condition-by-time interaction, this transient lactate effect did not materially differ across populations.

Perceived recovery

Perceived recovery, assessed with the Total Quality of Recovery (TQR) scale, is summarized in Figure 7. Ordinal analyses indicated a condition-by-time pattern that differed by population. The omnibus rank-based model also showed a main effect of population ($\chi^2 = 6.1$, $p = .002$, $\eta p^2 = .022$) and a population-by-condition-by-time interaction ($\chi^2 = 3.1$, $p = .006$, $\eta p^2 = .033$). Within-population comparisons favored CC at T2-T4 in MMA athletes, at T2-T3 in older adults, and at T3 in young adults. The T2 comparison should be interpreted as an immediate post-session response rather than as a 24 - 48 h recovery endpoint.

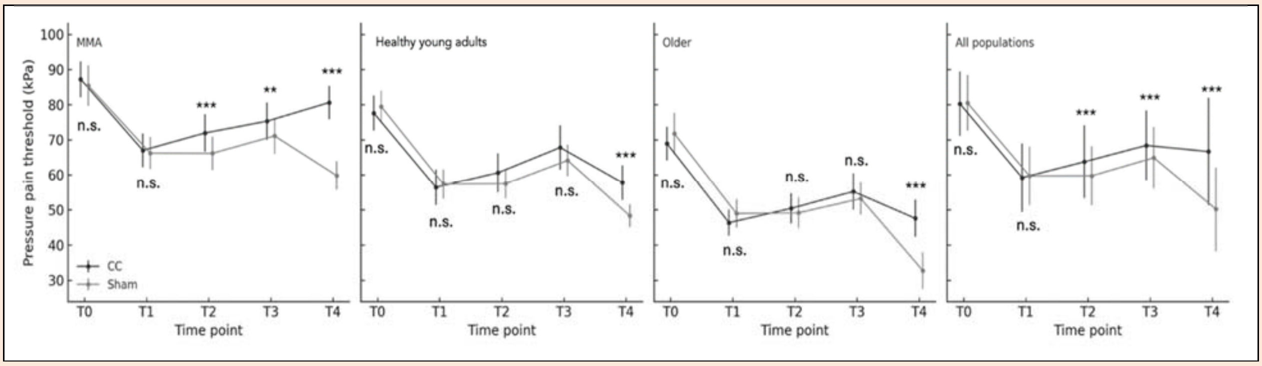

Figure 5. Pressure pain threshold (PPT) across time points (T0–T4). CC: pneumatic cold compression. Between-conditions (CC vs. sham) differences per time point are indicated by asterisks (**$p < 0.010$. *** $p < 0.001$) ns: no significant. MMA, n = 40; young healthy adults, n = 20; Older, n = 20.

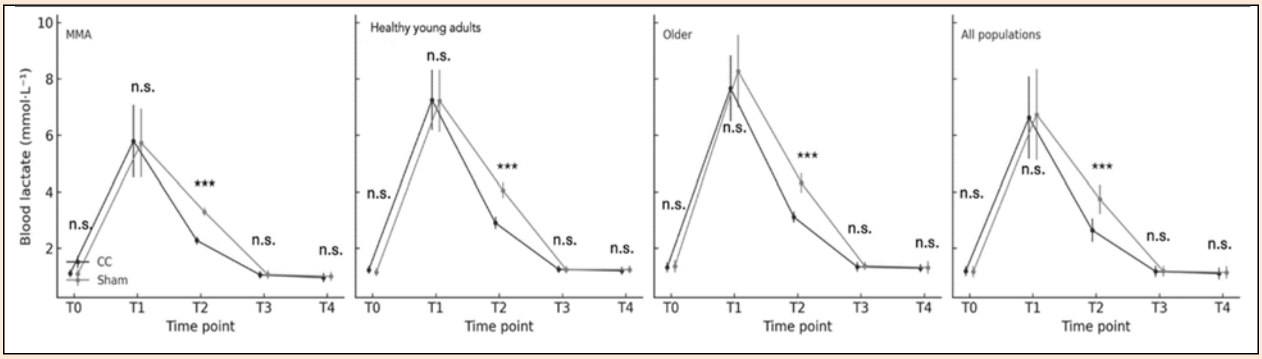

Figure 6. **Blood lactate concentrations (mmol·L^{-1}) across time points (T0–T4).** CC: pneumatic cold compression. Between-conditions (CC vs. sham) differences per time point are indicated by asterisks (*** $p < 0.001$). ns: no significant. MMA, n = 40; young healthy adults, n = 20; Older, n = 20.

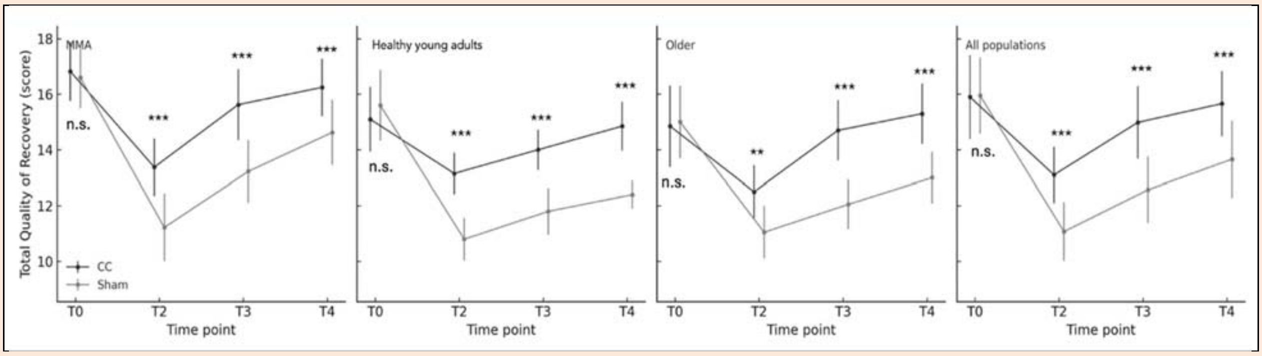

Figure 7. **Total quality recovery across time points (T0–T4).** CC: pneumatic cold compression. Between-conditions (CC vs. sham) differences per time point are indicated by asterisks (** $p < 0.010$; *** $p < 0.001$). n.s.: no significant. MMA, n = 40; young healthy adults, n = 20; Older, n = 20.

Perceived exertion and harms

Borg CR10 ratings recorded immediately after the fatigue protocol are shown in Table 2. Perceived exertion did not differ between CC and sham within any population. Population nevertheless remained a significant determinant of Borg ratings: compared with MMA athletes, older adults (OR = 19.44, $p < 0.001$) and young adults (OR = 8.10, $p < 0.001$) reported higher exertion, whereas the population-by-condition terms were non-significant. Accordingly, across conditions, MMA athletes reported lower exertion than both young adults and older adults, whereas the latter two groups did not differ materially from one another. No adverse events occurred in either condition, and no participant discontinued treatment or assessment because of pain, skin reaction, cold intolerance, or cardiovascular symptoms.

Discussion

Our results suggest that CC accelerated recovery following a standardized hamstring fatiguing task across three distinct populations. Relative to Sham, CC produced faster and larger restoration of MVC at 48 h (T4), lower hamstring stiffness during recovery, higher microvascular perfusion from immediately post-intervention through 48 h (T2 - T4), greater PPT, earlier reduction in blood lactate at T2, and higher TQR. All randomized participants completed both arms without adverse events, and effects were consistent across subgroups, supporting the robustness and generalizability of the treatment effect. An important interpretive point is that T2 was assessed immediately after the first intervention session and therefore does not represent recovery in isolation. At this timepoint, the observed differences may partly reflect acute physiological responses to cold and compression, including transient hemodynamic, sensory, and mechanical effects, rather than a sustained recovery benefit per se. Accordingly, T2 findings should be interpreted as an immediate post-intervention response, whereas T3 and T4 provide a more informative indication of the recovery trajectory over time.

CC substantially improved MVC recovery by 48 h, but the onset varied since MMA athletes and students showed earlier recovery (T2), whereas older adults exhibited delayed recovery (T3). The superiority of CC over Sham for MVC should be interpreted as an improvement in the recovery trajectory rather than full restoration of neuromuscular function. This distinction was especially important in older adults, in whom MVC under CC remained at only 69.0% of baseline at 48 h, indicating a persistent residual strength deficit despite the significant between-condition benefit. Generally, the results on CC and MVC are directionally consistent with contemporary meta-analytic evidence that cold-water immersion (a proxy for the cooling component of CC) can aid short-term recovery of strength following strenuous exercise (Moore et al., 2023). Previous meta-analysis similarly reported modest but significant benefits of cold-water immersion on post-exercise performance (Leeder et al., 2012), supporting the plausibility of cooling-assisted recovery of force. The compression component of CC is also plausible, as external pneumatic compression has been shown to improve acute recovery of anaerobic power and to accelerate post-exercise lactate removal in randomized crossover designs (Martin et al., 2015). Micro-mobile compression, which uses a wearable foot-pump device to deliver intermittent, low-intensity compressive pulses to the plantar venous plexus during non-weight-bearing rest, has likewise augmented lactate clearance and modestly improved subsequent performance in trained cyclists (Miller et al., 2013). Such findings resonate with our results, where CC not only hastened MVC recovery but also promoted significantly faster lactate clearance at T2 compared with Sham. The convergence of improved metabolite washout and restoration of force suggests that compression-enhanced circulatory dynamics may contribute to the superior contractile recovery observed under CC. Evidence from a clinical trial (Quesnot et al., 2024) indicates that adding dynamic compression to cryotherapy yields superior functional recovery and symptom control compared with cryotherapy alone in postoperative care, supporting synergy between the two modalities that may translate to exercise-recovery contexts.

Hamstring stiffness rose after the fatiguing task and remained consistently lower under CC than Sham from T2 through T4, indicating faster mechanical recovery with cold-compression. However, stiffness did not return to baseline by 48 h in either condition. Accordingly, the present results support accelerated or partial recovery rather than complete mechanical restoration within the observation period. This should be interpreted in light of the relatively short 48 h follow-up, which may not have been sufficient to capture the full time course of recovery. Post-exercise increases in passive muscle stiffness over 24 - 96 h are well documented with myotonometry (Kong et al., 2018). Randomized evidence shows intermittent pneumatic compression decreases post-exercise swelling and stiffness after eccentric muscle injury, aligning with our between-condition differences favoring CC at later time points (Chleboun et al., 1995). Possibly, external compression reduces interstitial fluid and edema and can improve limb hemodynamics pathways that plausibly lower passive tension of muscle and fascia during recovery (Partsch, 2012). By possibly reducing interstitial fluid and passive muscle tension while improving microvascular supply, CC likely created a more favorable contractile milieu, helping translate mechanical normalization into greater voluntary force restoration at 48 h. Subgroup analyses revealed that overall effects were consistent across participants, although the magnitude differed, since MMA athletes showed the highest absolute stiffness values at all-time points, older adults were intermediate, and students consistently exhibited the lowest values. Importantly, in each population, CC produced significantly lower stiffness than Sham from T2 onward, suggesting a broadly effective recovery mechanism regardless of training background or age. However, the present study did not directly quantify edema, interstitial fluid shifts, fascial mechanics, or intramuscular hemodynamics. Therefore, interpretation should remain cautious. It is plausible that the combined cooling-compression stimulus may have influenced tissue-fluid distribution and transient vascular dynamics, thereby contributing to the lower stiffness observed under CC, but this mechanism cannot be confirmed from the current data alone.

CC yielded higher perfusion units from T2 - T4 than Sham, which is plausible given that compression acutely increases limb blood flow during and after exercise (Zuj et al., 2018). Although perfusion improved under CC from T2 onward, subgroup analyses indicated earlier changes in MMA athletes and young adults, whereas older adults responded later. This may reflect vascular aging and slower microcirculatory adaptation. Recent work using cryo-compression in combat-sport athletes reports favorable acute changes in tissue properties and perfusion, consistent with our direction of effect under a combined cooling-compression stimulus (Trybulski et al., 2024a). Prior study indicates that intermittent pneumatic compression can transiently increase blood-flow velocity during application, particularly at higher pressures, but these hemodynamic changes may diminish rapidly after treatment (Maia et al., 2024). Thus, our perfusion findings are consistent with a possible acute vascular contribution of compression, but they do not establish sustained improvement in limb hemodynamics as a direct mechanism of recovery.

CC increased pressure pain thresholds, again with earlier improvements in MMA athletes and young adults and delayed improvements in older adults, consistent with both cryotherapy-induced hypoalgesia and compression-related modulation of soreness. General improvements after CC are consistent with cryotherapy-induced hypoalgesia (Algafly and George, 2007). Possibly, local cooling can increase mechanical pain thresholds while concurrently slowing sensory nerve conduction (Algafly and George, 2007), providing a direct physiological substrate for the PPT improvements we observed. Reductions in sensory nerve conduction velocity with common cooling methods (ice massage, packs, cold-water immersion) are substantial, supporting analgesia that may lessen inhibitory drive on voluntary contraction during recovery (Herrera et al., 2010). These effects are consistent with the known hypoalgesic effects of cooling, including reduced receptor sensitivity and slower nerve conduction velocity, although the present design cannot isolate the relative contribution of cooling versus compression. It is therefore more appropriate to interpret these findings as evidence of a favorable perceptual and sensory response to the combined intervention, rather than proof of a specific underlying neural mechanism.

These findings suggest that the PPT improvements under CC are more likely attributable to the combined cryo-compression stimulus than to compression alone (Draper, 2020). Additionally, perceived recovery improved with CC, yet effects varied: strong and consistent in MMA athletes, more modest in young healthy adults, and transient in older adults. This indicates that subjective benefits may be influenced by training background and recovery expectations. Our overall findings accord with evidence that cryotherapy improves subjective recovery and reduces DOMS within the 24 - 48 h window after strenuous exercise. For the compression component, randomized and systematic evidence suggests intermittent pneumatic compression can reduce perceived soreness in some contexts (Hoffman et al., 2016; Cranston and Driller, 2022). Cooling may also increase pain threshold and tolerance while slowing sensory nerve conduction, offering a justification for improved perceptual recovery after CC (Algafly and George, 2007).

Several limitations warrant consideration. This study has some limitations. First, the achieved sample (n = 80) was smaller than the original a priori target (n = 117), and the subgroup allocation was unequal (40 MMA athletes, 20 young adults, and 20 older adults). This reflected feasibility constraints, including multicenter logistics, the predefined recruitment window, and the limited availability of elite MMA athletes, who represented the population of greatest applied interest in this study. Although the crossover design increased statistical efficiency by allowing within-participant comparisons and all enrolled participants completed both periods, the reduced and unbalanced sample still limits precision, particularly for between-population comparisons. Therefore, subgroup findings should be interpreted as exploratory and confirmed in larger, prospectively powered studies with more balanced allocation.

Moreover, while myotonometry provided a valid and reliable index of muscle stiffness, this approach does not capture deeper muscle or tendon adaptations, and we did not employ shear-wave elastography or MRI to complement mechanical data. Also, our trial design did not include direct biochemical markers of inflammation (e.g., cytokines) or imaging of intramuscular blood flow, restricting mechanistic inference. Third, we standardized the device set-points (3 °C cold mode, high intermittent compression nominally targeting 75 mmHg) but did not directly measure individual skin or intramuscular temperatures, nor did we log real-time cuff pressures at the limb. As a result, we cannot quantify the actual mechanothermal dose delivered at the tissue level or examine inter-individual variability in temperature or pressure responses. This limitation constrains interpretation and means that our findings should be interpreted as effects of a pragmatic device protocol rather than of a precisely characterized thermal and mechanical dose. Finally, the intervention was delivered with a single commercial device under a fixed protocol; whether alternative cooling temperatures, pressures, or application schedules yield similar results remains to be clarified.

Despite the limitations, our findings suggest that CC can be integrated as a safe and effective recovery modality across populations spanning elite athletes to older active adults. In high-performance sport, CC may facilitate more rapid restoration of strength, muscle mechanics, and pain thresholds, supporting readiness for subsequent training or competition. In clinical or rehabilitation settings, particularly in older populations, cryo-compression may provide a non-pharmacological strategy to enhance comfort, vascular supply, and perceived recovery after strenuous activity or therapy. Importantly, the protocol we used (cooling at 3 °C with 75 mmHg intermittent compression for 10 minutes, twice daily across 3 days) was both feasible and well tolerated, offering a replicable template for practitioners. The convergence of physiological, perceptual, and functional benefits emphasizes the value of CC as an adjunct recovery tool that can complement, but not replace, other strategies such as active recovery, nutrition, and sleep. However, CC improved the short-term recovery trajectory after eccentric exercise, although complete recovery of muscle stiffness was not observed within 48 h.

Conclusion

This multicenter, randomized, sham-controlled, crossover trial demonstrated that CC accelerates recovery following hamstring fatigue across elite mixed martial arts athletes, healthy young adults, and physically active older adults. Compared with Sham, CC enhanced restoration of maximal voluntary contraction, reduced post-exercise muscle stiffness, improved microvascular perfusion, elevated pressure pain thresholds, facilitated early lactate clearance, and increased subjective recovery. While benefits were observed in all groups, their onset differed: athletes and young adults showed earlier gains, whereas older adults responded later but achieved comparable improvements by 48 h. These findings underscore both the broad applicability of CC and the influence of age and training status on recovery dynamics. Further research should refine dosing parameters, integrate mechanistic biomarkers, and benchmark CC against other recovery modalities.

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The authors have no funding to disclose. The authors declare no conflicts of interest. The datasets generated during the current study are not publicly available but are available from the corresponding author upon reasonable request. All experimental procedures were conducted in compliance with the relevant legal and ethical standards of the country where the study was carried out. The authors declare that no Generative AI or AI-assisted technologies were used in the writing of this manuscript.

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Key points

- Pneumatic cryo-compression (3 °C) improved hamstring recovery versus sham, with faster benefits in young/MMA athletes and delayed effects in older adults, and no adverse events.
- A 10-min protocol twice daily for 3 days is a practical adjunct after heavy eccentric hamstring work, but expect slower onset in older adults.
- Results may not generalize to injured/high-risk patients or other devices/doses.

✉ **Filipe Clemente**
Department of Biomechanics and Sport Engineering, Gdansk University of Physical Education and Sport, Gdansk, Poland

AUTHOR BIOGRAPHY

Robert TRYBULSKI

Employment

Upper Silesian University in Katowice, Poland and Provita Medical Centre, Żory, Poland

Degree

Ph.D.

Research interests

Sports medicine; physiotherapy; rehabilitation.

E-mail: roberttrybulski@proton.me

Adrian KUŻDŻAŁ

Employment

Inst. of Physiotherapy, Faculty of Health Sciences and Psychology, Collegium Medicum, Univ. of Rzeszów, Poland

Degree

Ph.D.

Research interests

Sports medicine; physiotherapy; rehabilitation

E-mail: akuzdzal@ur.edu.pl

Gracjan OLANISZYN

Employment

Degree

MSc

Research interests

Sports medicine; physiotherapy; rehabilitation

E-mail: gracjan.olaniszyn@wp.pl

Ana Filipa SILVA

Employment

Faculty of Sport Sciences and Physical Education, University of Coimbra, Coimbra, Portugal

Degree

Ph.D.

Research interests

Sports medicine; physical exercise; sports training

E-mail: anafilsilva@gmail.com

Filipe Manuel CLEMENTE Employment

Depart. of Biomechanics and Sport Engineering, Gdansk University of Physical Education and Sport, Gdansk, Poland

Degree

Ph.D.

Research interests

Sports training; sports performance; recovery.

E-mail: filipe.clemente5@gmail.com

Wang HSING-KUO

Employment

School and Graduate Institute of Physical Therapy, National Taiwan University, Taipei and Center of Physical Therapy, National Taiwan University Hospital, Taipei

Degree

Ph.D.

Research interests

Sports medicine; physiotherapy; rehabilitation

E-mail: hkwang@ntu.edu.tw

Supplementary Material 1.

Supplementary Table S1. Maximal voluntary contraction (MVC, N).

Panel A. Observed values and paired between-condition contrasts.

Population	Time	CC (mean ± SD)	Sham (mean ± SD)	Mean difference (CC−Sham)	95% CI	Statistic	Effect size	p_adj
All participants	T0	688.22 ± 135.83	688.37 ± 145.68	-0.15	-18.52 to 18.22	t(79)=-0.02	0.00	1.000
All participants	T1	492.93 ± 118.94	491.96 ± 123.58	0.97	-13.75 to 15.69	t(79)=0.13	0.01	1.000
All participants	T2	548.61 ± 137.56	492.70 ± 123.70	55.91	39.64 to 72.18	t(79)=6.84	0.76	<0.001
All participants	T3	593.81 ± 157.09	522.04 ± 156.02	71.77	55.32 to 88.22	t(79)=8.69	0.97	<0.001
All participants	T4	592.54 ± 181.74	504.66 ± 207.72	87.88	68.68 to 107.09	t(79)=9.11	1.02	<0.001
MMA athletes	T0	785.90 ± 61.37	792.58 ± 84.99	-6.67	-36.95 to 23.60	t(39)=-0.45	-0.07	1.000
MMA athletes	T1	588.77 ± 49.64	589.78 ± 71.14	-1.01	-26.40 to 24.39	t(39)=-0.08	-0.01	1.000
MMA athletes	T2	662.47 ± 55.18	590.27 ± 72.34	72.20	45.05 to 99.36	t(39)=5.38	0.85	<0.001
MMA athletes	T3	727.46 ± 56.80	655.16 ± 71.06	72.30	45.75 to 98.85	t(39)=5.51	0.87	<0.001
MMA athletes	T4	754.95 ± 59.95	695.21 ± 75.05	59.74	31.69 to 87.79	t(39)=4.31	0.68	<0.001
Young adults	T0	607.30 ± 115.82	595.75 ± 112.20	11.55	-19.52 to 42.62	t(19)=0.78	0.17	1.000
Young adults	T1	422.34 ± 84.63	415.50 ± 75.83	6.85	-17.33 to 31.02	t(19)=0.59	0.13	1.000
Young adults	T2	459.92 ± 90.32	416.02 ± 77.83	43.89	17.81 to 69.98	t(19)=3.52	0.79	0.011
Young adults	T3	494.92 ± 94.63	424.86 ± 84.99	70.06	39.17 to 100.95	t(19)=4.75	1.06	<0.001
Young adults	T4	463.61 ± 89.94	363.90 ± 80.36	99.70	64.48 to 134.92	t(19)=5.93	1.32	<0.001
Older adults	T0	573.76 ± 121.63	572.56 ± 121.74	1.20	-32.82 to 35.23	t(19)=0.07	0.02	1.000
Older adults	T1	371.85 ± 81.14	372.80 ± 78.17	-0.95	-24.47 to 22.57	t(19)=-0.08	-0.02	1.000
Older adults	T2	409.56 ± 91.37	374.23 ± 76.27	35.33	9.05 to 61.62	t(19)=2.81	0.63	0.055
Older adults	T3	425.40 ± 96.29	352.98 ± 79.29	72.42	42.06 to 102.77	t(19)=4.99	1.12	<0.001
Older adults	T4	396.64 ± 91.83	264.29 ± 57.18	132.35	97.29 to 167.41	t(19)=7.90	1.77	<0.001

Panel B. Within-condition temporal contrasts.

Population	Condition	Contrast	Mean change	95% CI	Statistic	Effect size	p_adj
All participants	CC	T1−T0	-195.28	-202.47 to -188.09	t(79)=-54.08	-6.05	<0.001
All participants	CC	T2−T1	55.67	51.06 to 60.28	t(79)=24.02	2.69	<0.001
All participants	CC	T3−T1	100.88	90.71 to 111.04	t(79)=19.75	2.21	<0.001
All participants	CC	T4−T1	99.60	83.50 to 115.71	t(79)=12.31	1.38	<0.001
All participants	Sham	T1−T0	-196.40	-203.98 to -188.82	t(79)=-51.60	-5.77	<0.001
All participants	Sham	T2−T1	0.73	-1.07 to 2.53	t(79)=0.81	0.09	1.000
All participants	Sham	T3−T1	30.07	20.54 to 39.61	t(79)=6.28	0.70	<0.001
All participants	Sham	T4−T1	12.69	-9.51 to 34.89	t(79)=1.14	0.13	1.000
MMA athletes	CC	T1−T0	-197.13	-204.57 to -189.68	t(39)=-53.57	-8.47	<0.001
MMA athletes	CC	T2−T1	73.70	71.17 to 76.22	t(39)=59.07	9.34	<0.001
MMA athletes	CC	T3−T1	138.69	131.23 to 146.14	t(39)=37.63	5.95	<0.001
MMA athletes	CC	T4−T1	166.18	158.86 to 173.49	t(39)=45.96	7.27	<0.001
MMA athletes	Sham	T1−T0	-202.79	-209.50 to -196.08	t(39)=-61.14	-9.67	<0.001
MMA athletes	Sham	T2−T1	0.49	-1.75 to 2.72	t(39)=0.44	0.07	1.000
MMA athletes	Sham	T3−T1	65.38	59.25 to 71.50	t(39)=21.58	3.41	<0.001
MMA athletes	Sham	T4−T1	105.43	100.04 to 110.83	t(39)=39.52	6.25	<0.001
Young adults	CC	T1−T0	-184.96	-201.57 to -168.36	t(19)=-23.31	-5.21	<0.001
Young adults	CC	T2−T1	37.58	31.73 to 43.42	t(19)=13.46	3.01	<0.001
Young adults	CC	T3−T1	72.58	60.11 to 85.05	t(19)=12.18	2.72	<0.001
Young adults	CC	T4−T1	41.27	24.48 to 58.05	t(19)=5.15	1.15	<0.001
Young adults	Sham	T1−T0	-180.26	-198.51 to -162.01	t(19)=-20.67	-4.62	<0.001
Young adults	Sham	T2−T1	0.53	-4.36 to 5.41	t(19)=0.23	0.05	1.000
Young adults	Sham	T3−T1	9.37	-2.87 to 21.60	t(19)=1.60	0.36	0.502
Young adults	Sham	T4−T1	-51.59	-67.78 to -35.40	t(19)=-6.67	-1.49	<0.001
Older adults	CC	T1−T0	-201.91	-221.77 to -182.05	t(19)=-21.28	-4.76	<0.001
Older adults	CC	T2−T1	37.72	32.29 to 43.15	t(19)=14.53	3.25	<0.001
Older adults	CC	T3−T1	53.55	41.66 to 65.44	t(19)=9.42	2.11	<0.001
Older adults	CC	T4−T1	24.79	13.22 to 36.37	t(19)=4.48	1.00	0.001
Older adults	Sham	T1−T0	-199.76	-220.81 to -178.71	t(19)=-19.86	-4.44	<0.001
Older adults	Sham	T2−T1	1.43	-2.26 to 5.12	t(19)=0.81	0.18	1.000
Older adults	Sham	T3−T1	-19.82	-30.31 to -9.33	t(19)=-3.96	-0.88	0.003

Panel C. Between-population comparison of condition effects.

Time	Mean diff, MMA	Mean diff, Young	Mean diff, Older	Statistic	Effect size	p_adj
T0	-6.67	11.55	1.20	F(2, 77)=0.32	0.01	1.000
T1	-1.01	6.85	-0.95	F(2, 77)=0.10	0.00	1.000
T2	72.20	43.89	35.33	F(2, 77)=2.11	0.05	0.638
T3	72.30	70.06	72.42	F(2, 77)=0.01	0.00	1.000
T4	-6.67	11.55	1.20	F(2, 77)=0.32	0.01	1.000

Effect size denotes Cohen’s dz in paired contrasts and eta squared (η^2) in one-way ANOVA models. Mean change in Panel B is calculated as the later time point minus the earlier time point shown in the contrast label.

Supplementary Table S2. Muscle stiffness (N/m).

Panel A. Observed values and paired between-condition contrasts

Population	Time	CC (mean ± SD)	Sham (mean ± SD)	Mean difference (CC−Sham)	95% CI	Statistic	Effect size	p_adj
All participants	T0	262.47 ± 18.55	262.06 ± 18.47	0.41	-2.68 to 3.51	t(79)=0.27	0.03	1.000
All participants	T1	354.72 ± 11.99	354.74 ± 12.69	-0.02	-3.41 to 3.37	t(79)=-0.01	0.00	1.000
All participants	T2	304.47 ± 12.99	361.91 ± 11.85	-57.44	-61.05 to -53.82	t(79)=-31.64	-3.54	<0.001
All participants	T3	249.54 ± 9.05	287.98 ± 13.34	-38.45	-42.18 to -34.71	t(79)=-20.47	-2.29	<0.001
All participants	T4	326.62 ± 12.92	388.57 ± 20.05	-61.95	-67.45 to -56.44	t(79)=-22.39	-2.50	<0.001
MMA athletes	T0	277.31 ± 9.29	276.37 ± 10.56	0.94	-3.94 to 5.82	t(39)=0.39	0.06	1.000
MMA athletes	T1	360.41 ± 13.52	360.24 ± 14.90	0.17	-6.42 to 6.76	t(39)=0.05	0.01	1.000
MMA athletes	T2	295.64 ± 11.42	360.27 ± 15.08	-64.63	-70.74 to -58.51	t(39)=-21.38	-3.38	<0.001
MMA athletes	T3	252.29 ± 9.46	279.04 ± 11.65	-26.76	-31.72 to -21.80	t(39)=-10.91	-1.72	<0.001
MMA athletes	T4	322.93 ± 11.22	401.66 ± 16.67	-78.74	-85.58 to -71.90	t(39)=-23.29	-3.68	<0.001
Young adults	T0	257.35 ± 9.07	255.29 ± 10.36	2.06	-4.23 to 8.36	t(19)=0.69	0.15	1.000
Young adults	T1	353.68 ± 4.14	353.33 ± 4.22	0.35	-2.34 to 3.04	t(19)=0.27	0.06	1.000
Young adults	T2	317.82 ± 6.49	367.71 ± 5.80	-49.90	-53.77 to -46.02	t(19)=-26.97	-6.03	<0.001
Young adults	T3	253.53 ± 3.33	301.82 ± 5.72	-48.28	-51.49 to -45.08	t(19)=-31.54	-7.05	<0.001
Young adults	T4	341.96 ± 6.14	383.40 ± 11.13	-41.44	-47.76 to -35.12	t(19)=-13.72	-3.07	<0.001
Older adults	T0	237.92 ± 6.79	240.20 ± 10.01	-2.28	-7.70 to 3.15	t(19)=-0.88	-0.20	1.000
Older adults	T1	344.37 ± 4.82	345.15 ± 5.75	-0.78	-4.40 to 2.84	t(19)=-0.45	-0.10	1.000
Older adults	T2	308.77 ± 4.53	359.37 ± 5.97	-50.60	-54.23 to -46.98	t(19)=-29.24	-6.54	<0.001
Older adults	T3	240.04 ± 4.23	292.03 ± 6.47	-51.99	-55.28 to -48.69	t(19)=-33.04	-7.39	<0.001
Older adults	T4	318.68 ± 7.41	367.54 ± 11.04	-48.86	-55.62 to -42.11	t(19)=-15.13	-3.38	<0.001

Panel B. Within-condition temporal contrasts

Population	Condition	Contrast	Mean change	95% CI	Statistic	Effect size	p_adj
All participants	CC	T1−T0	92.24	89.41 to 95.08	t(79)=64.73	7.24	<0.001
All participants	CC	T2−T1	-50.25	-53.75 to -46.76	t(79)=-28.62	-3.20	<0.001
All participants	CC	T3−T1	-105.18	-106.46 to -103.90	t(79)=-163.44	-18.27	<0.001
All participants	CC	T4−T1	-28.10	-30.94 to -25.25	t(79)=-19.65	-2.20	<0.001
All participants	Sham	T1−T0	92.68	89.85 to 95.51	t(79)=65.22	7.29	<0.001
All participants	Sham	T2−T1	7.17	5.13 to 9.20	t(79)=7.01	0.78	<0.001
All participants	Sham	T3−T1	-66.76	-70.25 to -63.26	t(79)=-38.03	-4.25	<0.001
All participants	Sham	T4−T1	33.83	30.93 to 36.72	t(79)=23.27	2.60	<0.001
MMA athletes	CC	T1−T0	83.10	81.12 to 85.08	t(39)=84.96	13.43	<0.001
MMA athletes	CC	T2−T1	-64.77	-66.06 to -63.47	t(39)=-101.22	-16.00	<0.001
MMA athletes	CC	T3−T1	-108.12	-109.42 to -106.83	t(39)=-168.65	-26.67	<0.001
MMA athletes	CC	T4−T1	-37.48	-39.18 to -35.79	t(39)=-44.71	-7.07	<0.001
MMA athletes	Sham	T1−T0	83.86	81.95 to 85.78	t(39)=88.72	14.03	<0.001
MMA athletes	Sham	T2−T1	0.03	-1.01 to 1.07	t(39)=0.06	0.01	1.000
MMA athletes	Sham	T3−T1	-81.19	-82.88 to -79.51	t(39)=-97.37	-15.40	<0.001
MMA athletes	Sham	T4−T1	41.43	38.84 to 44.01	t(39)=32.39	5.12	<0.001
Young adults	CC	T1−T0	96.33	91.13 to 101.53	t(19)=38.78	8.67	<0.001
Young adults	CC	T2−T1	-35.87	-40.10 to -31.63	t(19)=-17.73	-3.96	<0.001
Young adults	CC	T3−T1	-100.15	-102.81 to -97.49	t(19)=-78.90	-17.64	<0.001
Young adults	CC	T4−T1	-11.72	-14.91 to -8.54	t(19)=-7.70	-1.72	<0.001
Young adults	Sham	T1−T0	98.04	93.26 to 102.82	t(19)=42.89	9.59	<0.001
Young adults	Sham	T2−T1	14.38	11.42 to 17.35	t(19)=10.15	2.27	<0.001
Young adults	Sham	T3−T1	-51.52	-54.27 to -48.76	t(19)=-39.16	-8.76	<0.001
Young adults	Sham	T4−T1	30.07	24.39 to 35.75	t(19)=11.08	2.48	<0.001
Older adults	CC	T1−T0	106.45	102.60 to 110.30	t(19)=57.93	12.95	<0.001
Older adults	CC	T2−T1	-35.61	-37.83 to -33.39	t(19)=-33.58	-7.51	<0.001
Older adults	CC	T3−T1	-104.33	-106.73 to -101.94	t(19)=-91.20	-20.39	<0.001
Older adults	CC	T4−T1	-25.70	-30.43 to -20.97	t(19)=-11.37	-2.54	<0.001
Older adults	Sham	T1−T0	104.95	99.38 to 110.52	t(19)=39.47	8.82	<0.001
Older adults	Sham	T2−T1	14.22	10.27 to 18.17	t(19)=7.53	1.68	<0.001
Older adults	Sham	T3−T1	-53.12	-56.58 to -49.67	t(19)=-32.20	-7.20	<0.001
Older adults	Sham	T4−T1	22.39	16.72 to 28.06	t(19)=8.26	1.85	<0.001

Panel C. Between-population comparison of condition effects.

Time	Mean diff, MMA	Mean diff, Young	Mean diff, Older	Statistic	Effect size	p_adj
T0	0.94	2.06	-2.28	F(2, 77)=0.54	0.01	1.000
T1	0.17	0.35	-0.78	F(2, 77)=0.03	0.00	1.000
T2	-64.63	-49.90	-50.60	F(2, 77)=9.54	0.20	<0.001
T3	-26.76	-48.28	-51.99	F(2, 77)=37.97	0.50	<0.001
T4	-78.74	-41.44	-48.86	F(2, 77)=35.22	0.48	<0.001

Effect size denotes Cohen's dz in paired contrasts and eta squared (η^2) in one-way ANOVA models. Mean change in Panel B is calculated as the later time point minus the earlier time point shown in the contrast label.

Supplementary Table S3. **Microvascular perfusion (PU).**

Panel A. **Observed values and paired between-condition contrasts.**

Population	Time	CC (mean ± SD)	Sham (mean ± SD)	Mean difference (CC−Sham)	95% CI	Statistic	Effect size	p_adj
All participants	T0	25.04 ± 1.83	25.14 ± 2.05	-0.10	-0.34 to 0.15	t(79)=-0.79	-0.09	1.000
All participants	T1	30.98 ± 1.96	31.04 ± 2.33	-0.05	-0.47 to 0.36	t(79)=-0.26	-0.03	1.000
All participants	T2	33.44 ± 2.89	26.40 ± 2.87	7.03	6.30 to 7.76	t(79)=19.17	2.14	<0.001
All participants	T3	26.09 ± 2.38	25.07 ± 2.17	1.02	0.75 to 1.29	t(79)=7.41	0.83	<0.001
All participants	T4	25.93 ± 2.48	24.83 ± 2.42	1.09	0.80 to 1.39	t(79)=7.29	0.82	<0.001
MMA athletes	T0	26.55 ± 0.80	26.75 ± 1.01	-0.20	-0.58 to 0.17	t(39)=-1.09	-0.17	1.000
MMA athletes	T1	32.44 ± 1.28	32.78 ± 1.52	-0.34	-1.00 to 0.32	t(39)=-1.03	-0.16	1.000
MMA athletes	T2	35.69 ± 1.72	27.97 ± 1.52	7.71	6.91 to 8.52	t(39)=19.36	3.06	<0.001
MMA athletes	T3	28.15 ± 0.84	26.76 ± 1.03	1.39	1.01 to 1.77	t(39)=7.35	1.16	<0.001
MMA athletes	T4	28.13 ± 0.88	27.03 ± 1.04	1.10	0.69 to 1.50	t(39)=5.50	0.87	<0.001
Young adults	T0	24.43 ± 0.70	24.72 ± 0.74	-0.29	-0.78 to 0.19	t(19)=-1.27	-0.28	1.000
Young adults	T1	30.30 ± 0.93	30.38 ± 1.21	-0.08	-0.84 to 0.69	t(19)=-0.21	-0.05	1.000
Young adults	T2	31.85 ± 1.53	27.01 ± 1.78	4.84	3.46 to 6.22	t(19)=7.34	1.64	<0.001
Young adults	T3	25.16 ± 0.82	24.71 ± 0.81	0.45	-0.13 to 1.03	t(19)=1.61	0.36	0.617
Young adults	T4	24.64 ± 0.88	22.91 ± 0.91	1.72	0.99 to 2.46	t(19)=4.89	1.09	<0.001
Older adults	T0	22.64 ± 0.94	22.33 ± 0.91	0.31	-0.13 to 0.75	t(19)=1.49	0.33	0.759
Older adults	T1	28.75 ± 1.24	28.22 ± 1.10	0.54	-0.18 to 1.25	t(19)=1.57	0.35	0.665
Older adults	T2	30.52 ± 1.99	22.65 ± 2.42	7.87	5.98 to 9.75	t(19)=8.72	1.95	<0.001
Older adults	T3	22.91 ± 0.98	22.06 ± 1.08	0.85	0.35 to 1.36	t(19)=3.53	0.79	0.011
Older adults	T4	22.82 ± 1.08	22.36 ± 0.90	0.46	0.01 to 0.90	t(19)=2.16	0.48	0.219

Panel B. **Within-condition temporal contrasts.**

Population	Condition	Contrast	Mean change	95% CI	Statistic	Effect size	p_adj
All participants	CC	T1−T0	5.94	5.78 to 6.09	t(79)=76.76	8.58	<0.001
All participants	CC	T2−T1	2.45	2.14 to 2.76	t(79)=15.77	1.76	<0.001
All participants	CC	T3−T1	-4.89	-5.11 to -4.67	t(79)=-44.29	-4.95	<0.001
All participants	CC	T4−T1	-5.06	-5.30 to -4.82	t(79)=-41.94	-4.69	<0.001
All participants	Sham	T1−T0	5.90	5.74 to 6.06	t(79)=74.08	8.28	<0.001
All participants	Sham	T2−T1	-4.63	-4.97 to -4.30	t(79)=-27.70	-3.10	<0.001
All participants	Sham	T3−T1	-5.96	-6.13 to -5.80	t(79)=-71.00	-7.94	<0.001
All participants	Sham	T4−T1	-6.20	-6.45 to -5.95	t(79)=-49.26	-5.51	<0.001
MMA athletes	CC	T1−T0	5.89	5.63 to 6.15	t(39)=46.15	7.30	<0.001
MMA athletes	CC	T2−T1	3.25	3.02 to 3.48	t(39)=28.60	4.52	<0.001
MMA athletes	CC	T3−T1	-4.29	-4.56 to -4.02	t(39)=-32.21	-5.09	<0.001
MMA athletes	CC	T4−T1	-4.31	-4.58 to -4.05	t(39)=-33.16	-5.24	<0.001
MMA athletes	Sham	T1−T0	6.03	5.76 to 6.30	t(39)=45.13	7.14	<0.001
MMA athletes	Sham	T2−T1	-4.80	-5.04 to -4.56	t(39)=-40.31	-6.37	<0.001
MMA athletes	Sham	T3−T1	-6.02	-6.29 to -5.75	t(39)=-44.82	-7.09	<0.001
MMA athletes	Sham	T4−T1	-5.75	-6.04 to -5.46	t(39)=-40.48	-6.40	<0.001
Young adults	CC	T1−T0	5.87	5.65 to 6.08	t(19)=57.87	12.94	<0.001
Young adults	CC	T2−T1	1.55	1.01 to 2.09	t(19)=6.00	1.34	<0.001
Young adults	CC	T3−T1	-5.14	-5.40 to -4.87	t(19)=-39.98	-8.94	<0.001
Young adults	CC	T4−T1	-5.66	-5.99 to -5.33	t(19)=-36.25	-8.11	<0.001
Young adults	Sham	T1−T0	5.65	5.37 to 5.93	t(19)=42.55	9.51	<0.001
Young adults	Sham	T2−T1	-3.37	-3.96 to -2.78	t(19)=-11.92	-2.67	<0.001
Young adults	Sham	T3−T1	-5.66	-5.96 to -5.37	t(19)=-40.01	-8.95	<0.001
Young adults	Sham	T4−T1	-7.46	-7.89 to -7.03	t(19)=-36.32	-8.12	<0.001
Older adults	CC	T1−T0	6.11	5.81 to 6.41	t(19)=42.85	9.58	<0.001
Older adults	CC	T2−T1	1.76	0.96 to 2.57	t(19)=4.58	1.02	<0.001
Older adults	CC	T3−T1	-5.84	-6.17 to -5.51	t(19)=-37.14	-8.30	<0.001
Older adults	CC	T4−T1	-5.94	-6.30 to -5.58	t(19)=-34.48	-7.71	<0.001
Older adults	Sham	T1−T0	5.89	5.68 to 6.09	t(19)=60.06	13.43	<0.001
Older adults	Sham	T2−T1	-5.57	-6.49 to -4.65	t(19)=-12.63	-2.82	<0.001
Older adults	Sham	T3−T1	-6.15	-6.42 to -5.89	t(19)=-48.28	-10.80	<0.001
Older adults	Sham	T4−T1	-5.86	-6.21 to -5.51	t(19)=-35.30	-7.89	<0.001

Panel C. **Between-population comparison of condition effects.**

Time	Mean diff, MMA	Mean diff, Young	Mean diff, Older	Statistic	Effect size	p_adj
T0	-0.20	-0.29	0.31	F(2, 77)=1.94	0.05	0.753
T1	-0.34	-0.08	0.54	F(2, 77)=1.50	0.04	1.000
T2	7.71	4.84	7.87	F(2, 77)=6.86	0.15	0.009
T3	1.39	0.45	0.85	F(2, 77)=4.52	0.11	0.070
T4	1.10	1.72	0.46	F(2, 77)=4.87	0.11	0.051

Effect size denotes Cohen's dz in paired contrasts and eta squared (η^2) in one-way ANOVA models. Mean change in Panel B is calculated as the later time point minus the earlier time point shown in the contrast label.

Supplementary Table S4. **Pressure pain threshold (N/cm^2).**
Panel A. **Observed values and paired between-condition contrasts.**

Population	Time	CC (mean ± SD)	Sham (mean ± SD)	Mean difference (CC−Sham)	95% CI	Statistic	Effect size	p_adj
All participants	T0	80.26 ± 9.11	80.52 ± 7.86	-0.26	-1.94 to 1.42	t(79)=-0.30	-0.03	1.000
All participants	T1	59.20 ± 9.76	59.69 ± 8.40	-0.49	-1.97 to 0.99	t(79)=-0.66	-0.07	1.000
All participants	T2	63.73 ± 10.35	59.73 ± 8.39	4.00	2.38 to 5.63	t(79)=4.91	0.55	<0.001
All participants	T3	68.41 ± 9.91	64.89 ± 8.76	3.52	1.83 to 5.21	t(79)=4.15	0.46	<0.001
All participants	T4	66.64 ± 15.31	50.18 ± 11.91	16.46	14.52 to 18.41	t(79)=16.85	1.88	<0.001
MMA athletes	T0	87.23 ± 5.10	85.44 ± 5.74	1.79	-0.81 to 4.38	t(39)=1.39	0.22	0.856
MMA athletes	T1	67.00 ± 4.78	66.22 ± 4.58	0.79	-1.51 to 3.08	t(39)=0.69	0.11	1.000
MMA athletes	T2	71.94 ± 5.32	66.16 ± 4.72	5.79	3.33 to 8.24	t(39)=4.77	0.75	<0.001
MMA athletes	T3	75.31 ± 5.28	71.11 ± 5.04	4.20	1.69 to 6.71	t(39)=3.39	0.54	0.008
MMA athletes	T4	80.61 ± 4.70	59.81 ± 4.02	20.80	18.68 to 22.92	t(39)=19.84	3.14	<0.001
Young adults	T0	77.63 ± 4.97	79.43 ± 4.56	-1.81	-4.83 to 1.22	t(19)=-1.25	-0.28	1.000
Young adults	T1	56.45 ± 5.07	57.36 ± 4.17	-0.91	-4.15 to 2.32	t(19)=-0.59	-0.13	1.000
Young adults	T2	60.61 ± 5.54	57.44 ± 4.19	3.17	-0.22 to 6.56	t(19)=1.96	0.44	0.327
Young adults	T3	67.80 ± 6.31	64.12 ± 4.49	3.68	-0.20 to 7.55	t(19)=1.99	0.44	0.307
Young adults	T4	57.77 ± 4.98	48.33 ± 3.23	9.43	6.44 to 12.43	t(19)=6.59	1.47	<0.001
Older adults	T0	68.96 ± 4.77	71.74 ± 5.93	-2.79	-5.83 to 0.26	t(19)=-1.92	-0.43	0.352
Older adults	T1	46.35 ± 3.71	48.96 ± 4.00	-2.62	-4.82 to -0.41	t(19)=-2.48	-0.56	0.112
Older adults	T2	50.43 ± 4.31	49.16 ± 4.40	1.27	-1.40 to 3.94	t(19)=0.99	0.22	1.000
Older adults	T3	55.21 ± 5.22	53.21 ± 4.55	2.01	-1.02 to 5.04	t(19)=1.39	0.31	0.906
Older adults	T4	47.57 ± 5.26	32.75 ± 5.20	14.82	10.34 to 19.30	t(19)=6.92	1.55	<0.001

Panel B. **Within-condition temporal contrasts.**

Population	Condition	Contrast	Mean change	95% CI	Statistic	Effect size	p_adj
All participants	CC	T1−T0	-21.06	-21.69 to -20.43	t(79)=-66.87	-7.48	<0.001
All participants	CC	T2−T1	4.53	4.29 to 4.78	t(79)=36.76	4.11	<0.001
All participants	CC	T3−T1	9.21	8.78 to 9.64	t(79)=42.88	4.79	<0.001
All participants	CC	T4−T1	7.44	5.86 to 9.01	t(79)=9.40	1.05	<0.001
All participants	Sham	T1−T0	-20.83	-21.59 to -20.06	t(79)=-54.20	-6.06	<0.001
All participants	Sham	T2−T1	0.04	-0.17 to 0.25	t(79)=0.38	0.04	1.000
All participants	Sham	T3−T1	5.20	4.87 to 5.52	t(79)=31.92	3.57	<0.001
All participants	Sham	T4−T1	-9.51	-10.74 to -8.29	t(79)=-15.47	-1.73	<0.001
MMA athletes	CC	T1−T0	-20.23	-21.14 to -19.31	t(39)=-44.73	-7.07	<0.001
MMA athletes	CC	T2−T1	4.94	4.65 to 5.24	t(39)=33.84	5.35	<0.001
MMA athletes	CC	T3−T1	8.31	8.05 to 8.57	t(39)=64.01	10.12	<0.001
MMA athletes	CC	T4−T1	13.61	12.67 to 14.54	t(39)=29.46	4.66	<0.001
MMA athletes	Sham	T1−T0	-19.23	-20.24 to -18.21	t(39)=-38.43	-6.08	<0.001
MMA athletes	Sham	T2−T1	-0.06	-0.24 to 0.13	t(39)=-0.64	-0.10	1.000
MMA athletes	Sham	T3−T1	4.89	4.63 to 5.16	t(39)=37.41	5.91	<0.001
MMA athletes	Sham	T4−T1	-6.41	-7.21 to -5.60	t(39)=-16.03	-2.54	<0.001
Young adults	CC	T1−T0	-21.18	-22.24 to -20.12	t(19)=-41.79	-9.34	<0.001
Young adults	CC	T2−T1	4.16	3.61 to 4.70	t(19)=15.93	3.56	<0.001
Young adults	CC	T3−T1	11.35	10.44 to 12.26	t(19)=26.01	5.82	<0.001
Young adults	CC	T4−T1	1.32	-0.53 to 3.16	t(19)=1.49	0.33	0.605
Young adults	Sham	T1−T0	-22.07	-23.27 to -20.88	t(19)=-38.64	-8.64	<0.001
Young adults	Sham	T2−T1	0.08	-0.48 to 0.63	t(19)=0.29	0.07	1.000
Young adults	Sham	T3−T1	6.76	6.08 to 7.44	t(19)=20.71	4.63	<0.001
Young adults	Sham	T4−T1	-9.03	-10.81 to -7.25	t(19)=-10.60	-2.37	<0.001
Older adults	CC	T1−T0	-22.61	-23.85 to -21.37	t(19)=-38.05	-8.51	<0.001
Older adults	CC	T2−T1	4.08	3.57 to 4.60	t(19)=16.49	3.69	<0.001
Older adults	CC	T3−T1	8.87	7.99 to 9.74	t(19)=21.19	4.74	<0.001
Older adults	CC	T4−T1	1.22	-0.59 to 3.04	t(19)=1.41	0.32	0.695
Older adults	Sham	T1−T0	-22.78	-24.33 to -21.23	t(19)=-30.73	-6.87	<0.001
Older adults	Sham	T2−T1	0.20	-0.38 to 0.78	t(19)=0.72	0.16	1.000
Older adults	Sham	T3−T1	4.24	3.66 to 4.83	t(19)=15.21	3.40	<0.001
Older adults	Sham	T4−T1	-16.21	-18.80 to -13.63	t(19)=-13.15	-2.94	<0.001

Panel C. **Between-population comparison of condition effects.**

Time	Mean diff, MMA	Mean diff, Young	Mean diff, Older	Statistic	Effect size	p_adj
T0	1.79	-1.81	-2.79	F(2, 77)=3.18	0.08	0.236
T1	0.79	-0.91	-2.62	F(2, 77)=1.83	0.05	0.834
T2	5.79	3.17	1.27	F(2, 77)=2.86	0.07	0.317
T3	4.20	3.68	2.01	F(2, 77)=0.56	0.01	1.000
T4	20.80	9.43	14.82	F(2, 77)=16.31	0.30	<0.001

Effect size denotes Cohen's dz in paired contrasts and eta squared (η^2) in one-way ANOVA models. Mean change in Panel B is calculated as the later time point minus the earlier time point shown in the contrast label.

Supplementary Table S5. Blood lactate (mmol/L).

Panel A. Observed values and paired between-condition contrasts.

Population	Time	CC (mean ± SD)	Sham (mean ± SD)	Mean difference (CC−Sham)	95% CI	Statistic	Effect size	p_adj
All participants	T0	1.19 ± 0.17	1.17 ± 0.20	0.02	-0.03 to 0.07	t(79)=0.75	0.08	1.000
All participants	T1	6.62 ± 1.46	6.73 ± 1.61	-0.11	-0.49 to 0.27	t(79)=-0.57	-0.06	1.000
All participants	T2	2.64 ± 0.41	3.74 ± 0.52	-1.10	-1.17 to -1.03	t(79)=-31.18	-3.49	<0.001
All participants	T3	1.17 ± 0.19	1.18 ± 0.19	-0.01	-0.05 to 0.04	t(79)=-0.31	-0.03	1.000
All participants	T4	1.10 ± 0.21	1.13 ± 0.22	-0.04	-0.09 to 0.01	t(79)=-1.50	-0.17	0.687
MMA athletes	T0	1.10 ± 0.14	1.08 ± 0.15	0.02	-0.05 to 0.09	t(39)=0.61	0.10	1.000
MMA athletes	T1	5.79 ± 1.28	5.72 ± 1.22	0.07	-0.55 to 0.69	t(39)=0.22	0.04	1.000
MMA athletes	T2	2.27 ± 0.14	3.29 ± 0.15	-1.02	-1.09 to -0.95	t(39)=-30.66	-4.85	<0.001
MMA athletes	T3	1.05 ± 0.14	1.06 ± 0.15	-0.01	-0.07 to 0.06	t(39)=-0.22	-0.04	1.000
MMA athletes	T4	0.95 ± 0.16	1.00 ± 0.16	-0.04	-0.13 to 0.04	t(39)=-1.09	-0.17	1.000
Young adults	T0	1.23 ± 0.14	1.15 ± 0.14	0.08	-0.01 to 0.17	t(19)=1.79	0.40	0.449
Young adults	T1	7.25 ± 1.07	7.21 ± 1.10	0.04	-0.62 to 0.69	t(19)=0.11	0.03	1.000
Young adults	T2	2.90 ± 0.22	4.05 ± 0.27	-1.15	-1.31 to -1.00	t(19)=-15.52	-3.47	<0.001
Young adults	T3	1.25 ± 0.13	1.23 ± 0.13	0.02	-0.07 to 0.10	t(19)=0.36	0.08	1.000
Young adults	T4	1.19 ± 0.14	1.24 ± 0.14	-0.04	-0.13 to 0.04	t(19)=-1.03	-0.23	1.000
Older adults	T0	1.32 ± 0.18	1.36 ± 0.22	-0.04	-0.19 to 0.11	t(19)=-0.58	-0.13	1.000
Older adults	T1	7.66 ± 1.17	8.27 ± 1.29	-0.61	-1.28 to 0.06	t(19)=-1.91	-0.43	0.354
Older adults	T2	3.11 ± 0.19	4.31 ± 0.34	-1.20	-1.41 to -1.00	t(19)=-12.55	-2.81	<0.001
Older adults	T3	1.34 ± 0.18	1.37 ± 0.14	-0.03	-0.13 to 0.08	t(19)=-0.58	-0.13	1.000
Older adults	T4	1.29 ± 0.14	1.31 ± 0.22	-0.02	-0.12 to 0.08	t(19)=-0.45	-0.10	1.000

Panel B. Within-condition temporal contrasts.

Population	Condition	Contrast	Mean change	95% CI	Statistic	Effect size	p_adj
All participants	CC	T1−T0	5.44	5.13 to 5.74	t(79)=35.65	3.99	<0.001
All participants	CC	T2−T1	-3.98	-4.28 to -3.69	t(79)=-27.14	-3.03	<0.001
All participants	CC	T3−T1	-5.45	-5.76 to -5.14	t(79)=-35.17	-3.93	<0.001
All participants	CC	T4−T1	-5.53	-5.83 to -5.22	t(79)=-35.71	-3.99	<0.001
All participants	Sham	T1−T0	5.56	5.23 to 5.90	t(79)=33.00	3.69	<0.001
All participants	Sham	T2−T1	-2.99	-3.30 to -2.69	t(79)=-19.58	-2.19	<0.001
All participants	Sham	T3−T1	-5.55	-5.89 to -5.21	t(79)=-32.43	-3.63	<0.001
All participants	Sham	T4−T1	-5.60	-5.94 to -5.25	t(79)=-32.03	-3.58	<0.001
MMA athletes	CC	T1−T0	4.69	4.31 to 5.06	t(39)=25.31	4.00	<0.001
MMA athletes	CC	T2−T1	-3.52	-3.93 to -3.11	t(39)=-17.37	-2.75	<0.001
MMA athletes	CC	T3−T1	-4.74	-5.14 to -4.34	t(39)=-23.91	-3.78	<0.001
MMA athletes	CC	T4−T1	-4.84	-5.25 to -4.43	t(39)=-23.85	-3.77	<0.001
MMA athletes	Sham	T1−T0	4.64	4.28 to 5.00	t(39)=26.35	4.17	<0.001
MMA athletes	Sham	T2−T1	-2.43	-2.82 to -2.03	t(39)=-12.35	-1.95	<0.001
MMA athletes	Sham	T3−T1	-4.66	-5.05 to -4.27	t(39)=-24.18	-3.82	<0.001
MMA athletes	Sham	T4−T1	-4.72	-5.12 to -4.32	t(39)=-23.88	-3.78	<0.001
Young adults	CC	T1−T0	6.02	5.50 to 6.55	t(19)=24.15	5.40	<0.001
Young adults	CC	T2−T1	-4.35	-4.86 to -3.84	t(19)=-17.86	-3.99	<0.001
Young adults	CC	T3−T1	-6.00	-6.50 to -5.51	t(19)=-25.55	-5.71	<0.001
Young adults	CC	T4−T1	-6.06	-6.56 to -5.56	t(19)=-25.37	-5.67	<0.001
Young adults	Sham	T1−T0	6.07	5.56 to 6.58	t(19)=24.99	5.59	<0.001
Young adults	Sham	T2−T1	-3.16	-3.74 to -2.59	t(19)=-11.56	-2.59	<0.001
Young adults	Sham	T3−T1	-5.98	-6.51 to -5.45	t(19)=-23.60	-5.28	<0.001
Young adults	Sham	T4−T1	-5.98	-6.51 to -5.44	t(19)=-23.39	-5.23	<0.001
Older adults	CC	T1−T0	6.34	5.82 to 6.87	t(19)=25.21	5.64	<0.001
Older adults	CC	T2−T1	-4.56	-5.16 to -3.95	t(19)=-15.75	-3.52	<0.001
Older adults	CC	T3−T1	-6.33	-6.89 to -5.76	t(19)=-23.34	-5.22	<0.001
Older adults	CC	T4−T1	-6.37	-6.93 to -5.82	t(19)=-24.11	-5.39	<0.001
Older adults	Sham	T1−T0	6.91	6.29 to 7.53	t(19)=23.35	5.22	<0.001
Older adults	Sham	T2−T1	-3.96	-4.52 to -3.40	t(19)=-14.84	-3.32	<0.001
Older adults	Sham	T3−T1	-6.91	-7.50 to -6.31	t(19)=-24.23	-5.42	<0.001
Older adults	Sham	T4−T1	-6.96	-7.61 to -6.31	t(19)=-22.46	-5.02	<0.001

Panel C. Between-population comparison of condition effects.

Time	Mean diff, MMA	Mean diff, Young	Mean diff, Older	Statistic	Effect size	p_adj
T0	0.02	0.08	-0.04	F(2, 77)=1.30	0.03	1.000
T1	0.07	0.04	-0.61	F(2, 77)=1.15	0.03	1.000
T2	-1.02	-1.15	-1.20	F(2, 77)=2.80	0.07	0.336
T3	-0.01	0.02	-0.03	F(2, 77)=0.24	0.01	1.000
T4	-0.04	-0.04	-0.02	F(2, 77)=0.07	0.00	1.000

Effect size denotes Cohen's dz in paired contrasts and eta squared (η^2) in one-way ANOVA models. Mean change in Panel B is calculated as the later time point minus the earlier time point shown in the contrast label.

Supplementary Table S6. **Total quality recovery (TQR) (AU).**
Panel A. **Observed values and paired between-condition contrasts.**

Population	Time	CC (mean ± SD)	Sham (mean ± SD)	Mean difference (CC−Sham)	95% CI	Statistic	Effect size	p_adj
All participants	T0	15.90 ± 1.51	15.95 ± 1.37	-0.05	W=819.0	-0.04	1.000	15.90 ± 1.51
All participants	T1	13.10 ± 1.00	11.07 ± 1.05	2.02	W=16.0	0.99	<0.001	13.10 ± 1.00
All participants	T2	14.99 ± 1.30	12.57 ± 1.19	2.41	W=21.0	0.98	<0.001	14.99 ± 1.30
All participants	T3	15.66 ± 1.17	13.66 ± 1.39	2.00	W=23.0	0.98	<0.001	15.66 ± 1.17
MMA athletes	T4	16.82 ± 1.06	16.60 ± 1.10	0.23	W=142.0	0.19	1.000	16.82 ± 1.06
MMA athletes	T0	13.38 ± 1.03	11.22 ± 1.21	2.15	W=0.0	1.00	<0.001	13.38 ± 1.03
MMA athletes	T1	15.62 ± 1.27	13.22 ± 1.12	2.40	W=10.5	0.97	<0.001	15.62 ± 1.27
MMA athletes	T2	16.25 ± 1.03	14.62 ± 1.17	1.62	W=12.0	0.95	<0.001	16.25 ± 1.03
Young adults	T3	15.10 ± 1.17	15.60 ± 1.27	-0.50	W=61.0	-0.29	1.000	15.10 ± 1.17
Young adults	T4	13.15 ± 0.75	10.80 ± 0.77	2.35	W=0.0	1.00	<0.001	13.15 ± 0.75
Young adults	T0	14.00 ± 0.73	11.80 ± 0.83	2.20	W=0.0	1.00	<0.001	14.00 ± 0.73
Young adults	T1	14.85 ± 0.88	12.40 ± 0.50	2.45	W=0.0	1.00	<0.001	14.85 ± 0.88
Older adults	T2	14.85 ± 1.46	15.00 ± 1.30	-0.15	W=45.0	-0.14	1.000	14.85 ± 1.46
Older adults	T3	12.50 ± 0.95	11.05 ± 0.94	1.45	W=8.0	0.88	0.007	12.50 ± 0.95
Older adults	T4	14.70 ± 1.08	12.05 ± 0.89	2.65	W=0.0	1.00	<0.001	14.70 ± 1.08
Older adults	T0	15.30 ± 1.08	13.00 ± 0.92	2.30	W=0.0	1.00	<0.001	15.30 ± 1.08

Panel B. **Within-condition temporal contrasts.**

Population	Condition	Contrast	Mean change	95% CI	Statistic	Effect size	p_adj
All participants	CC	T2−T0	-2.80	W=6.0	-1.00	<0.001	-2.80
All participants	CC	T3−T0	-0.91	W=352.5	-0.61	<0.001	-0.91
All participants	CC	T4−T0	-0.24	W=742.5	-0.21	0.405	-0.24
All participants	Sham	T2−T0	-4.88	W=0.0	-1.00	<0.001	-4.88
All participants	Sham	T3−T0	-3.38	W=0.0	-1.00	<0.001	-3.38
All participants	Sham	T4−T0	-2.29	W=69.0	-0.95	<0.001	-2.29
MMA athletes	CC	T2−T0	-3.45	W=0.0	-1.00	<0.001	-3.45
MMA athletes	CC	T3−T0	-1.20	W=75.0	-0.72	0.001	-1.20
MMA athletes	CC	T4−T0	-0.57	W=118.5	-0.49	0.050	-0.57
MMA athletes	Sham	T2−T0	-5.38	W=0.0	-1.00	<0.001	-5.38
MMA athletes	Sham	T3−T0	-3.38	W=0.0	-1.00	<0.001	-3.38
MMA athletes	Sham	T4−T0	-1.98	W=28.0	-0.92	<0.001	-1.98
Young adults	CC	T2−T0	-1.95	W=0.0	-1.00	<0.001	-1.95
Young adults	CC	T3−T0	-1.10	W=8.0	-0.85	0.013	-1.10
Young adults	CC	T4−T0	-0.25	W=42.5	-0.19	1.000	-0.25
Young adults	Sham	T2−T0	-4.80	W=0.0	-1.00	<0.001	-4.80
Young adults	Sham	T3−T0	-3.80	W=0.0	-1.00	<0.001	-3.80
Young adults	Sham	T4−T0	-3.20	W=0.0	-1.00	<0.001	-3.20
Older adults	CC	T2−T0	-2.35	W=3.5	-0.96	<0.001	-2.35
Older adults	CC	T3−T0	-0.15	W=47.5	-0.10	1.000	-0.15
Older adults	CC	T4−T0	0.45	W=55.5	0.27	0.922	0.45
Older adults	Sham	T2−T0	-3.95	W=0.0	-1.00	<0.001	-3.95
Older adults	Sham	T3−T0	-2.95	W=0.0	-1.00	<0.001	-2.95
Older adults	Sham	T4−T0	-2.00	W=7.0	-0.91	0.003	-2.00

Panel C. **Between-population comparison of condition effects.**

Time	Mean diff, MMA	Mean diff, Young	Mean diff, Older	Statistic	Effect size	p_adj
T0	0.23	-0.50	-0.15	H(2)=2.06	0.00	1.000
T1	2.15	2.35	1.45	H(2)=3.83	0.02	0.590
T2	2.40	2.20	2.65	H(2)=1.18	-0.01	1.000
T3	1.62	2.45	2.30	H(2)=5.50	0.05	0.256
T4	0.23	-0.50	-0.15	H(2)=2.06	0.00	1.000

Effect size denotes Cohen’s dz in paired contrasts and eta squared (η^2) in one-way ANOVA models. Mean change in Panel B is calculated as the later time point minus the earlier time point shown in the contrast label.

Supplementary Table S7. **Perceived exertion (Borg CR10) (AU).**

Panel A. **Observed values and paired between-condition contrasts.**

Population	Time	CC (mean ± SD)	Sham (mean ± SD)	Mean difference (CC−Sham)	95% CI	Statistic	Effect size	p_adj
All participants	T1	5.62 ± 1.18	5.53 ± 1.16	0.10	—	W=699.0	0.09	0.538
MMA athletes	T1	4.92 ± 0.89	4.83 ± 0.84	0.10	—	W=169.5	0.10	0.628
Young adults	T1	6.10 ± 0.91	6.25 ± 0.91	-0.15	—	W=46.0	-0.12	0.672
Older adults	T1	6.55 ± 1.10	6.20 ± 1.11	0.35	—	W=27.0	0.49	0.084

Panel B. **Between-population comparison of condition effects.**

Time	Mean diff, MMA	Mean diff, Young	Mean diff, Older	Statistic	Effect size	p_adj
T1	0.10	-0.15	0.35	H(2)=1.95	0.00	0.377

Supplementary Table S8. **Sphericity diagnostics for repeated-measures effects involving Time.**

Outcome	Within-subject effect	N	Mauchly's W	χ^2	df	p	Greenhouse–Geisser ε	GG correction applied
Maximal voluntary contraction	Time	80	0.0005	591.735	9	<.001	0.312	Yes
Maximal voluntary contraction	Condition × Time	80	0.1510	146.342	9	<.001	0.541	Yes
Muscle stiffness	Time	80	0.0282	276.158	9	<.001	0.355	Yes
Muscle stiffness	Condition × Time	80	0.0485	234.332	9	<.001	0.384	Yes
Microvascular perfusion	Time	80	0.1750	134.938	9	<.001	0.666	Yes
Microvascular perfusion	Condition × Time	80	0.0211	298.565	9	<.001	0.398	Yes
Pressure pain threshold	Time	80	0.0036	435.366	9	<.001	0.353	Yes
Pressure pain threshold	Condition × Time	80	0.0300	271.474	9	<.001	0.449	Yes
Blood lactate	Time	80	0.0011	526.037	9	<.001	0.288	Yes
Blood lactate	Condition × Time	80	0.0023	469.396	9	<.001	0.288	Yes

Abbreviation: GG, Greenhouse–Geisser. Test statistics were derived from the uploaded subject-level datasets (N=80) for maximal voluntary contraction, muscle stiffness, microvascular perfusion, pressure pain threshold, and blood lactate.