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The effect of medical grade compression garments on the repeated-bout effect in non-resistance trained men

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Abstract

Whilst compression garments (CG) may enhance recovery from exercise-induced muscle damage (EIMD), many recovery strategies can attenuate adaptative responses. Therefore, the effects of CG on recovery from EIMD, and the rapid protective adaptations known as the repeated bout effect (RBE) were investigated. Thirty-four non-resistance trained males (18–45 y) randomly received class II medical-grade CG or placebo for 72 h following eccentrically-focused lower-body exercise, in a double-blind, randomised controlled trial. Indices of EIMD were assessed at baseline, 0, 24, 48 and 72 h post-exercise, before exercise and testing were repeated after 14 d. Results were analysed using a three-way (time x condition x bout) linear mixed-effects model. Exercise impaired isometric and isokinetic strength, with soreness and thigh circumference elevated for 72 h ($p < 0.001$). Compression did not enhance recovery ($p > 0.05$), despite small to moderate effect sizes (ES, reported alongside 90% confidence intervals) for isokinetic strength (ES from 0.2 [-0.41, 0.82] to 0.65 [0.03, 1.28]). All variables recovered faster after the repeated bout ($p < 0.005$). However, RBE for peak isokinetic force was impaired in CG at 60 $^{o}.s^{-1}$ (group x bout interaction: $\chi^2 = 4.24$, $p = 0.0395$; ES = -0.56 [-1.18, 0.07]) and completely absent at 120 $^{o}.s^{-1}$ ($\chi^2 = 16.2$, $p < 0.001$, ES = -0.96 [-1.61, -0.32]) and 180 $^{o}.s^{-1}$ ($\chi^2 = 10.4$, $p = 0.001$, ES = -0.72 [-1.35, -0.09]). Compression blunted RBE at higher isokinetic velocities without improving recovery in non-resistance trained males, potentially contraindicating their use following unaccustomed exercise in this population.

New findings:

The study sought to determine the effects of compression garments on recovery from unaccustomed damaging exercise, and subsequent protective adaptations. Compression did not influence recovery, but was associated with blunted protective adaptations for isokinetic performance, which were completely absent at high velocities. Based on these findings, the use of CG for recovery would not be recommended following unaccustomed exercise, particularly if the maintenance of high-velocity performance following EIMD is desirable.

Introduction

The concept of recovery describes the reestablishment of post-exercise performance, with important implications for recreational exercisers and athletes alike (Peake, 2019; Skorski et al., 2019). Sufficient recovery allows athletes to achieve and maintain an optimal training stimulus (Peake, 2019; Skorski et al., 2019), whilst perceptual symptoms of under-recovery may reduce adherence in recreational exercisers (Flack, Johnson, & Roemmich, 2017). Importantly, however, some anti-inflammatory and/or antioxidant recovery strategies have been shown to ameliorate the physiological stressors required for muscular adaptation (Figueiredo et al., 2016; Peake, 2019). The use of particular recovery strategies may therefore represent a compromise between optimising short-term recovery and maximising the response to training.

The time-course of post-exercise recovery depends upon the specific physiological demands of an exercise bout (Skorski et al., 2019), with exercise-induced muscle damage (EIMD) contributing to prolonged declines in muscular performance (Nosaka, Chapman, Newton, & Sacco, 2006). Describing the disruption of muscle fibres and associated reductions in contractile force, EIMD may be associated with strength deficits of up to 30% in untrained participants (Clarkson & Hubal, 2002; Nosaka et al., 2006) and is most commonly caused by unaccustomed, eccentric (muscle-lengthening) exercise, such as plyometrics, resistance exercise and running (Brown et al., 2017; Goto & Morishima, 2014; Hill et al., 2017; Thomas, Ziogas, Smith, Zhang, & Londeree, 1995). The progression of EIMD is mediated by post-exercise inflammation (Deyhle et al., 2016; Hyldahl, Chen, & Nosaka, 2017), with symptoms such as soreness and impaired mobility persisting for up to 10 days (Clarkson & Hubal, 2002). One seemingly effective recovery strategy for EIMD is the use of compression garments (CG), which has been associated with ameliorated strength losses, swelling and cellular disruption in both trained and untrained participants (Brown et al., 2017; Marques-Jimenez, Calleja-Gonzalez, Arratibel, Delextrat, & Terrados, 2016). However, the effects of CG on adaptation have received little attention (Baum, Carter, Neufeld, & Dolezal, 2020; Edgar, Beaven, Gill, & Driller, 2022). Robust data on the effects of compression on muscular adaptation are required to guide the use of CG for recovery.

Muscle-damaging exercise is unique in that as little as a single exposure may elicit adaptations which confer protection from subsequent bouts (Hyldahl et al., 2017). This “repeated bout

effect" (RBE) may be observed after as little as three days and is most pronounced following unaccustomed exercise (Chen & Nosaka, 2006; Hyldahl et al., 2017). Although the mechanisms responsible for RBE are unclear, post-exercise inflammation is thought to at least partially mediate the protective adaptations and modified inflammatory responses to EIMD (Deyhle et al., 2016; Hyldahl et al., 2017). Importantly, researchers have suggested that the benefits of CG may be related to an ameliorative effect on local inflammation (Hill et al., 2017; Peake, 2019), with anti-inflammatory effects reported in both sporting (Valle et al., 2013) and clinical settings (Beidler et al., 2009). As compression may influence mediators of the repeated bout effect, the effects of CG on RBE require further investigation.

Whilst the use of CG for recovery from EIMD is supported by academic consensus, the literature is still beset by the varied quality of supporting evidence (Brown et al., 2017; Marques-Jimenez et al., 2016). For example, most studies have failed to implement a placebo or sham condition (reviewed by Brown et al., 2017), or where used, to report on the effectiveness of blinding (Brown et al., 2017; de Glanville & Hamlin, 2012; Hill et al., 2017). The few double-blind studies that exist have compared CG to non-compressive garments - a "sham treatment" of questionable efficacy (Baum et al., 2020; de Glanville & Hamlin, 2012). Although previous meta-analyses have reported large benefits to strength recovery when CG are worn following EIMD (Brown et al., 2017; Marques-Jimenez et al., 2016), the placebo effect can explain benefits of this magnitude (Clark, Hopkins, Hawley, & Burke, 2000). Such issues prevent researchers from making informed, quantitative judgements on the benefits of CG, compared with the potential risks to adaptation. Accordingly, the aims of this investigation were to examine the effects of CG on recovery from EIMD using a double-blind approach, and to determine the effects of compression on RBE in non-resistance trained participants. Given the ambiguity of existing evidence and uncertainties over the mechanisms involved, results were compared to a two-tailed null hypothesis - that no differences in recovery or RBE would be observed.

Materials and methods

Ethical approval

Institutional ethics approval was obtained from Coventry University Ethics Board (Ref P93660) before written informed consent was provided by all participants. The study conformed to the standards set by the Declaration of Helsinki, except for registration in a database.

Design

The effects of CG on muscular recovery and RBE following EIMD were assessed using a double-blind, 3-way (condition x time x bout) design. Analysis was performed unblinded to allow assessment of participant adherence. Performance measures and indices of EIMD were taken at baseline, then at 0, 24, 48 and 72 h (± 2 h) after an initial bout of exercise (B1) to assess recovery in participants wearing CG or taking placebo (PLA). A repeated bout (B2) was completed after 14 d without any recovery intervention, and recovery monitored at the same time-points. To account for the highly individual (Clarkson & Hubal, 2002; Hyldahl et al., 2017), and potentially sex-specific (Fernandez-Gonzalo, Lundberg, Alvarez-Alvarez, & de Paz, 2014), nature of EIMD responses, only male participants were recruited, and pair-matched following familiarization according to body mass and the number of weekly exercise bouts of various types that were undertaken (self-report). Exercise was categorised into running, non-load bearing exercise (swimming and cycling) and multi-directional exercise (e.g. team sports) to account for the protective effects of prior damage, which is greater following load-bearing activity (Thomas et al., 1995). Participants were also matched by body mass to control for the effects of total work and eccentric forces on EIMD responses to the load-bearing exercise challenge employed (depth-jumps) (Paschalis, Koutedakis, Jamurtas, Mougios, & Baltzopoulos, 2005). Participants were then randomly assigned to either group, using open-access statistical software ('optmatch' package, R Foundation for Statistical Computing, Vienna, Austria).

Participants

Selecting an alpha value of 0.05 with 80% statistical power, a sample size calculation was carried out with the G*Power software package (version 3.1.9.7, Heinrich Heine University, Düsseldorf, Germany), based upon an expected Cohen's d effect size of 1 from previous studies assessing

the effects of CG on recovery from EIMD on knee-extension performance (Goto & Morishima, 2014; Hill et al., 2017). While a matched-pair design required a minimum sample of n = 10 (2 x n = 5), a conservative estimate of 34 (2 x n = 17) was chosen, based on an independent group design. Accordingly, 34 males (18–45 y) who met national physical activity guidelines (Care, 2019) were recruited. Those who had completed lower-body resistance exercise within 6 months were excluded to maximise the likelihood of observing RBE (Deyhle et al., 2016; Hyldahl et al., 2017), as were participants whose habitual exercise had been disrupted by injury for at least one week of the preceding 28 days. Participants were asked to refrain from taking NSAIDs or supplements (including antioxidants and whey protein) throughout testing, from 48 h before the start of the study.

Procedures

Familiarization was conducted over two sessions, 1-2 weeks before the trial. Body mass was measured (seca 875 Class III scales, seca Medical Measuring Systems, Birmingham UK), before anthropometry was assessed in accordance with the recommendations of the International Society for the Advancement of Kinanthropometry by a level 1 practitioner. Skinfolds (Σ8), mid-thigh girth (MTG) and calf circumference were measured in a standing position, with the latter used to guide the selection of appropriately sized British class II (moderate) compression stockings, according to manufacturer guidelines (DUOMED soft thigh length compression stockings, Medi UK Ltd., Hereford, UK). Subsequently, CG were measured for applied pressures in all participants (Picopress, Microlab, Padua, Italy) at the mid-thigh, medial calf, ankle (Bjork & Ehmann, 2019), and “manufacturer’s B1 point” (MB1) (Uhl, Benigni, & Cornu-Thenard, 2013). To ensure physiologically relevant pressures, smaller CG were provided if stockings failed to apply 14 mmHg at the thigh; a proposed threshold in the literature (Hill, Howatson, van Someren, Davidson, & Pedlar, 2015). The entire battery of performance tests was then completed in the same order as subsequent experimental trials (Brown et al., 2022).

After a standardised warm-up (3 min cycling at 100 W; 10 repetitions of body-weight squats, lunges on either leg and countermovement jumps), peak force was assessed from three (5 s) maximal isometric voluntary contractions (MIVC) of the knee extensors at 85° flexion (KinCom, Chattanooga, TN, USA – 100 Hz), followed by three consecutive isokinetic contractions at each

of 60 °·s^{-1} 120 °·s^{-1} and 180 °·s^{-1} (Figure 1). Participants sat reclined at 15°, were secured with straps, and were prevented from gripping the chair during contractions. Finally, peak power output in the 6 s cycle sprint test (PPT) was assessed in a standing position from a stationary start (Brown et al., 2022). Participants were positioned so that the knee was just flexed at the bottom of the stroke when seated (handlebars adjusted for comfort), with settings recorded and repeated for each visit. Resistance was determined from manufacturer settings (Wattbike Pro, Wattbike Ltd., Nottingham, UK). Verbal encouragement was given for all tests. A minimum of three repetitions per test was completed during each familiarization session, or until performance plateaued as defined by the final two efforts resulting in coefficients of variation (CV) ≤ 5%. Between day reliability values (CV) were 6% for MVIC and 9.4%, 3.5% and 7.5% for peak isokinetic force at 60°.s.$^{-1}$, 120°.s.$^{-1}$ and 180°.s.$^{-1}$, respectively. Within session CVs were 6%, 8.9%, 5.5%, 5.4%. Peak cycle sprint power was described by CVs of 4.8% and 3.9% for between-day and within-session values, respectively.

At baseline, soreness, MTG and capillary blood samples from the finger were taken as previously described (Brown, Hill, van Someren, Howatson, & Pedlar, 2021), with changes in MTG taken as a measure of post-exercise swelling (Brown et al., 2017; Goto & Morishima, 2014; Marques-Jimenez et al., 2016). Performance was assessed as above, taking peak values from the best of three attempts separated by 90 s recovery. Serum was assessed for creatine kinase activity ([CK]) using spectrophotometric assay with a between-run precision of < 1%, as determined in our laboratory (CK-NAC, RX Daytona, Randox, County Antrim, Northern Ireland). A repeated sprint protocol (Duffield, Cannon, & King, 2010) (20 x 20 m sprints with a 5 m deceleration) followed by 10 sets of 10 depth-jumps (DJs) was then completed (Hill et al., 2017) to induce EIMD (Figure 1). Participants completed sprints every 60 s, with sprint times (TC PhotoGate, Brower timing Systems, Utah, USA) relayed to participants to encourage maximal effort. Sets of 10 DJs were completed every 2.5 min from a 0.6 m box onto two force plates sampling at 1000 Hz (AMTI BP900900, Watertown, MA, USA) to measure vertical ground reaction forces. Jump height was determined from take-off velocity for each jump using forward integration (McMahon, Lake, Stratford, & Comfort, 2021), first calculating impact velocity from the 0.6 m descent. Peak and average forces during breaking and propulsion, as well as the work performed for each jump (equivalent to the sum of average breaking and propulsive forces multiplied by countermovement depth), were calculated to characterise the exercise challenge (Table 2),

239 alongside starting and peak heart rates for each sprint and set of DJs (S810iTM, Polar, Kempele,
240 Finland). Participants told they would have to repeat any sprint where they continued beyond
241 the marked 5 m deceleration zone, and any DJ for which the knee angle at the bottom of the
242 jump failed to reach 90^{o} flexion.

243

244 Following B1, participants received either CG or placebo tablets providing < 0.1 g carbohydrate
245 (6 mm hard lactose/sucrose tablets, HSC, Holt, UK) and instructed to either consume a tablet or
246 don CG in private before leaving the building. Garments were worn for 72 h post-exercise, with
247 participants instructed to remove CG only to wash, and before arriving for subsequent testing.
248 Participants assigned to PLA were given 3 tablets to consume (daily) immediately after testing,
249 having been told by a researcher that they contained magnesium to aid recovery. Participants
250 were randomised into groups A and B by the lead researcher, and informed of their specific
251 interventions by a third party. To aid placebo blinding, participants were told there was an
252 additional control group (group C) for comparison. This group did not exist, and participants
253 were informed of this deception at the conclusion of data collection. Participants were
254 requested to record their dietary intake from the day before the trial until 72 h post-exercise,
255 and to replicate this for the repeated bout. The effectiveness of blinding was assessed at the
256 conclusion of the trial by asking participants to rate their intervention for perceived efficacy from
257 0 to 10, accepting half-marks (Karanicolas, Farrokhyar, & Bhandari, 2010). Finally, baseline
258 performance tests, eccentrically-focused exercise and assessments of recovery were repeated
259 after 14 d to investigate RBE.

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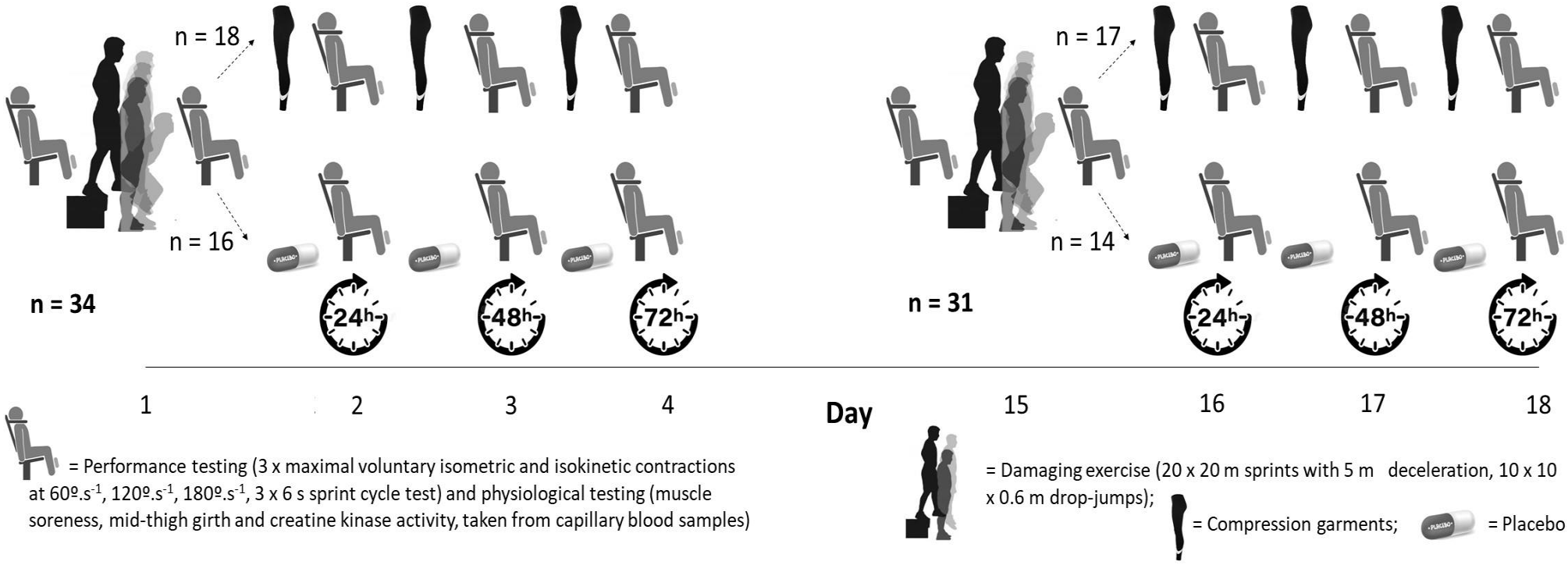

Figure 1. Study design and procedures

Statistical analysis

An open-access statistical software package was used for all statistical analyses (R Foundation for Statistical Computing, Vienna, Austria), which were carried out on raw data (although changes in MTG were graphically presented as normalised values for clarity). Despite initial efforts at pair-matching, follow-up questioning on adherence revealed that one participant mistakenly took the wrong allocation, resulting in n = 18 and n = 16 for CG and PLA, respectively. Accordingly, a between-group design was employed, using a linear mixed effects model with random intercepts for each participant to account for individual variation in EIMD (Gandotra et al., 2021). The consideration of random effects in a statistical model also allows for participants to be included up until the point of withdrawal to enhance statistical power and reduce sample bias (Nich & Carroll, 2002). Visually comparing fitted and observed values, and calculating root mean squared error (RMSE) from residuals, revealed this model better matched observed data for every variable compared with analysis of variance (ANOVA). The assumption of normality was verified by running QQ plots on residual values**,** with the mixed effects model independent of the assumption of sphericity. *Post hoc* testing was carried out with the 'emmeans' package, adjusting for multiple comparisons (Gandotra et al., 2021). Ordinal soreness data were assessed with a non-parametric alternative to the split-plot ANOVA (Feys, 2016). All values were reported as means ± SD. Additionally, effect sizes (ES - Cohen's d) were calculated as between-group differences in changes from baseline, and reported alongside 90% confidence intervals as (ES [LCL, UCL]), where LCL and UCL represent lower and upper 90% confidence limits. Effect sizes were defined as trivial/small, moderate or large using thresholds of ≥0.2, ≥0.5 and ≥0.8, respectively (Batterham & Hopkins, 2006). *Post hoc* power assessments were carried out for all performance tests using G*Power.

Results

Due to COVID-19 pandemic restrictions (n = 1) and injuries during the second exercise bout (n = 2), data on the repeated bout were missing for three participants (CG, n = 1; PLA, n = 2). Baseline participant characteristics and garment pressures are detailed below, alongside exercise responses (Tables 1-2), which did not differ between bouts or groups at either time-point (p > 0.05). Perceived efficacy did not differ (p = 0.558) between CG (5 ± 2) and PLA (4.5 ± 2), suggesting blinding was effective. Stockings were worn for 20.9 ± 3.7 $h.d^{-1}$, while participants in PLA each consumed all three tablets.

Muscle damage and RBE were apparent from post-exercise declines in all isometric and isokinetic strength measurements, which were attenuated between bouts, and recovered more rapidly in B2 (Figure 2). For MVIC, significant effects were observed for time (χ^2 = 268, p < 0.001), bout (χ^2 = 84.3, p < 0.001) and their interaction (χ^2 = 15.6, p = 0.004), without differences between groups (p > 0.05 – Figure 2). Performance was impaired for 72 h following B1 (post – 48 h: p < 0.001; 72h, p = 0.006) but had recovered by 48 h after B2 (p = 1 at each time-point – Supplementary Table), with peak force higher at all post-exercise timepoints (p < 0.001 to 0.005).

Peak isokinetic forces at 60 °.s^{-1}, 120 °.s^{-1} and 180 °.s^{-1} (Figure 2) were subject to significant effects (p < 0.001) of time (χ^2 = 182, 184 and 92.7 respectively) and bout (χ^2 = 22.6, 15.0, 14.0), as well as time x bout interactions (χ^2 = 35.1, 36.7, 25.0). Demonstrating RBE, performance following B1 was impaired for 72 h at each velocity (p < 0.001), whereas strength recovered by 24 h following B2 (p = 0.1165, p =0.3568, p = 1). Accordingly, peak force was greater in B2 at each velocity from 24 – 72 h post-exercise (p < 0.001 to 0.0186). Of note, baseline performance was also lower (p = 0.0071, p = 0.0026 and p = 0.0343 for 60 °.s^{-1}, 120 °.s^{-1} and 180 °.s^{-1}, respectively). Neither group, nor time x group effects were apparent, with the moderate improvements observed in CG following B1 at 60 °.s^{-1} and 180 °.s^{-1} failing to reach significance (p > 0.05, ES from 0.51 [-0.11, 1.13] to 0.65 [0.03, 1.28] – Table 3). Observed RBE for isokinetic strength was lower in CG than PLA for each velocity, as shown by significant bout x group interactions (p < 0.001 to 0.0395; Tables 3 and 4). At 60 °.s^{-1}, although performance deterioration was attenuated following B2 in both CG (p = 0.0336) and PLA (p < 0.001), RBE was significantly smaller in CG (χ^2 = 4.24, p = 0.0395; ES = -0.56 [-1.18, 0.07]; Tables 3 and 4). Conversely, the bout x group interactions observed at 120 °.s^{-1} (χ^2 =16.2, p < 0.001) and 180 °.s^{-1} (χ^2 =10.4, p = 0.001) revealed that RBE was absent in CG. Whilst *post hoc* testing demonstrated greater peak forces in PLA following B2 at both 120 °.s^{-1} and 180 °.s^{-1} (p < 0.001 for both), no increase was observed in CG (p = 0.875, p = 0.5507; Tables 3 and 4).

A decline in PPT was observed over time (χ^2 =153, p <0.001), with peak power recovering by 48 h (p = 1). Cycle power improved over B2 compared to B1 (p < 0.001). *Post hoc* power analyses at individual time-points following B1 yielded β values of 0.14–0.58 for force dynamometry, and

0.11–0.32 for peak cycling power. Power from observed differences for RBE between groups ranged from 0.29 to 0.86 for force dynamometry and was 0.13 for PPT.

Changes in MTG were observed over time ($\chi^2 = 14.2$, $p < 0.001$) and between bouts ($\chi^2 = 8.25$, $p = 0.004$), with mean values greater than baseline from 24 h ($p = 0.049$, $p = 0.0114$, and $p = 0.0382$ for 24 h, 48 h and 72 h, respectively – Figure 3, Supplementary Table). Neither group x time ($\chi^2 = 1.15$, $p < 0.886$), three-way ($\chi^2 = 1.26$, $p = 0.868$), nor bout x time interactions were significant ($\chi^2 = 0.585$, $p = 0.630$). However, a bout x group effect was observed ($\chi^2 = 6.66$, $p = 0.01$), with *post hoc* testing demonstrating that swelling in CG was greater following B2, when compression was not worn ($p < 0.001$). Conversely, swelling did not differ between bouts in PLA ($p = 0.984$). Soreness (Figure3) changed over time ($\chi^2 = 2.87$, $p < 0.001$), and between bouts ($\chi^2 = 62.8$, $p < 0.001$), and demonstrated a significant time x bout interaction ($\chi^2 = 6.3$, $p < 0.001$). No significant differences or interactions between groups were apparent ($p > 0.05$). *Post hoc* testing revealed that while soreness remained elevated from baseline at all times during B1 ($p < 0.001$), values returned to baseline by 72 h in B2 ($p = 0.151$).

In addition to participant attrition, CK analysis was limited further by insufficient blood samples from one participant, with a further two participants giving anomalous pre-exercise readings. Technical error was ruled out by analysing dilutions of the original sample, which all indicated similar CK activity (within 1–15%), while elevated baseline readings did not reflect impaired muscular performance compared to the previous/subsequent bout. These anomalous readings resulted in between-bout differences at least 3-times greater than the group SD of the differences (exceeding the 99% confidence interval), so were removed from the analysis. Creatine kinase activity in the resulting 28 participants changed over time $\chi^2 = 16.7$, $p = 0.002$), and between bouts ($\chi^2 = 12.1$, $p < 0.001$), with no other differences or interactions observed ($p > 0.05$). Hypothesis testing was not affected by the inclusion or exclusion of the anomalous results (main effects for set and bout; $\chi^2 = 11.9$, $p = 0.0179$ and $\chi^2 = 13.3$, $p < 0.001$, respectively). *Post hoc* testing revealed that average values at 24 h were greater than those recorded at both pre-exercise ($p = 0.0124$) and post-exercise ($p = 0.0444$) time points.

Table 1. Participant characteristics

	CG	PLA
Age (y)	27.3 ± 6.7	25.1 ± 8.5
Body mass (kg)	77 ± 11.3	78.1 ± 10.4d
Stature (m)	1.78 ± 0.1	1.77 ± 0.1
Σ8 skinfolds (mm)	89 ± 44.8	112 ± 55.5
MVIC (N)	639 ± 122	635 ± 141
MTG (cm)	55.3 ± 5.9	54.5 ± 4.5
Calf (cm)	37.5 ± 2	39.7 ± 8.5
CG Pressure (mmHg)		
Thigh	16 ± 3	
Calf	23 ± 6	
MB1	21 ± 5	
Ankle	16 ± 2	

CG = Compression garments; PLA = Placebo; MVIC = Maximal isometric voluntary contraction, MTG = Mid-thigh girth; Calf = Medial calf (circumference or site for interface pressure measurement); Thigh = Mid-thigh skinfold site; Calf = point of widest circumference at the medial calf; MB1 = Manufacturer's B1 point; Ankle = Interface pressure taken at point of narrowest circumference of the ankle

Table 2. Exercise responses from a combined repeated-sprint (20 x 20 m) and depth-jump (10 x 10) muscle-damage protocol

	CG		PLA	
	B1	**B2**	**B1**	**B2**
Repeated sprints				
20 m sprint time (s)	3.66 ± 0.47	3.56 ± 0.27	3.53 ± 0.2	3.5 ± 0.24
HR_{med} (beats.min^{-1})	146 ± 15	144 ± 20	144 ± 21	140 ± 19
HR_{pk} (beats.min^{-1})	155 ± 15	148 ± 15	154 ± 18	151 ± 17
Depth-jumps				
Breaking F_{pk} (N)	4463 ± 1005	4263 ± 710	4743 ± 895	4606 ± 857
Breaking F_{ave} (N)	1424 ± 123	1421 ± 75	1436 ± 67	1447 ± 77
Propulsive F_{pk} (N)	1648 ± 198	1682 ± 211	1600 ± 207	1631 ± 207
Propulsive F_{ave} (N)	1085 ± 99	1086 ± 58	1075 ± 72	1046 ± 62
Jump Height TOV (cm)	13 ± 2	13 ± 1	12 ± 1	13 ± 1
Total work (J)	176904 ± 284	184384 ± 173	163703 ± 167	176416 ± 184
Total work (J.kg^{-1} per jump)	23 ± 4	24 ± 2	22 ± 2	22 ± 2
HR_{med} (beats.min^{-1})	156 ± 14	150 ± 16	153 ± 18	152 ± 18
HR_{pk} (beats.min^{-1})	170 ± 12	164 ± 16	166 ± 16	166 ± 18

CG = Compression garments; PLA = Placebo; B1 = Bout 1; B2 = Repeated bout; HR_{med} = Median heart-rate; HR_{pk} = Peak heart-rate; F_{pk} = Peak force; F_{ave} = Average force; TOV = As calculated from take-off velocity

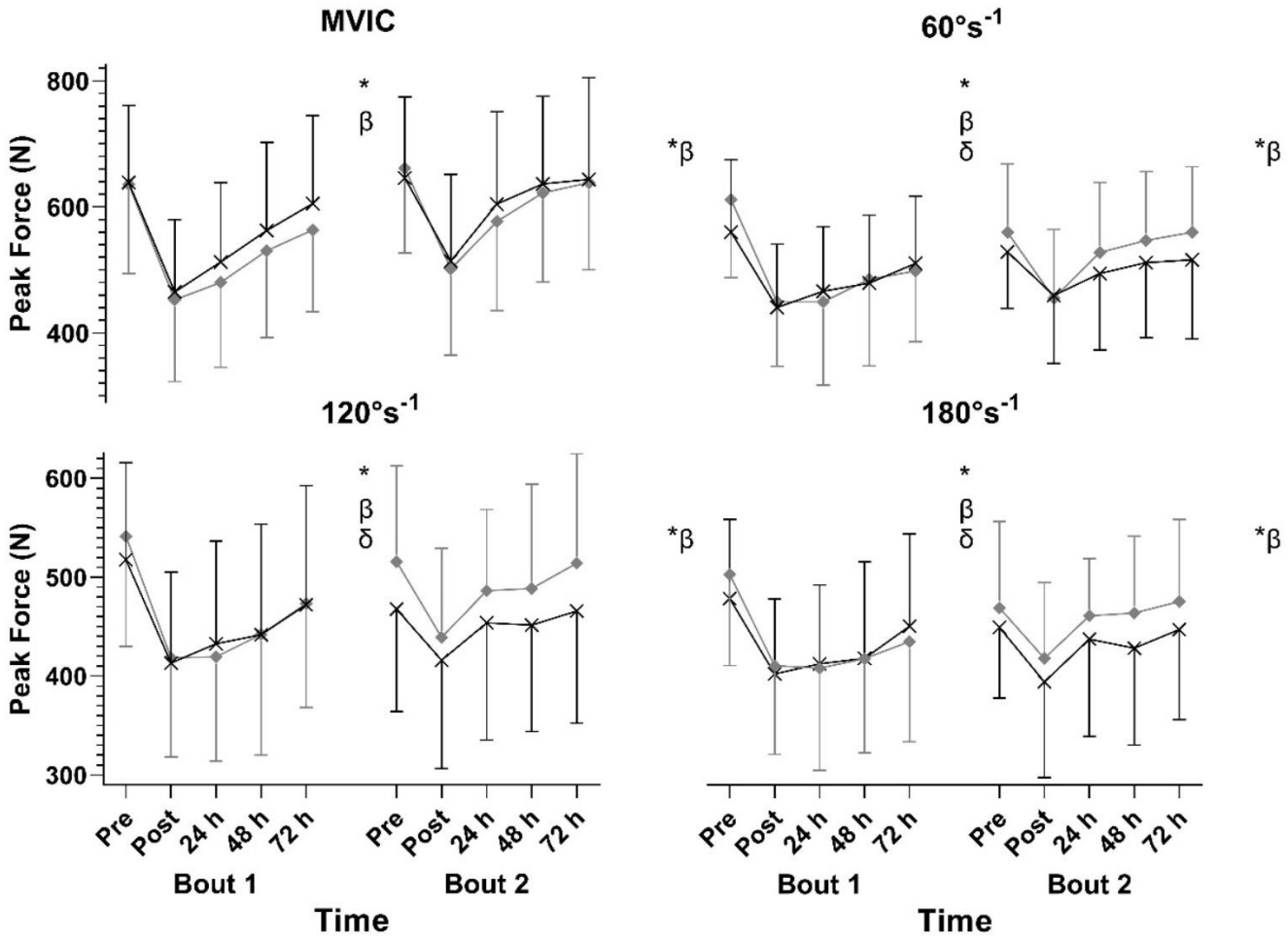

Figure 2. Peak maximal voluntary contraction force for isometric (MVIC) and isokinetic contractions at 60 °.s^{-1}, 120 °.s^{-1}, 180 °.s^{-1}, over an initial (left) and repeated bout (right) of eccentrically-focused exercise

Black line and crosses = Compression garments; Grey line and diamonds = Placebo; * = Significant effect of time ($p < 0.001$ for each variable); β = Significant difference between bouts ($p < 0.001$ for each variable); *β = Significant time x bout interaction ($p < 0.001$ for all isokinetic speeds, $p = 0.004$ for MVIC) δ = Significant bout x group interaction ($p = 0.0395$, $p < 0.001$, $p = 0.001$ for 60 °.s^{-1}, 120 °.s^{-1} and 180 °.s^{-1}, respectively. MVIC: $p = 0.128$)

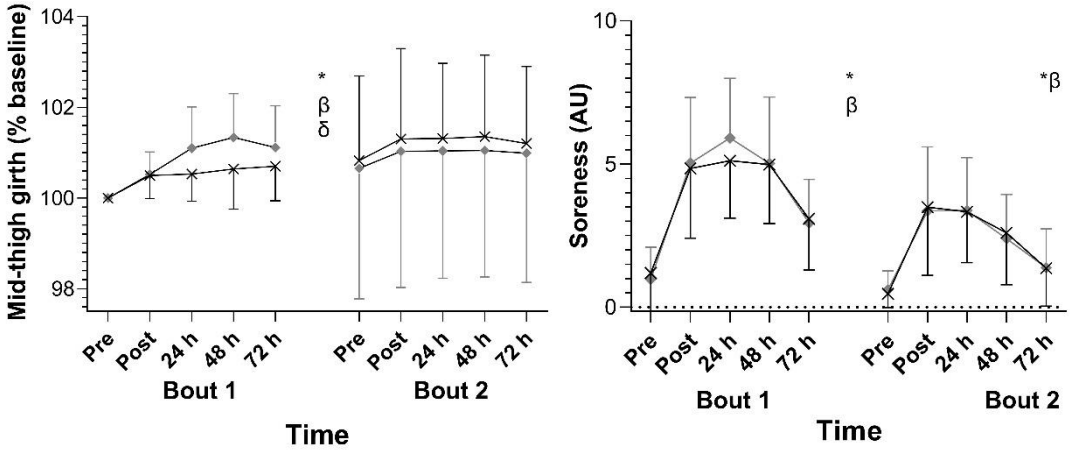

Figure 3. Mid-thigh girth and soreness over an initial (left) and repeated bout (right) of eccentrically-focused exercise Black line and crosses = Compression garments; Grey line and diamonds = Placebo; * = Significant effect of time ($p < 0.001$); β = Significant difference between bouts (mid-thigh girth: $p = 0.004$; soreness: $p < 0.001$); δ = Significant bout x group interaction ($p = 0.01$); *β = Significant time x bout interaction ($p < 0.001$)

Table 3. Effect sizes and 90% confidence limits for between group differences

Time	Post	24 h	48 h	72 h	RBE	Time	Post	24 h	48 h	72 h	RBE
MVIC	0.09 [-0.53, 0.7]	0.34 [-0.28, 0.96]	0.27 [-0.35, 0.88]	0.33 [-0.28, 0.95]	-0.38 [-1, 0.23]	**IKD 60°.s^{-1}**	0.4 [-0.22, 1.01]	0.65 [0.02, 1.27]	0.46 [-0.16, 1.08]	0.65 [0.03, 1.28]	-0.56 [-1.18, 0.07]
IKD 120°.s^{-1}	0.24 [-0.38, 0.86]	0.48 [-0.14, 1.11]	0.25 [-0.36, 0.87]	0.2 [-0.41, 0.82]	-0.96 [-1.61, -0.32]	**IKD 180°.s^{-1}**	0.32 [-0.29, 0.94]	0.38 [-0.24, 1]	0.3 [-0.32, 0.92]	0.51 [-0.11, 1.13]	-0.72 [-1.35, -0.09]
PPT	0.32 [-0.3, 0.94]	0.25 [-0.36, 0.87]	0.41 [-0.21, 1.03]	0.15 [-0.47, 0.76]	0.18 [-0.43, 0.8]	**MTG**	0.4 [-0.22, 1.01]	0.65 [0.02, 1.27]	0.46 [-0.16, 1.08]	0.65 [0.03, 1.28]	0.16 [-0.45, 0.78]
Soreness	-0.08 [-0.69, 0.54]	-0.39 [-1.01, 0.23]	-0.02 [-0.63, 0.59]	0.09 [-0.53, 0.7]	0.09 [-0.53, 0.7]	**[CK]**	-0.47 [-1.09, 0.15]	0.09 [-0.52, 0.7]	-0.22 [-0.84, 0.39]	-0.35 [-0.97, 0.27]	0.33 [-0.29, 0.95]

Effect sizes (Cohen's d) reported as ES [LCL, UCL]), where LCL and UCL represent the lower and upper 90% confidence limits. Effect size thresholds were as follows: ≤ 0.2 (trivial), 0.2 - 0.49 (small), 0.5–0.79 (moderate), > 0.8 (large). Post = Post-exercise; RBE = Repeated bout effect (defined as the difference between the means of the repeated and the initial bout); MVIC = Maximal voluntary isometric contraction; IKD = Maximal voluntary isokinetic contraction; PPT = peak power output in the 6 s cycle sprint test; MTG = Mid-thigh girth; [CK] = Creatine kinase activity

Discussion

The present study investigated the effects of CG on recovery and adaptation following EIMD. Whilst the effects of CG on recovery were not significant, RBE for isokinetic performance was impaired each velocity. Although these findings were specific to isokinetic strength, these data provide novel and robust evidence that CG may undermine aspects of RBE in non-resistance trained males.

The current findings do not support previous studies which suggest that CG enhance recovery from EIMD (Brown et al., 2017; Hill et al., 2017; Marques-Jimenez et al., 2016; Peake, 2019). These observations may be related to several discrepancies between the current study and previous trials - including differences in interface pressures, populations, and exercise protocols (Brown et al., 2017; Marques-Jimenez et al., 2016). However, as the placebo effect can enhance performance by up to 6% (ES = 1.2) (Clark et al., 2000), it is also possible that the effective blinding strategy employed was at least partly responsible (Tables 3 and 4). Effective blinding has also been postulated to explain non-significant findings on cold water immersion (CWI) which contradict those from earlier studies (Wilson et al., 2018). Furthermore, the current study was conducted double-blind to eliminate the possibility of providing subconscious cues to participants, which can further inflate treatment effects (Karanicolas et al., 2010). These data highlight the need to implement and evaluate a double-blind approach to elucidate the true effects of CG on recovery.

The non-significant effects of CG for recovery in the current study are somewhat surprising, as observed interface pressures were similar to previously proposed pressure optima. For example, benefits have been commonly observed from garments applying around 14–20 mmHg at the thigh, above or below which pressures CG may be ineffective (Hill et al., 2017; Miyamoto & Kawakami, 2014). A 15% improvement in recovery of countermovement jump performance was previously reported in recreationally active participants (Hill et al., 2017) when class II CG, providing almost identical interface pressures to those we report, were worn for 72 h following 100 DJs (14.8 ± 2.2 vs 16 ± 3 mmHg at the thigh and 24.3 ± 3.7 vs 23 ± 6 at the calf). However, pressure optima yet to be conclusively established (Brown et al., 2017; Hill et al., 2017; Hill et al., 2015). Furthermore, even directly measured interface pressures may vary with small

changes in sensor placement and non-uniformities in limb profile (Bjork & Ehmann, 2019), complicating comparisons between trials. Error also arises from the different sensors used, with the Kikuhime device used by Hill et al. (Hill et al., 2017) known to overestimate applied pressures by 10–15% compared to the Picropress (Partsch & Mosti, 2010). Discrepancies may also be related to differences in the recovery of jumping versus isometric performance (Byrne & Eston, 2002), or the mixed sex population studied by Hill et al., considering potential sex-specific responses to EIMD (Clarkson & Hubal, 2002; Fernandez-Gonzalo et al., 2014). Further research is required to establish pressure optima for recovery, with a pressing need for researchers in the field to report directly measured pressures using standardised procedures.

The findings we present are the first to report deleterious effects from CG on muscular adaptation, contradicting previous findings which suggest variable, but likely positive effects on strength, power and endurance outcomes (Baum et al., 2020; Edgar et al., 2022). However, the adaptations underpinning RBE are likely distinct to those elicited by either hypertrophy or endurance training (Hyldahl et al., 2017). Additionally, the compression stimulus provided in the current trial likely differed from previous studies. The military recruits in Edgar's study wore compression leggings for 4–6 $h.d^{-1}$ only, with reported interface pressures (15.0 ± 4.3 and 11.8 ± 3.1 mmHg at the thigh, before and after the training intervention, respectively) measured with the Kikuhime. No placebo was given to the control group. Conversely, Baum et al. (2020) studied the effects of sports compression leggings worn *during* training (pressures not reported), presumably to investigate the cumulative effects of enhanced training performance. The data we present suggest the negative effects of medical-grade CG on RBE are greater than any potential benefits for recovery following unaccustomed exercise in non-resistance trained males.

The current findings are the first to demonstrate negative effects from compression on adaptation – specifically on RBE for isokinetic strength. Furthermore, these effects appear to be velocity-specific, with RBE reduced at 60 $^{o}.s^{-1}$, but completely absent in CG at 120 $^{o}.s^{-1}$ and 180 $^{o}.s^{-1}$. That these observations were made following the use of an effective placebo intervention, double-blind design, and reported alongside a reduction in swelling following B1 strengthens the case for a physiologically-mediated effect of CG, with the combined alpha value from all three isokinetic interactions equating to $p < 3.95 \times 10^{-8}$. These findings are also

concordant with previous observations that protective adaptations to EIMD are associated with a greater relative recruitment of oxidative motor-units and subsequent preservation of high velocity performance (Hinks et al., 2021; Hortobagyi et al., 1996; Hyldahl et al., 2017). In the current study, however, these adaptations were absent in CG. Although it is important to note that no other indices of EIMD were blunted (e.g. isometric strength or CK), these findings have important implications for the use of compression throughout unaccustomed training. The utility of strength training for improving high-velocity performance is well established (Cronin, Ogden, Lawton, & Brughelli, 2007; García-Valverde, Manresa-Rocamora, Hernández-Davó, & Sabido, 2022), with greater isokinetic strength commonly associated with improved power performance in active and athletic populations (Janicijevic, Knezevic, Garcia-Ramos, Cvetic, & Mirkov, 2020; Moreira et al., 2021).

Whilst the mechanisms involved were not explicitly investigated, nor inflammation directly measured, several physiological observations in the current study are concordant with previous findings suggesting that CG reduce tissue damage by moderating inflammation (Beidler et al., 2009; Valle et al., 2013). Interestingly, impaired RBE in CG was observed following an attenuated swelling response after B1 (Figures 2-3). As swelling is known to propagate the inflammatory response by facilitating leukocyte adhesion (Lawrence & Springer, 1991), and RBE is thought to be mediated by inflammation (Deyhle et al., 2016; Figueiredo et al., 2016), it is possible these two observations are related. Although CG have not been shown to reliably reduce circulating inflammatory markers when worn for recovery (Duffield et al., 2010; Hill et al., 2017; Peake, 2019), previous findings suggest CG can moderate leukocyte infiltration; which was reduced in professional footballers 48 h after CG were worn *during* downhill-running (Valle et al., 2013). Research is required to establish the biochemical effects of compression, the relevance to recovery and specific adaptations**.**

Limitations

The current study is subject to a number of important limitations; most notably the small sample size. The double-blind (initially pair-matched) design made it inappropriate to replace participants who withdrew, while the initial sample size was calculated from single blind studies, which may overestimate treatment effects (Karanicolas et al., 2010). Interestingly, isokinetic performance at baseline was lower in B2 at all three velocities, despite the fact that

RBE manifested as greater mean values over B2 due to more rapid recovery. This may suggest that either recovery following B1 was incomplete, or that having undergone a previous bout of damaging exercise, participants were dissuaded from providing maximal efforts. Indeed, an apparent trend for lower baseline performance in a repeated bout has been reported previously (Falvo, Schilling, & Smith, 2010). However, it is important to note that this lower baseline for B2 did not differ between groups (no three-way interaction), and was not observed for MIVC (a criterion measure for assessing EIMD). As such, this observation does not affect our conclusion - that RBE was attenuated in CG.

Another limitation of the current study is the loss of CK data, which may also have masked meaningful differences. The non-significant 31-62% reductions in CG are perhaps noteworthy considering the variable nature of this measure (Clarkson & Hubal, 2002; Hill et al., 2017; Paschalis et al., 2005). Individual EIMD responses were also highly variable, with pre-post declines in isometric strength varying from 5.3% to 59.6% in this sample. Similarly, the lack of effects from CG on soreness are also likely due in part to the highly subjective nature of this measure (Fitzgerald, Rothstein, Mayhew, & Lamb, 1991). Finally, as RBE is population and exercise specific (Hyldahl et al., 2017) it would be unwise to extrapolate these findings to other scenarios. Research on females and studies investigating the effects of compression pressure on strength and endurance adaptations are required.

Conclusion

Compression garments did not enhance muscular recovery in non-resistance trained males, although RBE for isokinetic strength was impaired. These findings provide the only evidence to date that the use of CG attenuates muscular adaptation. Based on these findings, the use of CG for recovery would not be recommended following unaccustomed exercise, particularly if the maintenance of high-velocity performance, and resilience to EIMD are desirable.

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Author contributions

FB, HJ, CP, GH and KvS conceived and designed the research. FB conducted experiments, acquiring and analysing all data, with JT contributing analytical tools, before FB, JT, MH, DR, GH and KvS all contributed to interpreting the results. FB analysed data and wrote the manuscript, with support in drafting, and critically revising the article provided by all authors.

All authors approved the final version of the manuscript, agree to be accountable for all aspects of the work, and qualify for authorship due to their contributions listed above. All those who qualify for authorship are listed.

Conflict of interests

The authors did not receive support or funding from any organization for the submitted work, and have no competing interests to declare.

Supplementary Table. Raw and relative values for indices of muscle damage over time

		Bout 1					Bout 2					T	B	T x B	G x B
Measure	**Time**	**Pre**	**Post**	**24 h**	**48 h**	**72 h**	**Pre**	**Post**	**24 h**	**48 h**	**72 h**	***p***	***p***	***p***	***p***
MVIC (N)	CG	639 ± 122	465 ± 115	513 ± 126	563 ± 140	606 ± 139	646 ± 128	514 ± 137	604 ± 146	637 ± 139	644 ± 161				
	PLA	635 ± 141	453 ± 130	480 ± 135	531 ± 138	563 ± 129	661 ± 135	502 ± 137	577 ± 141	622 ± 142	638 ± 138	***	***	**	
IKD	CG	560 ± 115	440 ± 100	466 ± 102	479 ± 107	510 ± 106	528 ± 89	459 ± 108	494 ± 121	511 ± 119	516 ± 125				
60°.s^{-1} (N)	PLA	611 ± 123	450 ± 102	450 ± 132	485 ± 137	498 ± 111	559 ± 108	455 ± 109	528 ± 111	546 ± 109	560 ± 104	***	***	***	*
IKD	CG	518 ± 98	413 ± 92	433 ± 104	442 ± 112	472 ± 121	468 ± 104	416 ± 109	454 ± 119	451 ± 107	466 ± 113				
120°.s^{-1} (N)	PLA	542 ± 112	419 ± 100	419 ± 105	442 ± 122	473 ± 105	516 ± 97	439 ± 90	486 ± 82	488 ± 106	514 ± 111	***	***	***	***
IKD	CG	480 ± 81	403 ± 76	413 ± 80	419 ± 98	451 ± 94	450 ± 72	395 ± 97	438 ± 99	429 ± 98	448 ± 91				
180°.s^{-1} (N)	PLA	504 ± 92	411 ± 90	409 ± 104	419 ± 96	436 ± 102	470 ± 88	419 ± 77	462 ± 58	465 ± 78	477 ± 83	***	***	***	***
PPT (W)	CG	1016 ± 205	918 ± 211	964 ± 221	1010 ± 223	1027 ± 217	1058 ± 232	990 ± 220	1061 ± 240	1079 ± 223	1101 ± 226				
	PLA	1017 ± 146	884 ± 184	941 ± 163	975 ± 141	1014 ± 144	1038 ± 154	947 ± 155	1021 ± 171	1046 ± 154	1069 ± 149	***	***		
MTG (cm)	CG	54.5 ± 4.5	54.8 ± 4.5	54.8 ± 4.5	54.9 ± 4.5	54.9 ± 4.7	54.7 ± 4.8	55 ± 4.9	54.9 ± 4.8	55 ± 4.8	54.9 ± 4.9				
	PLA	55.5 ± 4.4	55.8 ± 4.4	56.1 ± 4.6	56.2 ± 4.6	56.1 ± 4.7	55.9 ± 4	56.1 ± 3.9	56.1 ± 4	56.1 ± 4	56.1 ± 4	***	**		**
SOR (AU)	CG	1.2 ± 1.3	4.8 ± 2.4	5.1 ± 2	5 ± 2.1	3.1 ± 1.8	0.5 ± 0.5	3.5 ± 2.4	3.3 ± 1.8	2.6 ± 1.8	1.4 ± 1.3				
	PLA	1 ± 1.1	5 ± 2.3	5.9 ± 2.1	5 ± 2.3	2.9 ± 1.5	0.6 ± 0.7	3.4 ± 2.2	3.4 ± 1.9	2.4 ± 1.6	1.4 ± 1.4	***	***	***	
[CK] (IU)	CG	264 ± 189	347 ± 226	1351 ± 1372	833 ± 839	672 ± 356	260 ± 160	305 ± 149	505 ± 229	380 ± 212	374 ± 447				
	PLA	360 ± 239	468 ± 228	1249 ± 1159	1205 ± 1427	1755 ± 4229	321 ± 159	398 ± 168	657 ± 283	451 ± 195	355 ± 124	**	***		

Values as percentage of baseline

		Bout 1					Bout 2				
Measure	**Time**	**Pre**	**Post**	**24 h**	**48 h**	**72 h**	**Pre**	**Post**	**24 h**	**48 h**	**72 h**
MVIC	CG	100 ± 0	73 ± 12	80 ± 13	88 ± 13	94 ± 12	102 ± 9	82 ± 19	95 ± 13	100 ± 12	101 ± 11
	PLA	100 ± 0	71 ± 15	76 ± 14	84 ± 15	90 ± 15	109 ± 13	83 ± 19	95 ± 20	103 ± 19	105 ± 17
IKD	CG	100 ± 0	79 ± 14	84 ± 13	86 ± 12	92 ± 10	97 ± 14	84 ± 14	89 ± 13	92 ± 11	93 ± 11
60°.s^{-1}	PLA	100 ± 0	74 ± 11	74 ± 17	79 ± 16	83 ± 16	95 ± 15	78 ± 17	90 ± 19	92 ± 13	95 ± 13
IKD	CG	100 ± 0	80 ± 11	83 ± 12	85 ± 11	91 ± 13	91 ± 9	81 ± 13	88 ± 11	87 ± 10	90 ± 10
120°.s^{-1}	PLA	100 ± 0	77 ± 11	78 ± 12	81 ± 15	88 ± 13	98 ± 11	84 ± 14	93 ± 10	93 ± 12	97 ± 10
IKD	CG	100 ± 0	84 ± 7	86 ± 10	87 ± 12	94 ± 13	95 ± 8	83 ± 13	91 ± 12	89 ± 11	94 ± 9
180°.s^{-1}	PLA	100 ± 0	81 ± 9	81 ± 15	83 ± 12	87 ± 15	96 ± 13	86 ± 13	95 ± 8	95 ± 13	98 ± 13
PPT	CG	100 ± 0	90 ± 9	95 ± 10	99 ± 9	101 ± 8	104 ± 6	98 ± 11	105 ± 10	107 ± 11	109 ± 10
	PLA	100 ± 0	87 ± 13	92 ± 8	96 ± 6	100 ± 7	104 ± 9	95 ± 12	103 ± 12	105 ± 11	108 ± 10
MTG	CG	100 ± 0	100.5 ± 0.5	100.5 ± 0.6	100.6 ± 0.9	100.7 ± 0.8	100.8 ± 1.9	101.3 ± 2	101.3 ± 1.7	101.4 ± 1.8	101.2 ± 1.7
	PLA	100 ± 0	100.5 ± 0.5	101.1 ± 0.9	101.3 ± 1	101.1 ± 0.9	100.7 ± 2.9	101 ± 3	101 ± 2.8	101 ± 2.8	101 ± 2.8
[CK]	CG	100 ± 0	139 ± 25	627 ± 741	402 ± 484	323 ± 228	122 ± 69	153 ± 114	255 ± 197	179 ± 105	195 ± 282
	PLA	100 ± 0	146 ± 40	495 ± 682	482 ± 646	700 ± 1692	113 ± 71	145 ± 84	244 ± 175	159 ± 97	129 ± 75

Results shown as mean ± SD; * = p ≤ 0.05; ** = p ≤ 0.01; *** = p ≤ 0.001; T = effect of time; B = effect of bout; T x B = Time x bout interaction; G x B = Group x bout interaction; CG = Compression garments; PLA = Placebo; Pre = Pre-exercise; Post = Post-exercise; MVIC = Maximal voluntary isometric contraction; IKD = Maximal voluntary isokinetic contraction; PPT = peak power output in the 6 s cycle sprint test; MTG = Mid-thigh girth; AU = Arbitrary units; [CK] = Creatine kinase activity; IU = International units

Abbreviations

ANOVA: Analysis of variance

B1: Initial exercise bout

B2: Repeated exercise bout

CG: Compression garments

CI: Confidence intervals

CK: Creatine kinase

CV: Coefficient of variation

DJ: Depth-jumps

EIMD: Exercise-induced muscle damage

ES: Effect size (Cohen's d)

F_{ave}: Average force

F_{pk}: Peak force

HR_{med}: Median heart rate

HR_{pk}: Peak heart rate

IKD: Maximal voluntary isokinetic contraction

LCL: Lower confidence limit

MB1: Manufacturer's B1 point, defined as equidistant between the point of narrowest circumference at the ankle, and the point of maximal calf circumference

MIVC: Maximal isometric voluntary contractions

MTG: Mid-thigh girth

PLA: Placebo

PPT: Peak power output in the 6 s cycle sprint test

RBE: Repeated bout effect

RMSE: Root mean squared error of residuals

TOV: Take-off velocity

UCL: Upper confidence limit