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Graded Compression Garments Worn During Resistance Exercise: Impact on Muscle Damage, Fatigue, and Oxygenation in Untrained Individuals

Joshua A. Cotter*, Makenzie R. Stade, Bria G. Morse, and Evan E. Schick

Physiology of EXercise and Sport (PEXS) Lab, Department of Kinesiology, California State University, Long Beach, 1250 Bellflower Blvd, Long Beach, CA, USA

Corresponding Author: Joshua A. Cotter, E-mail: joshua.cotter@csulb.edu

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ABSTRACT

Background: Use of compression garments during and after exercise has gained notable popularity, yet their utility in augmenting performance and recovery from resistance exercise remains elusive. **Objective**: The purpose of this study was to evaluate the effects of wearing compression garments during resistance exercise on exercise-induced muscle damage (EIMD), muscle fatigue and muscle oxygenation. **Methods:** Ten healthy, untrained individuals (8 females, 2 males, 22.10 ± 2.23 years, 159.09 ± 3.47 cm, 66.22 ±15.93 kg; mean ± SD) performed two exercise trials in a randomized crossover (within-subject) design: 1) with compression garments worn on the legs and 2) without compression. Exercise trials were randomized and separated by seven days. Participants performed 12 sets of 10 maximal repetitions of knee extension, at a velocity of 120 degrees per second, in the CON/ECC mode of a HUMAC NORM isokinetic dynamometer. Muscle oxygenation of the vastus medialis oblique was assessed using time-resolved near-infrared spectroscopy (TRS-21, Hamamatsu). Leg circumference, ratings of perceived muscle soreness (RPMS) and blood samples for creatine kinase (CK) were collected before, immediately after, and 24, 48 and 72 hours after exercise. **Results:** Total hemoglobin ($p = 0.021$) and deoxyhemoglobin ($p < 0.001$) were significantly reduced by 8.6% and 9.2% respectively with compression compared to control. No significant differences were found in oxyhemoglobin, oxygen saturation, muscle fatigue, leg circumference, RPMS and CK ($p = 0.0791$) between conditions. **Conclusions:** Although lower body compression worn during resistance exercise reduced total hemoglobin and deoxyhemoglobin, there was no impact on muscle fatigue, RPMS, leg circumference or CK.

Key words: Creatine Kinase, Isokinetic Dynamometry, Muscle Fatigue, Spectroscopy, Near-Infrared, Resistance Training, Hemodynamics

INTRODUCTION

Use of graded compression garments (GCG) has surged in popularity among athletes in various sports and competitive levels (Born et al., 2013). Although GCG has traditionally been used to treat vascular pathologies, the athletic apparel industry has helped fuel a non-clinical outgrowth by incorporating GCG into a variety of athletic sleeves, stockings, tops, and lower-body garments. Apparel manufacturers purport that GCG accelerates recovery and improves performance by enhancing blood flow and muscle oxygenation while also attenuating fatigue and exercise–induced muscle damage (EIMD) (Lawrence & Kakkar, 1980; Liu, et al., 2008; MacRae et al., 2011). To date, substantiating such claims has proven challenging as reports investigating the use of GCG, worn intra- and/or post- aerobic or anaerobic exercise, offer conflicting findings (MacRae et al., 2011).

Periods following strenuous or unaccustomed exercise are often associated with EIMD, characterized by mechanical damage to the sarcomere, inflammation, increased muscle protein plasma concentrations and reduced strength (Clarkson & Hubal, 2002). Utilizing post-exercise GCG for periods ranging from 80 minutes to five days has been found to reduce plasma creatine kinase (CK) concentrations, limb circumference and ratings of perceived muscle soreness (RPMS) (Gill et al., 2006; Goto & Morishima, 2014; Kraemer et al., 2001; Kraemer et al., 2010). However, others have reported that post-exercise GCG does not appear to influence measures of plasma CK, limb circumference or RPMS following strenuous plyometric exercise (Davies et al., 2009; Jakeman et al., 2010).

Post-exercise GCG, worn as a means of reducing skeletal muscle fatigability, yields similarly mixed results. Although post-exercise GCG has been found to aid in strength and power maintenance during repeated bouts of resistance exercise and maximal cycling (Chatard et al., 2004; Goto & Morishima, 2014), other investigations of endurance running

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and cycling, intermittent sprints and resistance exercise have failed to demonstrate any benefit (Ali et al., 2007; Bieuzen et al., 2014; Kraemer et al., 1998; Martorelli et al., 2015; Scanlan et al., 2008; Trenell et al., 2006).

Analyses of aerobic modes of exercise illustrate that intra-exercise GCG may impact metabolism by enhancing muscle oxygenation and venous hemodynamics, facilitating the clearance of metabolites and deoxygenated blood (Bieuzen et al., 2014; Born et al., 2013; Scanlan et al., 2008; Sear et al., 2010). This may help explain improvements in performance with the use of GCG during endurance tasks of running and jumping (Ali et al., 2007; Doan et al., 2003; Kraemer et al., 1996). Although intra-exercise GCG appears to influence muscle metabolism through improved muscle oxygenation during aerobic exercise, this relationship is yet to be examined with resistance exercise.

The above-mentioned research has produced conflicting results when assessing post-exercise usage of GCG. Additionally, intra-exercise GCG has focused predominantly on aerobic modes of exercise, neglecting its usage during resistance exercise. Given these gaps in the literature, the impact of utilizing GCG during and following a damaging bout of resistance exercise remains unclear. Herein, the aim of the current study was to evaluate the effect of lower body GCG, worn intra- and immediately post-resistance exercise, on indices of EIMD, muscle fatigue and muscle oxygenation in untrained individuals. Both males and females were recruited for the study as there is evidence of a similar stress response to a heavy bout of resistance exercise in trained individuals (Kraemer et al., 2010). A randomized crossover study design was employed, incorporating two exercise trials: 1) with compression garments worn on the legs and 2) without compression (wearing loose fitting shorts). It was hypothesized that compression would reduce measures of EIMD, mitigate decreases in muscular fatigue, and improve muscle oxygenation.

METHODS

Participants and Study Design

The study utilized a randomized crossover design (within-group) with each participant performing the exercise protocol with and without graded compression garments. The study design was chosen to allow each participant to serve as their control and to increase power and statistical efficiency thereby requiring a lower sample size compared to parallel-group trials (Wellek & Blettner, 2012). An a priori sample size calculation was conducted with Statmate 2.0 (GraphPad Software, San Diego, CA, USA) utilizing CK data from Chapman (Chapman, Newton, Sacco, & Nosaka, 2006). With an expected standard deviation of 84 U/L and correlation (r) among pairs equaling 0.9, the analysis determined that ten participants would be needed to detect a difference between means of 35.29 U/L with a significance level (alpha) of 0.05 (two-tailed) and power = 80%. Ten individuals (8 females, 2 males, 22.10 ± 2.23 years, 159.09 ± 3.47 cm, 66.22 ±15.93 kg; mean ± SD) participated in the study. Participants were evaluated with a physical activity readiness questionnaire (PAR-Q) to assess any risks associated with exercise. Any participant that answered “Yes” to any of the questions was excluded from the study. Participants also completed an activity and injury assessment form. Inclusion criteria required participants to be between 18 and 30 years of age and free of any musculoskeletal injuries, cardiovascular or metabolic disorders and compromised blood circulation. Additionally, it was required that they had not regularly participated in a resistance training exercise program in the two years preceding their involvement in the study. Prior to study involvement, all participants provided written consent to participate. Study procedures were approved by the Institutional Review Board at California State University, Long Beach.

Exercise Protocol

The exercise protocol was performed on a HUMAC NORM Extremity System (Computer Sports Medicine Inc., Stoughton, MA, USA). This mode of exercise was chosen as each repetition can be of maximal exertion. Participants completed one to three familiarization trials where they were introduced to the protocol and equipment. The number of familiarization trials was dictated by the participant’s level of comfort with the equipment and protocol. During the familiarization sessions, participants were set up on the HUMAC NORM to ensure the anatomical axis of the knee joint, determined by the lateral condyle of the femur, was aligned with the mechanical axis of the dynamometer (Akima et al., 2004). Range of motion for the flexion/extension motion was set to 90 degrees of motion measured from full knee extension (0 degrees of knee flexion). Adjustments for comfort were made at the participant’s request and measurements were recorded and replicated for the subsequent exercise sessions. A warm-up of 10 submaximal repetitions was employed for both familiarization and testing sessions. The exercise protocol consisted of 12 sets of 10 repetitions of knee extension in the CON/ECC mode of the isokinetic dynamometer with 60 seconds of rest between sets (Paschalis et al., 2005). The velocity of movement was set to 120 degrees per second for both knee extension and resisting knee flexion (pliometric/eccentric contraction of the quadriceps). A velocity of 120 degrees per second was utilized as previous research has demonstrated that faster velocity contractions induce greater amounts of muscle damage in comparison to slower velocities (Chapman et al., 2006). Average torque, measured in newton-meters (Nm), was evaluated for the assessment of muscular fatigue throughout the 12 sets of knee extension. Strong verbal encouragement was given during each exercise session to ensure maximal effort during both miometric/concentric and pliometric/eccentric contractions.

The GCG (independent variable) were commercially available and provided by a company requesting to remain anonymous. The garments were designed with a graduated pressure profile and covered the lower body from the superior aspect of the lateral malleolus up to the iliac crest. The GCG were fit to each participant according to the manufacturer’s guidelines. The order of the exercise trials was randomized and separated by seven days. Compression garments were removed after all the immediate post-exercise measurements were collected.

After each exercise trial, participants were instructed to refrain from exercising and from using any nonsteroidal anti-inflammatory drugs, ice, massage, topical ointments, or any other type of post-exercise recovery modality for 72 hours (Davies et al., 2009; Jakeman et al., 2010; Pruscinom et al., 2013).

Measurement Protocols

Blood samples, leg circumferences and RPMS were collected before, immediately after, and 24, 48 and 72 hours after exercise. All near-infrared spectroscopy (NIRS) measurements were collected before, during and immediately after the exercise protocol. Details for the measurement of the dependent variables are found in the below subsections.

Biochemistry

Approximately 250-300 µL of capillary blood was collected into microvette EDTA-coated tubes (Sarstedt Inc., Newton, NC, USA) and centrifuged at 14 000 RPM for 10 minutes at 4 ºC. Approximately 100 µL of plasma was then extracted from the sample and stored in 200 µL PCR tubes at -20 ºC before analysis. Creatine kinase concentration was analyzed using a creatine kinase activity colorimetric assay kit (RayBiotech, Norcross, GA, USA) (Fan et al., 2013). The assay was performed according to the manufacturer's instructions. Creatine kinase quantification occurred by allowing the assay reaction to proceed for thirty minutes, during which time a SpectraMax M2 microplate reader (Molecular Devices, Sunnyvale, CA, USA) set in kinetic mode measured the absorbance of the reaction at 450 nm every two minutes (Fan et al., 2013).

Leg circumference

Leg circumference at the mid-point between the lateral side of the patella and the greater trochanter was measured with a flexible tape measure. Two measurements were taken immediately before the exercise protocol, immediately after and at each subsequent data collection visit. The two measurements were then averaged for each collection time (Goto & Morishima, 2014).

Rating of perceived muscle soreness

A visual rating scale was used to assess the participant's RPMS (Bieuzen et al., 2014; Kraemer et al., 2010; Trenell et al., 2006). The scale ranged from 0 indicating "No Soreness" to 10 indicating "Extreme Soreness." The measurement was taken in a standing position and participants were encouraged to shift their weight from leg to leg and perform several knee flexion/extension movements before rating.

Near-infrared spectroscopy

Micromolar (µM) concentrations of oxyhemoglobin (HbO_2), deoxyhemoglobin (Hb), total hemoglobin (tHb) and oxygen saturation (SO_2) of the vastus medialis oblique (VMO) were measured immediately before, during and immediately after the exercise protocol using a time-resolved near-infrared spectroscopy (TR-NIRS) instrument (TRS-21, Hamamatsu KK, Japan). The VMO was chosen due to its perceived importance in injury reduction of the knee and patellofemoral pain syndrome assessment (Patterson & Ferguson, 2010; Prior et al., 2004). Additionally, Ganesan et al. (2015) has reported data obtained from the TRS-21 during knee extension on an isokinetic dynamometer (Ganesan et al., 2015). It is important to note that the TR-NIRS is unable to distinguish between hemoglobin and myoglobin (de Ruiter et al., 2005). It can be assumed that myoglobin concentrations remain unchanged and any fluctuations in concentrations are associated with changes in hemoglobin (Messere & Roatta, 2013). Therefore, the measured concentrations of HbO_2, Hb and tHb are actually the sum of hemoglobin and myoglobin proteins.

The laboratory lights were dimmed to avoid any light interference and the TRS-21 was calibrated by measuring the instrument function according to the manufacturer's guidelines prior to each exercise session. The optical fibers were then secured in a rubber holster with an interoptode distance of 30 mm. The site was shaved and cleaned with alcohol and the fibers and holster were placed parallel to the oblique fibers of the muscle belly of the VMO using double-sided adhesive tape and were further secured with an elastic covering (Ganesan et al., 2015). The location of the fibers was marked with a surgical pen to ensure the placement was accurately replicated during the subsequent exercise session.

Statistical Analysis

Data analysis was performed with GraphPad Prism 8 (GraphPad Software, San Diego, CA, USA) with significance set at $p < 0.05$. A two-way (condition x time) repeated measures analysis of variance (ANOVA) was used for assessing differences in the dependent variables using the Geisser-Greenhouse correction for sphericity. When significant main or interaction effects were found, post-hoc comparisons with Sidak's multiple comparisons test were conducted to identify where mean differences occurred. Area under the curve (AUC) was assessed by a two-tailed t-test. Data is presented as mean ± standard deviation (SD) and 95% confidence intervals (CI) as CI: lower limit, upper limit.

RESULTS

Exercise-induced Muscle Damage

All ten participants completed both exercise trials. Leg circumference, RPMS, and plasma CK were measured to assess EIMD. There were no significant differences in leg circumference; however, there was a significant main effect of time for RPMS ($F(2.55, 22.95) = 12.20$, $p < 0.001$) with no differences between conditions ($F(1, 9) = 1.04$, $p = 0.335$). Compared to baseline, RPMS scores were elevated immediately post ($p < 0.001$; CI: 0.911, 4.189), 24 hours post ($p < 0.001$; CI: 1.461, 4.739), 48 hours post ($p < 0.001$; CI: 1.811, 5.089) and 72 hours post ($p = 0.009$; CI: 0.3613, 3.639; Figure 1). There was no significant main effect of time ($F(1.90, 17.06) = 2.99$, $p = 0.079$) or condition

(F(1, 9) = 0.588; p = 0.463) for CK (Figure 2). Area under the curve was 11 661 ± 4114 U/L·hr (CI: 3597, 19 726) and 11 913 ± 2905 U/L·hr (CI: 6219, 17 606) for the control and compression conditions respectively with no differences between conditions (t(89) = 0.05, p = 0.960).

Muscle Fatigue

There was a significant main effect of time showing decreased average torque in sets 5 through 12 compared to set 1 (F(1.75, 15.78) = 23.85, p < 0.001), but no effect of condition (F(1, 9) = 2.124, p = 0.179; Figure 3). Average torque was decreased by 20.7% (p = 0.032; CI: 5.761, 20.21), 25.1% (p = 0.008; CI: 8.503, 22.95), 27.8% (p = 0.002; CI: 10.16, 24.61), 28.7% (p = 0.003; CI: 10.72, 25.17), 32.1% (p < 0.001; CI: 12.87, 27.31), 34.4% (p < 0.001; CI: 14.33, 28.78), 35.6% (p < 0.001; CI: 15.05, 29.50), and 33.3% (p < 0.001; CI: 13.65, 28.10) respectively for sets 5 through 12.

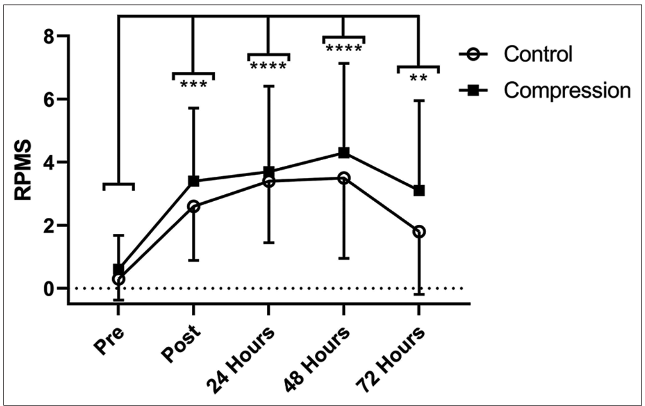

Figure 1. Ratings of perceived soreness before exercise (pre), and immediately (post), 24 hours, 48 hours, and 72 hours post exercise. **p < 0.01, ***p < 0.001, and ****p < 0.0001 denote time effects compared to baseline values (pre) for both conditions combined). Data presented as mean ± SD. Abbreviation: RPMS = ratings of perceived soreness

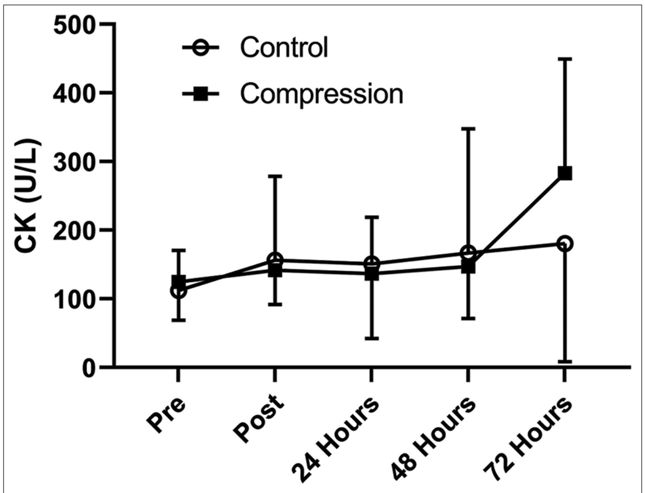

Figure 2. Plasma concentrations of creatine kinase before exercise (pre), and immediately (post), 24 hours, 48 hours, and 72 hours post exercise. Data presented as mean ± SD. Abbreviation: CK = creatine kinase

Blood Flow and Muscle Oxygenation

Total hemoglobin was decreased by 8.6% while wearing GCG compared to control (F(1, 9) = 7.75, p = 0.021). Furthermore, there was a main effect of time (F(1.35, 12.17) = 6.774, p = 0.017) but no interaction effect (F(1.87, 16.84) = 1.922, p = 0.179). Compared to baseline, tHb was reduced by 12.56% in set 1 only (p = 0.031; CI: 0.64, 13.42) with subsequent sets and rest periods not being significantly different (p > 0.05; Figure 4a). There was a main effect of condition for Hb (F(1, 9) = 26.290, p < 0.001) but no time (F(1.34, 12.05) = 3.986, p = 0.060) or interaction effect (F(3.01, 27.12) = 1.420, p = 0.259). Deoxyhemoglobin was reduced 9.2% while wearing GCG compared to control (CI: 1.081, 2.789); Figure 4b). A main effect of time (F(1.42, 12.79) = 6.984, p = 0.014) was found for HbO_2 with no condition (F(1, 9) = 3.856, p = 0.081) or interaction effect (F(1.40, 12.59) = 0.758, p = 0.444). Compared to baseline, HbO_2 was reduced in set 1 only by 17.9% (p = 0.017; CI: 0.648, 12.690 (Figure 4c). Oxygen saturation showed a main effect of time (F(1.72, 15.43) = 18.38, p < 0.001) but no condition (F(1, 9) = 4.035, p = 0.076) or interaction effect (F(3.31, 29.76) = 0.751, p = 0.542). Compared to baseline, SO_2 was reduced by 7.8% (p < 0.001; CI: 2.46, 7.59), 7.9% (p < 0.001, CI: 2.55, 7.67), 8.2% (p < 0.001; CI: 2.77, 7.90), 8.5% (p < 0.001; CI: 2.92, 8.05), 7.8% (p < 0.001; CI: 2.50, 7.63), 6.8% (p < 0.001; CI: 1.82, 6.95), 6.3% (p < 0.001; CI: 1.49, 6.61), 5.4% (p = 0.004; CI: 0.923, 6.05), 5.0% (p = 0.005; CI: 0.683, 5.81), and 4.2% (p = 0.022; CI: 0.208, 5.34) respectively in sets 1 through 10 but showed an increase of 6.7% during recovery (p = 0.004; CI: 1.75, 6.88; Figure 4d).

DISCUSSION

Given the popularity of GCG the purpose of this study was to evaluate the use of intra-exercise lower body compression on indices of EIMD, muscular fatigue and hemodynamics during and after strenuous resistance exercise. There are sev-

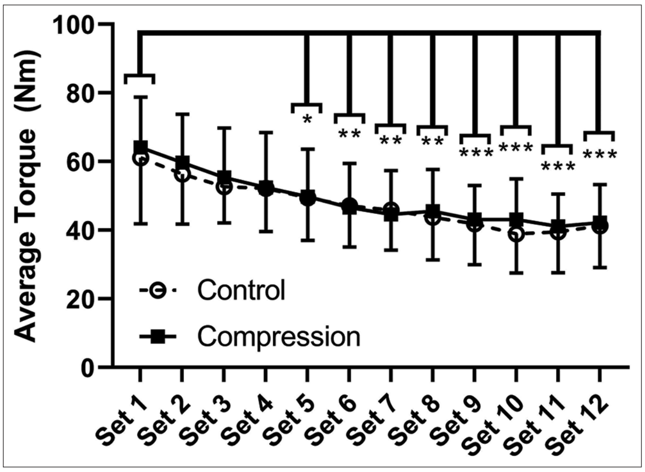

Figure 3. Average torque (Nm) during the exercise protocol. *p < 0.05, **p < 0.01, and ***p < 0.001 denote time effects compared to set 1 for both conditions combined. Data presented as mean ± SD

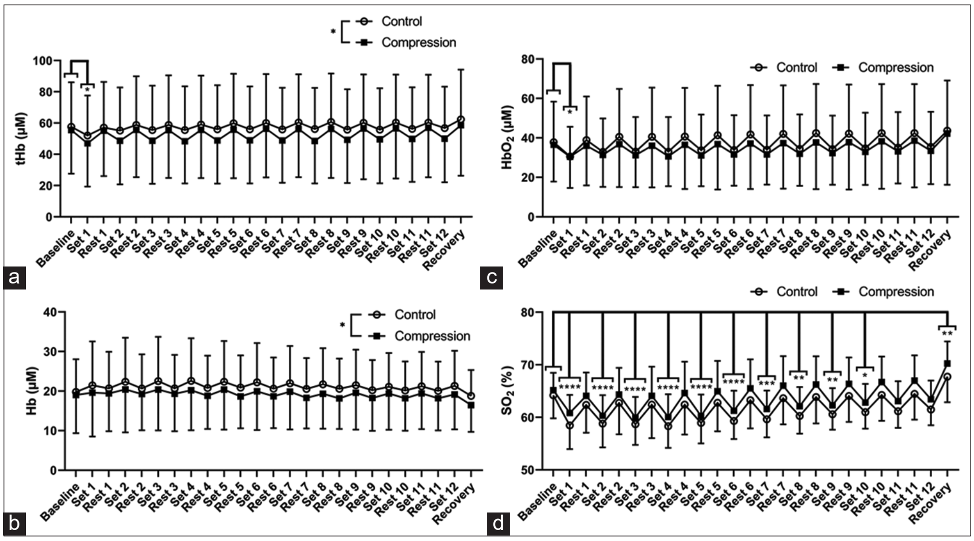

Figure 4. Total hemoglobin (a), deoxyhemoglobin (b), oxyhemoglobin (c), and oxygen saturation (d) at baseline, during set and rest periods, and during recovery following the exercise protocol. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, and ****$p < 0.0001$ denote a main effect of time compared to baseline for both conditions combined and a main effect of condition. Data presented as mean ± SD. Abbreviation: Hb = deoxyhemoglobin; HbO_2 = oxyhemoglobin; SO_2 = oxygen saturation; tHb = total hemoglobin

eral important findings of the study. First, the exercise protocol, designed to elicit a muscle damage response, increased RPMS but did not have an effect on leg circumference or plasma CK. Second, the incorporation of compression had no effect on the indices EIMD nor any effect on the average torque produced during the exercise protocol. Third, compression decreased the amount of Hb and tHb in the VMO but did not significantly affect levels of HbO_2. This however did not result in higher SO_2 when wearing GCG during the exercise protocol ($p = 0.076$). These findings are in contrast to the investigators' hypotheses which may have several potential explanations as discussed herein.

Compression and control conditions experienced a similar EIMD response as illustrated by comparable changes in plasma CK, leg circumference, and RPMS. An inflammatory response accompanied by edema partly characterizes the EIMD response (Clarkson & Hubal, 2002). The measurement of limb circumference is a method used to capture the morphological change caused by swelling (Chapman et al., 2006). In the present study, the exercise protocol did not affect leg circumference at any time point post-exercise with or without GCG worn during and post-exercise. This result mirrors previous research which showed no effect on mid-thigh circumference during a 48-hour recovery period following maximal drop-jumps with or without compression worn only during the recovery period (Davies et al., 2009). Additionally, Kraemer et al. (2010) showed that whole-body compression did not alter upper or lower body limb circumferences which, like in the current study, also did not change following a heavy bout of resistance training (Kraemer et al., 2010). Yet, in this same study, ultrasound imaging showed significantly lower measures of swelling in comparison to the control condition. This evidence suggests that limb circumference alone may not be a sensitive measure of muscle swelling (MacRae et al., 2011). Given the results of the current study and the aforementioned research on the EIMD response, multiple measures of edema should be incorporated when studying the effects of compression garments during and following resistance or plyometric training.

Although RPMS increased throughout post-exercise time points, it did not differ between conditions. This finding, which suggests that compression did not mitigate feelings of soreness, agrees with studies by Trenell et al. (2006) and Ali et al. (2007), which found that compression failed to alter soreness following downhill walking and intermittent shuttle runs, respectively (Ali et al., 2007; Trenell et al., 2006). Additionally, in trained males and females following a heavy bout of resistance exercise, soreness ratings of the upper body, but not the lower body, were significantly different between whole body compression garment and control garment (Kraemer et al., 2010). Nevertheless, RPMS is a subjective measure of EIMD, and consequently, in a repeated measures design, it is possible that the absence of a placebo or participant blinding may have influenced subjective measures like RPMS. The results of the current study suggest that the implemented exercise protocol of 12 sets of 10 repetitions of maximal knee extension in the CON/ECC mode of an isokinetic dynamometer was conducive at creating a condition of muscle soreness in untrained participants.

Elevated serum CK following exercise indicates damage to myofibrillar machinery and increased permeability of the muscle fiber (Friden et al., 1983). Whether intra-exercise compression may influence post-exercise CK remains unclear. The current study found that compression worn during resistance exercise did not seem to confer an artificial "dynamic casting" effect, wherein faster recovery of muscle function is due to more normal soft tissue alignments and thus, hypothetically, greater protection of myofibrillar protein structures (Kraemer et al., 2001). Peak CK levels in the current study occurred at the 72 hour mark with values of 180.80 U/L and 283.20 U/L for the control and compression conditions respectively. These levels are small compared to

1,350 U/L observed by Kraemer (2001) 72 hours post-exercise with 12 sets of 50 maximal pliometric/eccentric contractions of the bicep curl exercise with no compression (Kraemer et al., 2001). In the same study, compression worn during the recovery period reduced CK to ~450 U/L; however, compression was not worn during the exercise bout. In a meta-analysis reviewing literature on compression and recovery of EIMD, it was reported that although GCG may assist athletic recovery following exercise, results have been isolated or inconclusive (Marques-Jimenez et al., 2016). More specifically, GCG do not appear to attenuate increases in CK following exercise (Marques-Jimenez et al., 2016). The velocity of movement for the exercise protocol in the current study was chosen based on data from Chapman (2006), which revealed an increase in CK responsiveness with faster velocity elbow flexion movements compared to slower velocity (Chapman et al., 2006). Peak CK levels were at 1298.2 U/L during the fast velocity trials. Together with Kraemer (2001), it appears that exercise involving elbow flexion may have a greater CK response following pliometric/eccentric exercise when compared to other joints (Chapman et al., 2006; Kraemer et al., 2001). In the present study, CK levels were measured up to 72 hours post-exercise with peak levels occurring at that time point. Conversely, Chapman (2006), observed peak CK levels at 96 hours post-exercise (Chapman et al., 2006). By failing to measure CK past the 72 hour time point, peak CK values may not have been observed in the current study. Lastly, CK, in both the Chapman study and current study, were measured in plasma using anticoagulated tubes, whereas as others have used serum tubes to capture circulating CK (Chapman et al., 2006; Kraemer et al., 2001; Totsuka et al., 2002). Comparing studies measuring plasma CK to those using serum CK is dubious, as the time-to-peak response of CK seems to differ widely depending on whether plasma or serum CK is measured (Baird et al., 2012). When assessing the effects of compression on indices of EIMD such as CK, several factors should be considered that may result in variable responses such as method of assessing blood markers (i.e. serum vs. plasma), length of time post-exercise the assessment occurs, and time periods when compression is worn (i.e. intra-exercise, post-exercise, intra- and post-exercise). Given that the current study did not observe any significant increase in CK 72 hours post-exercise, it is suggested for future research to measure CK to at least 96 hours post-exercise.

The current study utilized isokinetic dynamometry as the exercise mode for examining the impact of GCG on muscular fatigue. It should be emphasized that 10 sets of 12 repetitions utilizing maximal muscle contractions both miometrically/concentrically and pliometrically/eccentrically is a very rigorous protocol that cannot typically be duplicated with conventional weight equipment (i.e. barbells and dumbbells). Given the maximal nature of the exercise protocol, both conditions experienced similar progressive reductions in muscular torque, indicating that muscular fatigue was unaffected by GCG worn during the exercise bout. Others have reported similar findings, showing that compression plays a limited role in aiding performance in running, cycling and resistance exercise (Kerherve et al., 2017; Martorelli et al., 2015; Scanlan et al., 2008). It is therefore concluded that GCG worn during an exercise bout of multiple sets of maximal contractions did not reduce the effects of fatigue on torque production.

Ample evidence exists supporting the use of compression in the clinical setting in order to improve venous hemodynamics. Yet, a paucity of data exists surrounding the nature of how intra-exercise compression impacts hemodynamics during and after strenuous resistance exercise. Although results of the current study are congruent with previous research showing that intra-exercise compression does influence hemodynamics, there are inconsistencies on how compression does this. As described in previous reviews, differences in findings may result from multiple factors including, but not limited to, type of GCG, differing levels of applied compression, mode of exercise, exercise protocol, populations studied and various methods for measuring hemodynamics (Hill et al., 2014; MacRae et al., 2011). It is reported in the current study that GCG decreased both Hb and tHb with no change in HbO_2 and SO_2 in response to a maximal protocol of 12 sets of 10 repetitions of knee extension. The decreased concentrations of tHb with compression indicates that blood volume was reduced (Van Beekvelt et al., 2001). Previous research has suggested that improved venous return indicates greater removal of deoxygenated blood and metabolic by-products (Scanlan et al., 2008; Sear et al., 2010). Although reductions in Hb and tHb were observed in the current study, there were no changes in performance or indices of EIMD. Similarly, in the assessment of compression on an ~24km trail run, Kerherve et al. (2017) observed improvements in tissue oxygenation immediately post-exercise with calf compression sleeves but no improvement in run times (Kerherve et al., 2017). Scanlan (2008) also reported positive hemodynamic changes with improved exercise muscle O_2 economy yet no performance enhancement with a cycling time trial when using lower body compression (Scanlan et al., 2008). Multiple reviews in the last decade show that data examining the effects of compression on a damaging bout of resistance exercise, especially from the perspective of hemodynamic responses, is clearly lacking (Hill et al., 2014; MacRae et al., 2011; Marques-Jimenez et al., 2016). The investigators utilized TR-NIRS which allows for the measurement of absolute hemoglobin concentrations in tissue while considering path length and scattering which may lead to more accurate results when dealing with large changes in blood that generally occurs with exercise (Ganesan et al., 2015). To date, most studies have used continuous-wave NIRS which report only relative changes in tissue hemoglobin concentrations. The current study therefore adds important information to the literature elucidating the hemodynamic response to compression during and following a strenuous bout of resistance exercise utilizing more accurate technologies.

In addition to the above-mentioned limitations, it is pertinent to acknowledge other limitations associated with the study. The participants in this study were untrained and therefore the results should not be applied to those who are recreational- or elite-level athletes as prior training generally reduces the negative effects associated with a bout of exercise (Barnett, 2006). A mixed-sex approach was utilized in this study as Kraemer et al. (2010) reported relatively similar stress and response patterns following a heavy bout of resistance exercise in resistance-trained men and women (Kraemer et al., 2010). It should be noted that women in the Kraemer study had a reduced magnitude of power production resulting in lower markers of muscle damage which may at least partially explain the relatively lower levels of CK reported here. Given that the study utilized a crossover (within-group) design, the repeated bout effect (RBE) cannot be discounted. This phenomenon is characterized by an attenuation of physiological and performance responses from a 2^{nd} bout of strenuous exercise performed within several weeks of an initial bout of strenuous exercise (McHugh, 2003). In 2010, Kraemer et al. studied the effects of whole body compression garments on highly trained participants and similarly utilized a crossover design, however, there were only 72 hours separating each exercise bout in comparison to the seven days utilized in the current study. Despite the potential for an RBE, the authors reported decreased fatigue ratings, muscle soreness, ultrasound swelling, and creatine kinase when wearing whole body compression 24 hours following the exercise bout (Kraemer, 2010). Davies et al. also utilized a randomized crossover design with exercise separated by seven days, which is the same as the current study, and concluded that compression tights may attenuate the CK response in females and perceived muscle soreness (both males and females) following drop-jump training however there were no benefits to performance (Davies, 2009). Although there is ample evidence supporting an RBE, it appears that physiological and performance effects following plyometric or heavy resistance training can still be detected. Lastly, comparison of the data collected by NIRS should be made in consideration of the muscle and equipment utilized in this study. The VMO was chosen, as previously mentioned, due to its perceived importance in the optimal health of the knee joint. However, research literature to date has predominantly reported on the vastus lateralis and differential responses of the various quadricep muscles should be considered.

Strengths and Practical Implications

Graded compression garments continue to be a popular ergogenic aid utilized by athletes aiming to improve performance and recovery. Although numerous studies have been conducted on GCG, there is a paucity of research relating to their usage during and following maximal exertion resistance training that has a high likelihood of EIMD. Information from this and other similar studies help athletes and coaches determine whether or not GCG are warranted for use in their specific condition. The strength of this study is in the range of dependent variables assessed including biochemistry markers of muscle damage, subjective scores of pain, leg circumference, fatigue, and hemodynamic responses during and following a rigorous and controlled exercise protocol. The practical application gained from the study is that GCG are unlikely to provide a beneficial response on muscle damage, muscle soreness, and fatigue management during and following a maximal bout of leg exercise in untrained individuals.

CONCLUSION

In conclusion, the purpose of this study was to investigate the effects of lower body compression worn during resistance training on EIMD, fatigue, and muscle oxygenation. Results demonstrated that intra-exercise use of compression did not influence indices of EIMD or fatigue but did reduce levels of tHb and Hb. These results also suggest that compression influenced blood flow by increasing venous return; however, those hemodynamic changes did not impact performance or indices of EIMD. This study has provided data helping to fill a void in the current body of literature on the use of compression garments during fatiguing resistance exercise. Although EIMD as measured by CK was statistically unaffected 72 hours post-exercise, the observed hemodynamic changes suggest future research to examine potential implications for compression on EIMD at time periods greater than 72 hours. The incorporation of TR-NIRS provides insight into a rather uncharted area of research on GCG.

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