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The repeated bout effect of traditional resistance exercises on running performance across three bouts

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Abstract

Purpose This study investigated the repeated bout effect of three typical lower-body resistance training (RT) sessions on maximal and sub-maximal effort running performance. *Methods* Twelve resistance-untrained men (age 24±4 years; height 1.81±0.10 m; body mass 79.3±10.9 kg; $\dot{V}O_{2peak}$ 48.2±6.5 mL·kg^{-1}·min^{-1}; six-repetition maximum squat 71.7±12.2kg) undertook three bouts of RT sessions at six-repetition maximum. Counter-movement-jump (CMJ), lower-body ROM, muscle soreness and creatine kinase (CK) were examined prior to (T0), immediately-post (T1), 24 (T24) and 48 (T48) h post each RT bout. Sub-maximal (i.e. below anaerobic threshold [AT]) and maximal (i.e. above AT) running performance were also conducted at T24 and T48. *Results* Most indirect muscle damage markers (i.e., CMJ, ROM and muscle soreness) and sub-maximal running performance were significantly improved ($P < 0.05$; 1.9%) following the third RT bout compared to the second bout. Whilst maximal running performance was also improved following the third bout ($P < 0.05$; 9.8%) compared to other bouts, the measures were still reduced by 12-20% vs. baseline. However, the increase in CK was attenuated following the second bout ($P < 0.05$) with no further protection following the third bout ($P > 0.05$). *Conclusions* The initial bout induced the greatest change in CK, however at least two bouts were required to produce protective effects on other indirect muscle damage markers and sub-maximal running performance measures. This suggests that sub-maximal running sessions should be avoided for at least 48 hours post RT until the third bout, although a greater recovery period may be required for maximal running sessions.

Key words

Neuromuscular performance; muscle damage; range of motion; running economy; time-to-exhaustion

Introduction

Several studies have shown that chronic resistance training improves running economy (RE) and performance (Ronnestad and Mujika 2014; Skovgaard et al. 2014). However, unaccustomed resistance exercise may acutely cause exercise-induced muscle damage (EIMD), which is indicated by impaired muscle force generation capacity, increased muscle soreness, reduced range-of-motion (ROM) and leakage of intramuscular enzymes (Warren et al. 1999; Lavender and Nosaka 2006). The symptoms associated with EIMD have been reported to impair RE, although the majority of such studies have incorporated downhill running (Chen et al. 2007; Chen et al. 2009b) or isokinetic contractions (Assumpcao Cde et al. 2013). These muscle-damaging exercises, whilst effective, do not replicate typical real-world training scenario, given that the accessibility to such complex equipment (e.g. isokinetic machine) may be restricted. Therefore, examining the acute effects of traditional lower body resistance exercises (e.g., isoinertial concentric-eccentric exercises such as squats or leg-press exercises) on RE would improve the ecological validity from a training standpoint. Indeed, more recent studies have shown that traditional lower body resistance training exercises caused EIMD, and as a result, impaired running performance measures at both sub-maximal (Doma and Deakin 2013a; Doma and Deakin 2015) and maximal (Doma and Deakin 2013b; Doma and Deakin 2014) effort intensities for up to 48 hours post-exercise. Consequently, these findings suggest that inadequate recovery following traditional resistance training sessions may compromise the quality of subsequent endurance training sessions (Hayter et al. 2016).

Despite the high level of EIMD observed after an initial bout of resistance training exercises, these symptoms have been attenuated following the second bout, a phenomenon commonly known as the repeated bout effect (RBE) (McHugh 2003). Interestingly, Burt and colleagues (2013) have reported a similar trend in RE using traditional lower body resistance training exercise. According to their study, RE was impaired for up to 48 hours following 10 sets of 10 repetitions of back squats at 80% of body mass following the initial resistance training bout, but was not impaired following the second bout. Whilst these findings suggest that the initial exposure to EIMD appears to provide protection against muscle damage for sub-maximal running performance, sole incorporation of back squats may not be indicative of traditional resistance training sessions that consist of multiple exercises. Furthermore, prescription of resistance training intensity based on percentage of body mass does not account for individual differences in maximal strength, whereas repetition maximum (RM) is more common practice (Baechle and Earle. 2008). More recently, Doma et al. (2015) examined the acute effects of two RT bouts consisting of multiple resistance training exercises (i.e., back squats, single-leg leg press, leg extension and leg curls) performed at 6RM. The results showed that RE measures were impaired for up to 48 hours post-exercise after both resistance training bouts despite an attenuated response for the indirect muscle damage markers (i.e., creatine kinase [CK] and muscle soreness measures) following the second bout. Doma et al. (2015) suggested that the initial bout of resistance training may not have provided protection against EIMD for RE measures due to the resistance training being prescribed at a high intensity. However, it is possible that if an additional resistance training bout (i.e., three resistance training bouts) had been incorporated, further reduction in muscle damage markers may have occurred with additive RBE effects, thereby attenuating the level of impairment in sub-maximal running performance.

A number of studies have examined the acute effects of more than two eccentric exercise bouts on EIMD markers (Chen et al. 2009a; Barroso et al. 2010; Hassan 2014), although the findings have been controversial. For example, Barroso et al. (2010) and Hassan (2014) showed that the initial bout of eccentric exercises attenuated the level of impairment in strength measures and lower body ROM following the second bout, although no further protection was evident after the third and fourth resistance training bouts. Conversely, Chen et al. (2009a) found further attenuation in strength deficit and lower body ROM from the third to the fourth bout of eccentric contractions. Discrepancies in these findings may be attributed to differences in sample size and analytical power with Chen et al. (2009a) examining almost twice the number of healthy men (i.e., 15 participants) than that by Hassan et al. (2014) and Barroso et al. (2010) (i.e., 6-8 participants) (Hazra and Gotgay 2016). Accordingly, the findings by Chen et al. (2009a) demonstrates the inherent acute adaptations that occur following eccentric exercises and suggest that an increased frequency of eccentric exercise bouts may provide further protection against muscle damage, hereafter referred to as the repeated-repeated bout effect (R-RBE). However, previous studies examining R-RBE have focused on indirect muscle damage markers (e.g. muscular strength measures, muscle soreness, ROM and CK activity) using eccentric contractions only, which limits the ecological validity of the findings for typical training regimes. Determining the presence of R-RBE using traditional lower body resistance training exercises on running performance measures will increase our understanding of the dynamics of resistance training-induced fatigue post-exercise across multiple bouts. As a result, practitioners may be able to prescribe training programs that minimises carry-over effects of fatigue across training sessions by considering R-RBE, which has been reported to affect the course of chronic training adaptation (Coutts et al. 2007). However, studies have yet to report on the R-RBE of traditional lower body resistance training exercises on running performance measures. Subsequently, the purpose of the current study was to examine the acute effects of resistance training exercises across three bouts on running performance measures. It was hypothesised that the additional bout of resistance training exercises (i.e. the third bout) would minimise the detrimental effects of acute resistance training exercise on running performance.

Materials and methods

Participants

Twelve healthy men (age 24 ± 4 yrs; height 1.81 ± 0.10 m; body mass 79.3 ± 10.9 kg; peak oxygen uptake [VO_{2peak}] 48.2 ± 6.5 $mL \cdot kg^{-1} \cdot min^{-1}$) were recruited for the study. Prior to study commencement, the participants had been undertaking 30-60 minutes of running at a moderate intensity regularly (2-3 $times \cdot week^{-1}$) for the past 12 months but had not performed lower body resistance training for the past 6 months. Biological variations were controlled for by conducting the training and testing sessions at the same time of day, having participants wear the same shoes for every training and testing session, avoiding high-intensity physical activity for at least 48 hours prior to any tests, refraining from caffeine and food intake for at least 2 hours prior to testing and avoiding supplementation and/or medication (e.g. non-steroidal anti-inflammatory aids) and recovery activities during the course of the study. The participants provided written informed consent prior to partaking in any testing procedures, which were approved by the Institutional Human Research Ethics Committee and were conducted according to the Declaration of Helsinki. According to an *a priori* sample size calculation based on previous studies examining RE, running time-to-exhaustion (TTE) and indirect muscle damage markers (Doma and Deakin 2013b; Doma and Deakin 2014), 12 participants were adequate to detect a significant change in variables (>80% of power at an alpha level of 0.05).

Research design

This study was conducted as part of a larger research project utilising similar protocols and outcome variables (Doma et al. 2015) across 7 weeks (Figure 1). A familiarisation session was conducted during the first week to allow participants to familiarise themselves with the protocols and to determine their 6RM for squats, single-leg leg press, leg extension and leg-curls. At least two days following the familiarisation session, a VO_{2peak} test was conducted. During the second week, two running performance tests, with at least 24 hours of rest in-between each testing session, were conducted to ensure participants were acquainted with the protocol and to report on the repeatability of the running performance measures. During weeks 3-7, the participants undertook three resistance training bouts with 10-14 days of recovery in-between the first and second resistance training bouts and 7-10 days of recovery in-between the second and third resistance training bouts. Repeat running performance tests were conducted at 24 (T24) and 48 (T48) hours following each resistance training bout. The measures collected during the running performance test at T24 and T48 following each resistance training bout were then compared to the second running performance test conducted in week 2 as baseline. Furthermore, indirect muscle damage markers were collected prior to (T0) and immediately post (T1) each resistance training bout, and at T24 and T48.

Figure 1 around here

Peak oxygen uptake test

Prior to the VO_{2peak} test, a progressive warm-up was conducted on the treadmill (TM 601, Trackmasster, Newton, USA) by walking at 5 $km \cdot hr^{-1}$ and then jogging at 8, 10 and 12 $km \cdot hr^{-1}$ for 1-minute at each speed. The VO_{2peak} test was conducted using a continuous, incremental method and started at 9 $km \cdot hr^{-1}$ that was increased by 1.5 $km \cdot hr^{-1}$ every minute until volitional exhaustion was reached using verbal encouragement (Doma et al. 2012b). During the VO_{2peak} test, expired air was collected using an indirect calorimetry system (Quark CPET, Cosmed, Italy, Rome) to determine the second ventilatory threshold (VT_2). The VT_2 was quantified by ascertaining the inflection point of ventilation (V_E) with respect to carbon dioxide production on a scatter diagram (Neder and Stein 2006). The corresponding exercise intensity at VT_2 was then used to establish the running speeds during the running performance tests.

Running performance test

Following a warm-up identical to that of the VO_{2peak} test, the running performance test was conducted and consisted of two discontinuous incremental stages of running at 90% and 110% of VT_2, respectively, with 2-minutes of passive rest in-between each stage (Doma et al. 2012a). The participants ran for 10 minutes during the first stage and then to volitional exhaustion during the last stage to determine running time-to-exhaustion (TTE). During the running performance test, respiratory parameters were collected using an indirect calorimetry system (Quark CPET, Cosmed, Italy, Rome) and averaged during the last 5-minutes of the first stage to report oxygen consumption (VO_2), carbon dioxide (VCO_2), ventilation (VE), ventilation/oxygen consumption (VE/VO_2) and ventilation/carbon dioxide (VE/VCO_2). Heart rate (HR; RS800CX, Kempele, Finland) and rating of perceived exertion (RPE) were also collected on the 9th minute of the first stage. Measures were not collected during the second stage as the intent of this stage was to determine TTE.

Repetition maximum assessment

The 6RM session was completed for squats on a Smith Machine (MPL 706, Maxim Fitness, Australia), horizontal leg press (NS4000, Nautilus, Canada), leg extension (NS4000, Nautilus, Canada) and leg curls (NS4000, Nautilus, Canada). The participants performed the squat and leg press exercises until their knees were flexed to approximately 45 degrees at the amortization phase (i.e. in-between the concentric and eccentric phases). The range of motion was standardised for the squat and leg press exercises by recording the displacement of the external load using markers which was then used during each resistance training bout. The leg press exercise was performed unilaterally commencing with the right leg. The 6RM of each exercise was established within three attempts using methods described previously (Doma et al. 2015). Specifically, the participants warmed up by performing 10 repetitions of squats on the Smith Machine at approximately 50% of their body weight. The participant's RPE upon completion of the warm-up was notified and used to perform 8-10 repetitions at a load of near maximal effort. After a 5-minute recovery, 20% was added to the load as the first 6RM attempt. Participants were encouraged to terminate the attempt on the third repetition if they perceived the load to either be light or heavy for a 6RM and the load altered accordingly by 5-10%. The load was also altered if participants were unable to complete 6 full repetitions or was not at maximal effort during the 6^{th} repetition. Participants were given 5-10 minutes of rest in-between each attempt.

Resistance training bout

The resistance training bout consisted of exercises performed in the same order as the 6RM session (i.e., squats, single-leg leg press, leg extension and leg curls) with 3 sets of 6 repetitions. The resistance training intensity was set at 95% of 6RM to allow participants to complete each set without failure. The participants rated their level of difficulty immediately following the completion of each set using a visual analogue scale from 1 to 10 with "very easy" to "very difficult", respectively. Whilst none of the participants had rated a level of difficulty below 8, if a participant rated a level of difficulty classified below 9 during the first set, then the load was increased by 5% for the subsequent sets to ensure sufficient stress was induced for each exercise. Any changes in the load that occurred during the first resistance training bout was recorded and replicated during the second and third resistance training bout to ensure consistency in training volume. A passive 2-minute rest period was provided in-between each set and exercise. Previous research has shown this resistance training protocol to be successful in inducing lower limb symptoms of EIMD (Doma et al. 2015).

Indirect muscle damage markers

The indirect muscle damage markers consisted of countermovement jump (CMJ), lower extremity joint ROM, muscle soreness and CK activity. For the CMJ, the participants performed three jumps which were measured using a vertical jump apparatus (Yard Stick, Swift Performance, Queensland, Australia) with 1cm increments. Approximately 30-60 seconds of rest was provided in-between each attempt with the highest jump reported. The lower extremity ROM was determined for hip/torso flexion using a standard sit-and-reach test (FLEX-ROM) (Baechle and Earle 2008) and for hip abduction (ABD-ROM). The ABD-ROM was obtained by having participants maximally abduct their hips in a seated position on the floor and measuring the distance between each heel. Three attempts were provided for the FLEX-ROM and ABD-ROM with the best scores reported. Muscle soreness was determined for the thigh (Thigh-S), gluteal (Glute-S) and hamstring (Ham-S) muscle groups using a visual analogue scale from 1-10 with 1 defined as ‘no soreness’ and 10 as ‘very, very sore’ (Doma et al., 2015). The Thigh-S and Glute-S were obtained during a body weight squatting manoeuvre until the knees were flexed to approximately 45°. Conversely, Ham-S was measured via maximal isometric contractions of the right hamstrings. This measure was obtained by having participants stand on their left leg whilst their right knee was flexed at a 90° angle and their right limb held at the ankle. The CK measure was determined by obtaining a 30-µL fingertip, capillary sample from participants following 20 minutes of supine rest. The blood sample was immediately pipetted to a test strip and assessed for CK using a colorimetric assay method (Reflotron, Boehringer Mannheim, Germany). The intra-assay coefficient of variation for CK within our laboratory was 7.2%.

Statistical analyses

All data is reported as mean ± standard deviation and analysed using the Statistical Package of Social Sciences (SPSS, IBM, version 23). For all parameters, a two-way (bout x time) repeated measures analysis of variance (ANOVA) with a Tukey's post hoc test was used to determine differences between bouts (i.e., the three resistance training bout), time points (i.e., T0, T1, T24 and T48) and the interaction of these factors. The level of statistical significance was set at an alpha level of 0.05. The intra-class correlation coefficient (ICC, two-way mixed) was calculated to determine the test-retest reliability of the running performance measures and CMJ with values above 0.75, between 0.4 and 0.75 and below 0.4 considered as excellent, moderate and poor, respectively (Matthews et al. 2017).

Results

Reliability

For the current study, the ICC's for the running performance measures, including VO_2, VE, VCO_2, HR, RPE, VE/VO_2, VE/VCO_2 and TTE, were 0.96 (0.87-0.99), 0.98 (0.92-0.99), 0.95 (0.82-0.99), 0.94 (0.77-0.98), 0.90 (0.67-0.97), 0.86 (0.52-0.96), 0.76 (0.15-0.93) and 0.89 (0.63-0.97), respectively. The ICC's for CMJ, ABD-ROM and FLEX-ROM were 0.92 (0.74-0.98), 0.98 (0.92-0.99) and 0.99 (0.97-0.99), respectively.

Indirect muscle damage markers

A bout x time interaction effect was found for Thigh-S, Glute-S, CMJ and ABD-ROM ($P < 0.05$; Table 1). Post-hoc analyses showed that Thigh-S and Glute-S were significantly lower during Bout 3 compared to Bout 1 at T24 but lower during both Bout 2 and 3 compared to Bout 1 at T48 ($p < 0.05$). Furthermore, the CMJ measure during Bout 3 was significantly greater than for Bout 1 at T24 and for ABD-ROM at T24 and T48 ($P < 0.05$).

A main effect of bout was also found for CK, Thigh-S, Glute-S, Ham-S, CMJ and ABD-ROM ($P < 0.05$) but not for FLEX-ROM ($P > 0.05$; Table 2). Post-hoc analyses showed that CK and Glute-S were significantly lower during Bout 2 and Bout 3 compared to Bout 1 ($P < 0.05$). For Thigh-S and Ham-S, the measures during Bout 3 were significantly lower than Bout 1 ($P < 0.05$) but no differences were found when compared with Bout 2 ($P > 0.05$). For CMJ and ABD-ROM, measures were significantly greater during Bout 3 compared to Bout 1 ($P < 0.05$), but no differences were found when compared with Bout 2 ($P > 0.05$).

Table 1 around here

Table 2 around here

Running performance measures

A bout x time interaction effect was found for RPE ($P < 0.05$; Figure 2) with post-hoc analyses showing that measures during Bout 3 at T24 and T48 were significantly lower than Bout 1 ($P < 0.05$). Furthermore, RPE during T24 and T48 were significantly greater than Baseline during Bout 1 and Bout 2 ($P < 0.05$), although this trend was not found for Bout 3 (P

> 0.05). No other statistically significant interaction effects were found for the other running performance measures.

Figure 2 around here

A main effect of bout was found for RPE, VE/VCO_2 and TTE ($P < 0.05$), but not for the other running performance measures ($P > 0.05$; Table 2). Post-hoc analyses showed lower values of RPE and VE/VCO_2 during Bout 3 compared with Bout 1 ($P < 0.05$). Furthermore, VE/VCO_2 during Bout 3 was significantly lower than for Bout 2 for ($P < 0.05$) while TTE was significantly greater during Bout 3 compared to Bouts 1 and 2 ($P < 0.05$).

Discussion

The current study investigated the effects of three traditional lower body resistance training bouts on running performance at sub-maximal and maximal effort and EIMD. The main results showed that more than two resistance training bouts were necessary to generate protective effects for sub-maximal (i.e., RPE and VE/VCO_2) and maximal (i.e., TTE) running performance measures as well as several indirect muscle damage markers (CMJ, Thigh-S, Ham-S and ABD-ROM).

The initial resistance training bout induced the greatest changes in CK measures with no further differences observed between the second and third resistance training bout in the current study. However, changes in other indirect muscle damage markers, including CMJ, muscle soreness (i.e., Thigh-S and Ham-S) and ABD-ROM were statistically significantly improved after the first resistance training bout compared to the third resistance training bout despite no differences between the first and second resistance training bouts in the current study. Such differences among indirect muscle damage markers have also been observed previously in the context of the R-RBE. For example, Chen and colleagues (2009a) reported that the first bout of eccentric exercises induced the greatest increase in CK with no differences in this measure between the subsequent three bouts. Conversely, the reduction in elbow flexor strength and muscle soreness were smaller during the fourth bout compared to the other bouts, suggesting that further adaptation was induced in these measures with greater exposure to muscle-damaging exercise. Caution should be taken when comparing our findings with that by Chen et al (2009a), given that they incorporated eccentric-only exercises which are not comparable to traditional resistance exercises that require the use of the stretch-shortening cycle and both concentric and eccentric movement patterns (Flanagan et al. 2014).

The discrepancy in trend between types of indirect muscle damage markers across multiple bouts of strenuous exercises suggests that each parameter may reflect distinct mechanisms that induce the RBE (Hyldahl et al. 2017). For example, muscle fibres have been suggested to become more resistant to eccentric exercise-induced stress when muscle fibres susceptible to stress are replaced with regenerated fibres (Newham et al. 1987). As blood biomarkers of muscle damage are typically indicative of muscle fibre degeneration (Koch et al. 2014), it is speculated that the reduction in CK measures during the second and third resistance training bout in the current study occurred as a result of increased regenerated fibres. Furthermore, Hyatt and Clarkson (1998) suggested that there is an accelerated clearance of CK after the initial bout of EIMD. This may also explain the lowered CK response after the second and third resistance training bout, a trend that was not observed for other indirect muscle damage markers (i.e., muscle soreness and CMJ). Conversely, muscular force impairment following eccentric contractions has been shown to occur primarily due to excitation-contraction failure (Ingalls et al. 1998). Whilst neuromuscular characteristics were not examined in the current study, it is possible that the RBE impact on CMJ occurred during the third resistance training bout due to a lesser degree of excitation-contraction coupling failure and alterations in muscle-tendon behaviour rather than muscle fibre necrosis alone.

An interesting disparity found in the current study was between the hip range-of-motion measures (i.e., ABD-ROM and FLEX-ROM) and muscle soreness measures. According to the results, the ABD-ROM demonstrated an R-RBE while no changes were observed in FLEX-ROM across the resistance training bouts. These findings were surprising, given that the resistance exercises were performed in the sagittal plane, which would be indicative of FLEX-ROM. Subsequently, we expected a reduction in FLEX-ROM because the primary movers in the lower body sagittal plane (i.e. quadriceps, gluteal muscles and hamstrings) would cause the greatest level of soreness. However, it is important to note that hip range-of-motion measured from sit-and-reach (i.e., FLEX-ROM) constitutes multi-articular movements from the hips and trunk, in contrast to the ABD-ROM which is mono-articular. Furthermore, previous studies have reported contribution of hip adductors during squatting exercises and single-leg resistance exercises (Han et al. 2013; Hollman et al. 2014), particularly for resistance-untrained individuals (Horan et al. 2014). Accordingly, ABD-ROM may be sensitive to changes as a result of EIMD due to mono-articular movement patterns and the contribution of hip adductors during hip extension exercises. In addition to ROM measures, the current study showed an R-RBE for Thigh-S and Ham-S despite no differences observed in Glute-S between the second and third resistance training bouts. These distinct time-course changes may be due to differences in muscle architecture between muscle groups (Apostolopoulos et al. 2015) and the method in which DOMS was measured. For example, Thigh-S and Glute-S were recorded during isotonic movements using body weight squats whereas Ham-S was measured using isometric contractions. Given the distinct fascicle behaviour during each contraction type (Narici et al. 2016) (i.e., concentric, eccentric and isometric contractions), and that muscular contraction type involved in fatiguing tasks can influence group III and IV afferent discharge patterns differently (Martin et al. 2009), it is possible that the different protocols used to determine DOMS of each muscle group may have resulted in discrepancies for each measure.

The improvement in VE/VCO_2, RPE and TTE during the third resistance training bout compared to the first resistance training bout despite no differences found between the first and second resistance training bouts suggests that the third resistance training bout was essential to provide further protection against muscle damage for running performance measures at sub-maximal and maximal intensity efforts. These protective effects may be attributed to the accelerated recovery of the neuromuscular system and the consequent reduction in perception of muscle soreness as indicated by improvements in CMJ, Thigh-S, Glute-S and Ham-S and ABD-ROM. Indeed, the neuromuscular system is considered to be one of the most important regulators of running performance (Assumpcao Cde, Lima et al. 2013). For example, several studies have reported impaired RE, running time-trial performance and running TTE with a concomitant reduction in muscle force production for 24-72 hours following a single bout of lower body resistance training exercises (Doma and Deakin 2013a; Doma and Deakin 2013b; Doma and Deakin 2014; Doma and Deakin 2015). Furthermore, it has been postulated that EIMD may attenuate the economy of movement and accelerate the onset of fatigue during running by altering neural recruitment patterns (Chen et al. 2007), reducing stretch-shortening cycle utilisation (Chen et al. 2007) and compromise proprioceptive feedback thereby altering running gait patterns (Doma and Deakin 2013b). In fact, a single bout of resistance training exercises has been reported to acutely reduce lower body ROM during running (Chen et al. 2007; Doma and Deakin 2013b), with suggestions that neuromuscular fatigue, muscle soreness and EIMD possibly result in kinematic changes and impaired movement efficiency (Chen et al. 2007; Doma and Deakin 2013a; Doma and Deakin 2013b). Whilst the current study did not examine running gait patterns, the reduction in ABD-ROM suggests that lower extremity ROM may have been limited during running performance as other studies have also reported that impaired sub-maximal and maximal running performance were accompanied by corresponding muscle damage-induced reduction in passive lower body ROM measures (Paschalis et al. 2005; Khan et al. 2016). However, further research is warranted to confirm whether improvement in running performance as a result of R-RBE is influenced by alterations in running gait patterns.

Direct comparison of the current findings to previous studies is at present difficult given that no other study has reported on the effects of R-RBE on running performance measures, particularly with the use of traditional resistance exercises. However, the lack of differences in running performance measures between the first two resistance training bouts reported in the current study support the observations by Doma et al. (2015). Similar to the current study, Doma et al. (2015) examined the RBE of lower body resistance exercises across two bouts. Their results showed that, whilst RE was impaired for 24 hours post-exercise, the magnitude of these differences were comparable across the two bouts, suggesting that a RBE was not observed. Conversely, when Burt et al. (2013) examined the acute effects of squatting exercises on RE across two bouts, the second bout attenuated the level of impairment in RE, indicating that the initial resistance training bout induced a RBE for the subsequent bout of sub-maximal running performance. The similarity in findings between the current study and that by Doma et al. (2015), yet distinct from Burt et al. (2013), maybe be due to the nature of the resistance training protocols. For example, Burt et al. (2013) incorporated squatting exercises at 80% of body weight whereas the current study and that by Doma et al. (2015) implemented squatting at 6-RM, which was equivalent to ~95% of body weight. In addition, peak CK values reported by Burt et al. (2013) were ~160 $U \cdot L^{-1}$ with values returning to baseline by 48 hours whilst the current study and that by Doma et al. (2015) generated CK values of ~575$U \cdot L^{-1}$ at 24 and 48 hours post, respectively, indicating a greater level of muscular stress than that of Burt et al. (2013). Previous studies have also reported greater CK values at higher resistance training intensities (Koch et al. 2014; Hasenoehrl et al. 2016) and that both sub-maximal and maximal running performances were impaired following high- compared to low-intensity resistance training (Doma and Deakin 2014). Accordingly, given the extent of physiological stress induced by the resistance training protocol in the current study, at least two resistance training bouts appeared to have been required to bring about a RBE for the third resistance training bout.

Conclusion

In conclusion, the current study reported that the initial resistance training bout induced the greatest change in CK although at least two resistance training bouts were required to produce an R-RBE on muscle soreness, range of motion, CMJ and running performance measures at sub-maximal and maximal efforts. From a practical standpoint, running sessions at sub-maximal and maximal intensity effort should be avoided for at least 48 hours following the first two bouts of heavy traditional lower body resistance training in resistance - untrained runners. Running sessions at sub-maximal effort could be implemented 48 hours post the third bout of heavy traditional lower body resistance training, although running sessions at maximal effort should be considered with caution given that TTE was still reduced by approximately 20% and 12% at 24 hours and 48 hours following the third resistance training bout, respectively.

Conflict of interest

The authors have no conflicts of interest associated with the manuscript.

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Table 1. Mean ± standard deviation of the indirect markers of muscle damage at prior to (T0), immediately post (T1) and 24 (T24) and 48 (T48) hours post the three resistance training bouts (Bout 1, Bout 2 and Bout 3, respectively)

Parameter	Bout	T0	T1	T24	T48	Bout x time interaction
CK (U·L^{-1})	Bout 1	153.5 ± 62.9	225.4 ± 111.4	570.8 ± 450.6	580.6 ± 598.8	P = 0.06
	Bout 2	163.7 ± 112.7	202.4 ± 105.7	327.0 ± 188.4	291.4 ± 181.2	
	Bout 3	134.2 ± 78.6	200.2 ± 131.3	237.1 ± 134.6	237.1 ± 171.2	
Thigh-S	Bout 1	1.6 ± 0.8	5.4 ± 2.3†	6.5 ± 2.0†	6.7 ± 2.0†	P = 0.005
	Bout 2	1.6 ± 1.0	5.3 ± 2.1†	5.4 ± 2.2†	5.0 ± 2.3*†	
	Bout 3	1.6 ± 1.2	4.7 ± 2.4†	4.6 ± 2.2*†	4.2 ± 1.5*†	
Glute-S	Bout 1	1.4 ± 0.8	4.7 ± 2.5†	6.3 ± 2.3†	5.9 ± 2.1†	P = 0.03
	Bout 2	1.4 ± 0.8	4.3 ± 2.0†	5.1 ± 2.0†	4.0 ± 2.3*†	
	Bout 3	1.4 ±1.0	4.0 ± 1.9†	4.8 ± 2.4*	4.1 ± 1.7*†	
Ham-S	Bout 1	1.7 ± 0.8	5.6 ±2.4	5.3 ± 2.0	4.9 ± 2.4	P = 0.44
	Bout 2	1.5 ±0.7	4.7 ± 2.1	4.6 ± 2.4	4.1 ± 2.1	
	Bout 3	1.5 ± 0.8	4.6 ± 2.5	4.0 ± 1.9	3.7 ± 1.8	
CMJ (cm)	Bout 1	56.2 ± 6.8	48.8 ± 6.4†	50.6 ± 4.9†	52.4 ± 6.3†	P = 0.02
	Bout 2	55.1 ± 6.7	50.5 ± 6.9†	53.0 ± 5.9	54.3 ± 6.3	
	Bout 3	54.8 ± 6.0	51.6 ± 5.6†	54.0 ± 5.0*	54.9 ± 5.9	
ABD-ROM (cm)	Bout 1	154.4 ± 19.8	151.5 ± 18.2	150.0 ± 17.9	150.9 ± 20.8	P = 0.04
	Bout 2	153.6 ± 18.7	154.5 ± 18.4	154.1 ± 18.3	154.9 ± 19.7	
	Bout 3	154.4 ± 18.1	153.9 ± 20.1	155.4 ± 20.2*	156.3 ± 19.8*	
FLEX-ROM (cm)	Bout 1	16.9 ± 12.6	18.4 ± 7.59	14.3 ± 11.7	13.8 ± 12.6	P = 0.26
	Bout 2	16.5 ±13.4	17.9 ± 10.4	14.8 ± 14.2	15.1 ± 14.1	
	Bout 3	16.1 ± 13.5	18.1 ± 11.5	17.3 ± 12.7	17.1 ± 12.6	

CK – creatine kinase; Glute-S – glute soreness; Ham-S – hamstring soreness; CMJ – countermovement jump; ABD-ROM – leg abductor flexibility; FLEX-ROM – sit and reach flexibility

* Significantly different from Bout 1 (P < 0.05)

† Significantly different from T0 (P < 0.05)

Table 2. Mean ± standard deviation of the indirect markers of muscle damage and running performance measures across the three resistance training bouts for the main effect of bout

Parameters	Bout 1	Bout 2	Bout 3	Main effect of bout
Indirect muscle damage markers				
CK ($U \cdot L^{-1}$)	382.6 ± 251.1	246.1 ± 133.7*	202.1 ± 116.0*	$P = 0.006$
Thigh-S	5.0 ± 1.5	4.3 ± 1.7	3.8 ± 1.5*	$P = 0.009$
Glute-S	4.9 ± 1.6	3.7 ± 1.6*	3.6 ± 1.5*	$P = 0.04$
Ham-S	4.4 ± 1.7	3.7 ± 1.6	3.4 ± 1.5*	$P = 0.03$
CMJ (cm)	52.0 ± 5.9	53.2 ± 5.9	53.8 ± 5.2*	$P = 0.002$
ABD-ROM (cm)	151.7 ± 19.1	154.3 ± 18.7	155.0 ± 19.4*	$P = 0.03$
FLEX-ROM (cm)	15.8 ± 10.7	16.1 ± 12.8	17.1 ± 11.8	$P = 0.50$
Running performance measures				
VO_2 ($mL \cdot kg^{-1} \cdot min^{-1}$)	41.5 ± 4.0	41.8 ± 4.4	41.7 ± 3.9	$P = 0.48$
VE ($L \cdot min^{-1}$)	105.7 ± 15.3	105.9 ± 13.5	104.0 ± 14.4	$P = 0.21$
VCO_2 ($L \cdot min^{-1}$)	3.4 ± 0.4	3.4 ± 0.4	3.4 ± 0.4	$P = 0.64$
HR ($beats \cdot min^{-1}$)	180.8 ± 10.7	181.7 ± 8.0	179.3 ± 9.7	$P = 0.080$
RPE	15.6 ± 2.2	15.3 ± 2.2	14.8 ± 2.0*	$P = 0.003$
VE/VO_2	32.1 ± 2.0	32.0 ± 2.1	31.4 ± 2.1	$P = 0.061$
VE/VCO_2	31.5 ± 1.9	31.4 ± 1.9	30.8 ± 2.1*†	$P = 0.004$
TTE (seconds)	133.5 ± 35.7	133.1 ± 45.7	147.4 ± 45.4*†	$P = 0.03$

CK – creatine kinase; Glute-S – glute soreness; Ham-S – hamstring soreness; CMJ – countermovement jump; ABD-ROM – leg abductor flexibility; FLEX-ROM – sit and reach flexibility; VO_2 – oxygen consumption; VE – ventilation; VCO_2 – carbon dioxide; HR – heart rate; RPE – rating of perceived exertion; VE/VO_2 – ventilation/oxygen consumption; VE/VCO_2 – ventilation/carbon dioxide; TTE – running time-to-exhaustion

* Significantly different from Bout 1 ($P < 0.05$)

† Significantly different from Bout 2 ($P < 0.05$)

Figure 1. The schematic of the research design with grey boxes denoting recovery between sessions and horizontal striped boxes denoting collection of indirect muscle damage markers

Figure 2. The physiological parameters during sub-maximal running for oxygen consumption (VO2), ventilation (VE), carbon dioxide production (VCO2), heart rate (HR), ventilatory equivalents for VO2 (VE/VO2), ventilatory equivalents for VCO2 (VE/VCO2) and rating of perceived exertion (RPE) and running time to exhaustion (TTE) above anaerobic threshold at baseline and 24 (T24) and 48 (T48) h post each strength training session

* Significantly lower than baseline ($P < 0.05$)

† Significantly lower than T24 ($P < 0.05$)

§ Significantly lower than Bout 1 of strength training at T24 and T48, respectively ($P < 0.05$)

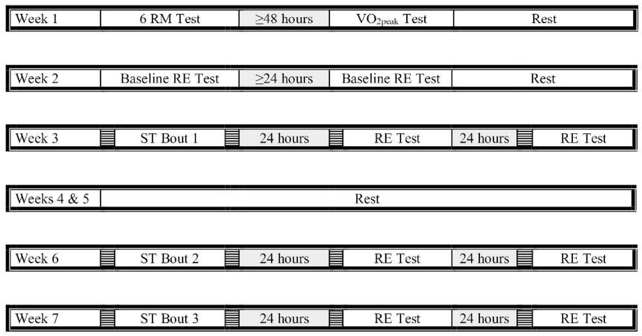

Figure 1. The schematic of the research design with grey boxes denoting recovery between sessions and horizontal striped boxes denoting collection of indirect muscle damage markers

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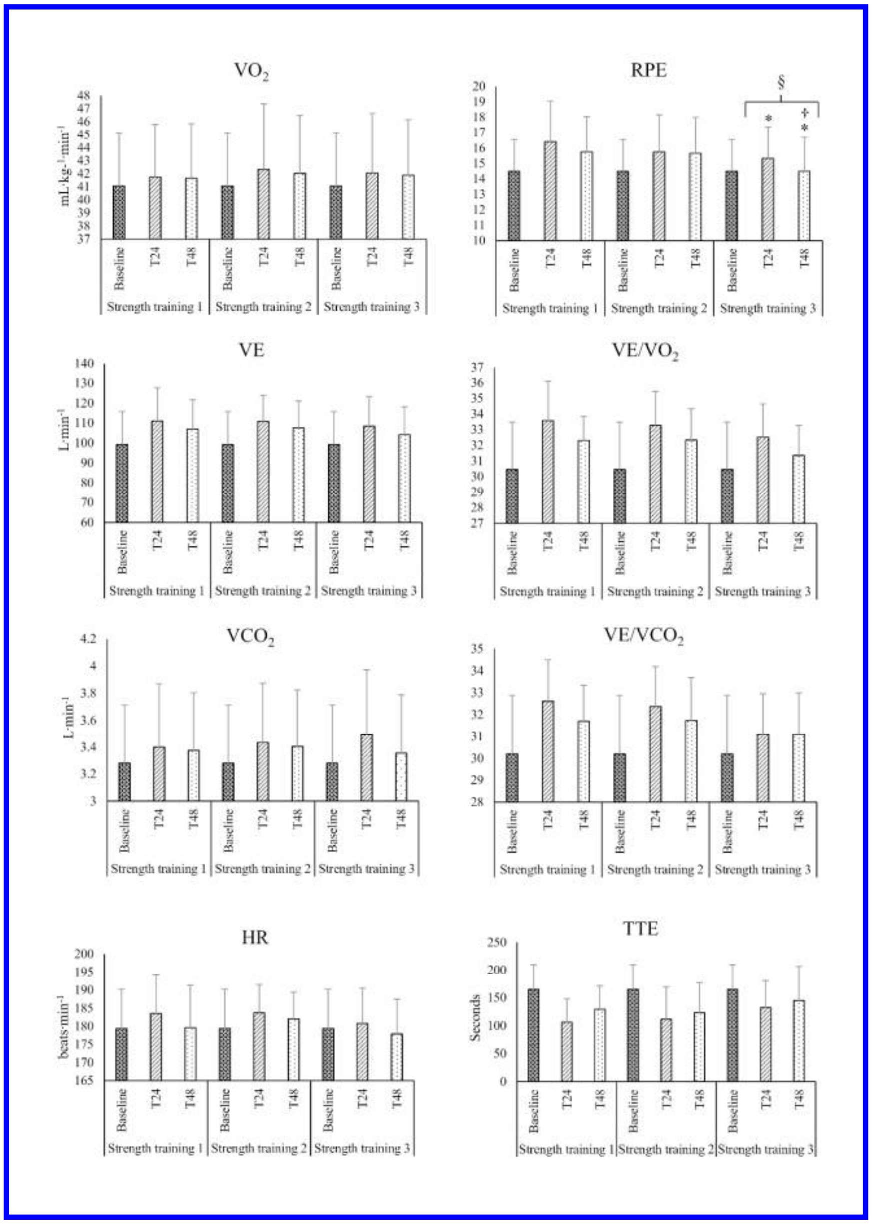

Figure 2. The physiological parameters during sub-maximal running for oxygen consumption (VO2), ventilation (VE), carbon dioxide production (VCO2), heart rate (HR), ventilatory equivalents for VO2 (VE/VO2), ventilatory equivalents for VCO2 (VE/VCO2) and rating of perceived exertion (RPE) and running time to exhaustion (TTE) above anaerobic threshold at baseline and 24 (T24) and 48 (T48) h post each strength training session
* Significantly lower than baseline ($P < 0.05$)
† Significantly lower than T24 ($P < 0.05$)
§ Significantly lower than Bout 1 of strength training at T24 and T48, respectively ($P < 0.05$)

280x396mm (300 x 300 DPI)