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TITLE PAGE

The fatigue of a full body resistance exercise session in trained men

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Abstract

Objectives
We examined the fatigue and recovery for 48h following a full-body resistance exercise session in trained men.

Design
Experimental cross-sectional study

Method
Eight resistance trained men volunteered to participate (mean ± SD; age 27.0 ± 6.0yrs, height 1.79 ± 0.05m, weight 81.8 ± 6.8kg, training experience 7.8 ± 5.0yrs). Fatigue and pain was measured before, after, 1h post, 24h and 48h post the full-body resistance exercise session, which was based on in-season models used in contact team sports (e.g. AFL, NRL). Other measures included maximal torque and rate of torque development, central motor output (quadriceps muscle activation, voluntary activation, H-reflexes), and muscle contractility (evoked twitch responses). Linear mixed-model ANOVA procedures were used for data analysis.

Results
Fatigue, soreness, and muscle pain did not return to pre-exercise levels until after 48h rest. Quadriceps maximal torque and muscle contractility were reduced from pre-exercise ($p<0.01$), and did not return to pre-exercise levels until 24h. Early rates of torque development and muscle activation were unchanged. The amplitude and slope of the normalized quadriceps H-reflex was higher immediately after exercise ($p<0.05$).

Conclusions

Full-body resistance exercise including multiple lower limb movements immediately reduced maximal torque, muscle contractility, and increased pain. While recovery of voluntary and evoked torque was complete within a day, 48h rest was required for fatigue and pain to return to baseline. Maximal voluntary effort may be compromised for lower-limb training (i.e. sprinting, jumping) prescribed in the 48h after the session.

Keywords

Fatigue, H-reflex, voluntary activation, pain

Introduction

Strength and conditioning clinicians and researchers have limited information about the acute fatigue and subsequent recovery from a resistance exercise session. Thus there is confusion about how to best schedule resistance exercise in the context of a training week within sports that include matches (weekend-to-weekend or multiple within-week matches), recovery sessions, on- and off-field skill and tactics sessions, and cardiorespiratory prescription. It is no surprise that measures associated with resistance exercise, such as strength and power, decline over the course of a competitive season in sports such as rugby union, league, and Australian Rules football[1-3].

Fatigue can be a disabling symptom for an athlete, where physical and cognitive function is limited in the hours and days following match-play or a training session[4]. Fatigue is commonly examined in the competitive sports environment, with up to 84% of sports science practitioners[5] reported to use self-report instruments (i.e. Recovery-Stress Questionnaire (REST-Q)) for monitoring player recovery[6], risk of overtraining, and readiness to play[7]. To date, changes in fatigue after a resistance exercise session have not been well documented[8]. There are numerous reports[4,9-12] of the immediate declines in maximal force following a single exercise such as a leg-extension or bicep curl. Some studies have examined changes in basal hormonal levels and measures of muscle pain in the days subsequent to a bout of resistance exercise, albeit using a single exercise such as the squat[12,13]. No studies have measured the fatigue and recovery from a full-body resistance exercise session typically used in a competitive sports season. Moreover there are no reports for the recovery of maximal force and rate of force development after a full-body resistance exercise session, which may provide further insight into the readiness of an individual for match performance or subsequent training sessions within the week.

Declines in maximal force and rate of force development are explained by changes in the activation (i.e. central motor output) and contractility (i.e. stimulated twitch force) of muscle[11,13]. Exercise physiology research has, albeit with an over-reliance on surface electromyography, extensively measured changes in muscle activation and contractility after prescription of a single exercise[5,8]. This research suggests that declines in maximal force are from a combination of reduced central motor output and muscle contractility, with the relative balance between the factors influenced by exercise volume, intensity, muscle, sex, and training status of participants[4-8]. The recovery of central motor output and muscle contractility after a full-body resistance exercise session has not been described. Moreover it is unclear whether the recovery of central motor output and muscle contractility will follow a similar or different pattern to changes in fatigue after resistance exercise. Thus there is a lack of information for practitioners scheduling resistance exercise session(s) in a week around other training modes (e.g. cardiorespiratory) and matches.

There is a lack of information about the fatigue and recovery from a full-body resistance exercise session. Thus clinicians are faced with difficult questions about the scheduling of resistance exercise during the season in various competitive sports. We designed this study to measure changes in fatigue, maximal torque, rate of torque, and concomitant measures of central motor output and muscle contractility immediately after and in the 48h following a full-body resistance exercise session in trained men.

Methods

Eight resistance trained men volunteered to participate (mean ± SD; age 27.0 ± 6.0yrs, height 1.79 ± 0.05m, weight 81.8 ± 6.8kg, training experience 7.8 ± 5.0yrs). All participants had a minimum 2-years of regular resistance exercise training history (average 3 times per week for the majority of training weeks per year), and reported experience in all movements required in the current study. No participant was currently engaged in sport or nutritional supplementation apart from protein usage, and reported no injuries to the lower limb in the last 2-years that required treatment or a missed day of training. All participants provided informed written consent before baseline testing, and procedures in this study were approved by the local University ethics committee.

Participants attended the University laboratory and training centre on four occasions. The first was a preliminary visit where participants performed the training session and were familiarized with the experimental procedures. Participants were instructed to refrain from any resistance or cardiorespiratory exercise and maintain normal dietary habits in the 24h preceding baseline testing and throughout the subsequent 48h recovery period. Between 5 and 7 days after familiarization, participants reported to the laboratory (9am-11am) for testing and the training session. Testing was performed before (PRE), immediately post (IP), 1h post (1H), as well as 24h (24H) and 48h (48H) hours after initial testing. All testing IP commenced 1.5 to 2 mins following completion of the final exercise.

Fatigue was measured PRE, 24H, and 48H using a five-item questionnaire that asked about fatigue, sleep quality, general soreness, stress and mood[7]. Each item was scored from 0-5, with lower scores indicating poor well-being. To examine muscle pain we used two visual analog pain scales[14,15] (scored 0-10cm: anchors, no pain – worst pain). One scale asked the participant to rate their quadriceps pain while seated at rest (VAS_{rest}). The second asked participants to rate their pain after performing a bodyweight squat (VAS_{squat})[15]. Training load (arbitrary units, AU) was estimated by measuring the time of the training session and multiplying this by the rating of perceived exertion (RPE[16]) given to the session by each participant (0 to 10 scale; numeric scale with wording descriptors).

The testing protocol for maximal isometric torque, rate of torque, central motor output, and muscle contractility was performed using an isokinetic dynamometer (KinCom 125, Version 5.32, Chattanooga). Participants were seated with their hip and knee flexed to 90° and 75° respectively, with the lever arm centre of rotation carefully aligned with the knee joint centre. Torque output signals were directly sampled from the dynamometer at 2000 Hz (Powerlab, ADI Instruments, Sydney, Australia), and low pass filtered at 10 Hz. For measurement of maximal voluntary torque (MVT, Nm), participants were required to push as fast and forcefully as possible for 3 to 5s (warm-ups involving efforts at 25%, 50%, and 75% perceived maximum were performed at all testing apart from IP). Three maximal efforts were performed at each time point, with femoral nerve stimulation applied during, and 3 to 4s after each contraction to elicit the quadriceps potentiated twitch ($Q_{.pot.tw}$).

Quadriceps electromyograms (EMG) were recorded from the left vastus lateralis (VL) and medialis (VM) using pairs of Ag/AgCl surface electrodes (10mm diameter; Maxsensor, Medimax Global, Australia)[9]. Permanent marker was used to maintain electrode positioning between sessions. EMG signals were recorded using the ML138 BioAmp (common mode rejection ratio > 85 dB at 50 Hz, input impedance 200MΩ) with 16-bit analog-to-digital conversion, sampled at 4,000 Hz (ADI instruments, Sydney, Australia). Raw signals were filtered with a fourth-order Bessel filter between 20 and 500 Hz. Root-mean-square (RMS) calculations were applied to smooth each muscle recording, using a 100ms moving window.

The knee extensors were stimulated by a single supramaximal doublet applied to the femoral nerve (0.2ms square wave pulse duration, 10Hz frequency) delivered at 400V using a constant current stimulator (Digitimer DS7AH, Welwyn Garden City, UK). A 20mm diameter Ag/AgCl surface electrode was positioned over the nerve in the femoral triangle, and the anode (6cm x 6cm aluminium foil) was placed midway between the greater trochanter and iliac crest. The current used during maximal and H-reflex curve modelling was based off progressively increasing the stimulation intensity in 10mA increments until a plateau in knee extensor twitch torque and M-waves (M_{max}) for VL and VM were observed (stimulation intensity range, 70-110mA). This intensity was used to establish the supra-maximal stimulation intensity (130%) applied during maximal efforts, and for modelling the H-reflex curve.

The quadriceps H-reflex[17] was measured using the 10Hz doublet to estimate changes in excitability of the α-motoneuron pool in response to afferent input, in addition to examining homonymous pre-synaptic inhibition from the second elicited H-reflex (after the second stimuli)[18]. Following recommended procedures[19], a 20-point logarithmic scale was calculated between the intensity for M_{max} and the minimum intensity where an H-reflex was observed (H_{thresh}). During all H-reflex testing, participants were required to perform a contraction at 10% MVT visibly displayed on a computer screen. At all time-points apart from IP, three stimuli were delivered at each intensity to model the H-reflex curve, with 10s rest between each trial. The H-reflex was calculated from the peak-to-peak value of the evoked response, typically occurring 20-25ms after stimulation for VM (VL H-reflexes were unable to be observed). The average H-reflex of the three stimuli was used for analysis[19]. After normalization to M_{max} and the current intensity at M_{max}, H_{slope} (the slope of the H-reflex at 50% maximal current intensity) and H_{max} (the maximal H-reflex amplitude) were calculated from sigmoidal curve fitting of the H-reflex curve[19]. The maximal normalized H-reflex elicited from the second stimuli of each doublet was also calculated (H_2). The ratio of H_{max}/H_2 was used to estimate pre-synaptic inhibition[18].

The full-body resistance exercise session was designed to approximate training used in the primary Australasian contact sports within season (rugby, rugby league, Australian Rules). Industry contacts and recent research was consulted for session design[20], to inform decisions about the types of exercises and prescription scheme (table. 1). This session was our interpretation of the commonalities across the primary Australasian team contact sports (rugby, rugby league, AFL) for general in-season resistance exercise. After IP testing participants were provided a recovery drink (0.4g whey protein/kg, 0.5g carbohydrate (maltodextrin)/kg; Bulk Nutrients, Grove, Tasmania). After 1H testing participants were encouraged to eat a meal including a protein and carbohydrate source as soon as possible.

Torque recordings were used to analyse, 1) the maximal voluntary torque recorded prior to stimulation (MVT, Nm), 2) rate of torque development (RTD) was calculated as the average slope of the torque-time curve (Δtorque/Δtime) during the time periods 0-25ms, 0-50ms, 0-100ms post contraction onset (onset derived from a computer based algorithm), 3) maximum RTD (RTD_{max}) was calculated as the greatest average 10ms slope throughout the first 100ms of the contraction. EMG recordings were used to analyse the following variables; 1) the electrically evoked muscle compound action potential (M-wave), calculated from the peak-to-peak amplitude of the VL and VM EMG raw signal elicited during contraction, 2) the maximal amplitude of the VL and VM EMG signal during MVTs based on processing the greatest average 250ms root-mean-square (RMS) value, 3) the rate of EMG rise for VL and VM calculated from the average slope of the EMG-time curve during the same time periods as RTD. All EMG variables during maximal contractions were normalized to the respective M-waves elicited during each contraction for data analysis (EMG/M, %).

Voluntary activation (VA) was estimated using the superimposed twitch technique according to the following formula[21]: VA (%) = 100 – (D * (T_{sup} / MVT) / $Q_{.pot.tw}$) * 100, where D is the difference between the torque level just before the superimposed twitch (T_{sup}) and the maximum torque recorded during the twitch, and $Q_{.pot.tw}$ is the maximal amplitude of the resting potentiated twitch. The time to peak twitch (TPT) and ½ relaxation time (½ RT) were also calculated from each $Q_{.pot.tw}$.

For variables analysed during each MVT, the average of the three trials at each time point was calculated for data analysis. Data were analysed (version 22; IBM SPSS Inc., Chicago, IL) using a repeated-measures linear mixed model ANOVA with three (perceived fatigue) or five levels of time. Post-hoc analyses of main effects were performed using Bonferroni's correction. Data are mean ± SD with significance set at $p \leq 0.05$.

Results

Main effects of time were observed for fatigue ($p=0.047$) and general soreness ($p<0.001$) with values reduced from PRE at 24H (table 2). Time effects were observed for VAS_{rest} ($p=0.002$) and VAS_{squat} ($p<0.001$), with increased pain scores IP (VAS_{rest} 3.8 ± 3.4cm, VAS_{squat} 5.8 ± 2.6cm) returning to values similar to PRE at 48H only.

Main effects of time were observed for MVT ($p<0.001$). MVT was reduced from PRE (214.3 ± 20.1 Nm) at IP and 1H by 27.8 and 24.4% respectively ($p<0.01$). RTD_{max} was 1344.0 ± 581.3 $Nm.s^{-1}$ at PRE, and did not change during the study (Fig. 1).

A main time effect was observed for VA (Fig. 1: p=0.009). Although values at IP (76.2 ± 16.2%) were lower than PRE (81.6 ± 6.9%), this was not significant. Values IP were lower than after 48H (88.9 ± 4.4%, p=0.008). Maximal and rates of rise in VL and VM surface EMG measures did not change (Fig. 1).

Main effects of time were observed for H_{slope} (p=0.002) and H_{max} (p=0.024). H_{slope} measured IP (2.4 ± 1.1) was higher than values at PRE (1.2 ± 0.7), 24H (1.4 ± 0.9), and 48H (1.4 ± 1.2). H_{max} measured IP (36.2 ± 24.3%) was higher than values at PRE (28.7 ± 18.7%) and 48H (28.4 ± 20.8%). The current at both H_{max} (52.7 ± 22.5%) and H_{slope} (36.7 ± 15.1%) remained unchanged. The ratio of H_{max}/H_2 was 3.4 ± 4.5 at PRE, and remained unchanged.

VL and VM M_{max} at PRE were 12.0 ± 4.9mV and 15.6 ± 6.8mV respectively, and remained unchanged during the study. $Q_{.pot.tw}$ was lower than all other time points at both IP and 1H (Fig. 1: p<0.05). ½ RT was 77.3 ± 5.2ms at PRE, and remained unchanged. A time effect was observed for reduced TTP measured IP (p=0.024), although post-hoc analysis for differences between IP and PRE (p=0.068), 24H (p=0.056), and 48H (0.057) did not reach significance.

Discussion

The main finding of this study was the mismatch between the recovery of physical measures and the fatigue reported by the trained men after the resistance exercise session. Reductions in maximal torque, voluntary activation, and muscle contractility returned to pre-exercise levels after 24h rest, while the fatigue and pain reported by participants had not recovered until 48h. A novel finding of this study was the maintenance of rate of torque development and early muscle activation, which appears explained by the increased input-output response of the α-motoneuron pool.

This is the first study to report the recovery after a full-body resistance exercise session in trained individuals. The session was modelled after that used in-season in Australasian team contact sports, and for the quadriceps included a combination of restricted range heavy squats (pin-squats), power movements (snatch and hang-clean), and a volume accrual exercise (barbell squats). While the exercise volume accrued for the quadriceps is a sufficient hypertrophic stimuli and would achieve squat movement specific strength gains over time[22,23], the upper body component would need to be repeated in the training week to accrue a sufficient volume for hypertrophy and strength gains[22,24]. For the quadriceps specific measurements, the acute response to the training session was a large decline in maximal torque and contractility, a small decline in voluntary activation, but no change in rate of torque development. In addition there was an immediate increase in muscle pain that, in addition to measures of fatigue, required 48h rest to return to pre-exercise levels. Thus, while recovery of maximal and rate of torque was relatively complete within 24h, it may not be reasonable to expect maximal volitional effort for vigorous lower limb exercises in the 48h after this resistance exercise session. It must be noted that, apart from providing post-exercise nutrition, we did not prescribe or have participants perform any form of recovery exercise after this session (e.g. passive stretching). Therefore factors such as increased passive stiffness, a potential explanatory factor for delayed muscle soreness after exercise[25], may be contributing to the pain after this session and could be alleviated by stretching[26].

The maintenance of rapid torque development and muscle activation was an unexpected observation, and demonstrates that the full-body resistance exercise session affected different mechanisms contributing to rapid and maximal torque. While voluntary activation was reduced, early rates of quadriceps muscle activation, a primary driver of voluntary rate of torque development[27], was well maintained after training. The unchanged early rate of muscle activation may, in part, be explained by the increased input-output response of the quadriceps α-motoneuron pool compensating for reduced voluntary activation. Voluntary rate of torque development is mediated by a combination of muscle morphology, supraspinal drive, and factors related to the input-output response of the α-motoneuron (i.e. recurrent inhibition[28], activation of high threshold motor units, firing rates[27],). This is the first study to report an increased α-motoneuron response to afferent input after resistance exercise, which might explain why voluntary rate of torque development was well maintained after the training session despite reduced maximal torque, voluntary activation, and muscle contractility. Moreover we probed homonymous pre-synaptic inhibition of the α-motoneuron as a mechanism that may explain changes in the H-reflex. The size of the second evoked H-reflex, expressed relative to the unconditioned H-reflex, did not change.

Other spinal pathways (i.e. recurrent/reciprocal inhibition) should be considered in future research for explaining why the H-reflex increased[18,28].

Limitations of this study include the isolated nature of the training session (i.e. not performed in the context of a multi-session training week, not representative of an acute response to training mid-season), measurement of the lower limb only, no dynamic testing such as vertical jump or sprint speed, and no standardization of diet in the 48h recovery period. Also, the result of this study must only be generalized to full-body training sessions that include a commensurate lower-body prescription.

Conclusions

Full-body resistance exercise including multiple lower limb movements immediately reduced maximal torque, muscle contractility, and increased pain. While recovery of voluntary and evoked torque was complete within a day, 48h rest was required for measures of fatigue and pain to recover. Voluntary rate of torque was maintained after training, with an increased input-output response of the α-motoneuron an explanatory mechanism.

Practical Implications

- Maximal torque and muscle function recovers within a day of performing full-body resistance exercise with multiple lower limb movements, but practitioners should be mindful that fatigue and pain require 48h recovery.
- On the same day as this session, short-duration explosive training could be used because voluntary rate of torque development was well maintained but muscle contractile function was impaired.
- On the following day recovery of maximal and rate of torque is complete, and a trained individual could likely perform any type of running-based training although lower limb resistance exercise should be avoided.

- The session used here should be prescribed early in the training week after match recovery is complete, with a supplementary upper body and/or power training session performed after 48h rest.

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References

1. Mitchell, J.A., K.L. Pumpa, K.J. Williams, et al., Variable changes in body composition, strength and lower-body power during an international rugby sevens season. *J Strength Cond Res*, 2016. **30**(4): p. 1127-1136.
2. Gabbett, T.J., Changes in physiological and anthropometric characteristics of rugby players during a competitive season. *J Strength Cond Res*, 2005. **19**(2): p. 400-408.
3. Cormack, S., R.U. Newton, M.M. McGuigan, et al., Neuromuscular and endocrine responses of elite players during an Australian Rules football season. *Int J Sports Physiol Perform,* 2008. **3**: p. 439-453.
4. Enoka, R.M. and J. Duchateau, Translating fatigue to human performance. *Med Sci Sports Exerc*, 2016. **48**(11): p. 2228-2238.
5. Taylor, K.L., D.W. Chapman, J.B. Cronin, et al., Fatigue monitoring in high performance sport: a survey of current trends. *J Aus Strength Cond*, 2012. **21**(1): p. 12-23.
6. Hooper, S.L., L.T. MacKinnon, A. Howard, et al., Markers for monitoring overtraining and recovery. *Med Sci Sports Exerc*, 1995. **27**(1): p. 106-112.
7. Mclean, D.B., A.J. Coutts, V. Kelly, et al., Neuromuscular, endocrine and perceptual fatigue responses during different length between-match micro-cycles in professional rugby league players. *Int J Sports Physiol Perform*, 2010. **5**: p. 367-383.
8. Scott, B.R., G.M. Duthie, H.R. Thornton, et al., Training monitoring for resistance exercise: Theory and applications. *Sports Med*, 2016. **46**(5): p. 687-698.
9. Marshall, P.W.M., H.T. Finn, and J.C. Siegler, The magnitude of peripheral muscle fatigue induced by high and low intensity single-joint exercise does not lead ot central motor output reductions in resistance trained men. *PLoS One*, 2015. **10**(10): p. e0140108.

10. Behm, D.G. and D.M.M. St-Pierre, Effects of fatigue duration and muscle type on voluntary and evoked contractile properties. *J Appl Physiol,* 1997. **82**: p. 1654-1661.

11. Enoka, R.M. and J. Duchateau, Muscle fatigue: what, why and how it influences muscle function. *J Physiol,* 2008. **586**(1): p. 11-23.

12. Gandevia, S.C., Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews,* 2001. **81**(4): p. 1725-1789.

13. Buckthorpe, M., M.T.G. Pain, and J.P. Folland, Central fatigue contributes to the greater reductions in explosive than maximum strength with high intensity fatigue. *Exp Physiol,* 2014. **99**(7): p. 964-973.

14. Huskisson, E.L., Measurement of pain. *Lancet,* 1974. **9**: p. 1127-1131.

15. Mohr, M., D. Draganidis, A. Chatzinikoloau, et al., Muscle damage, inflammatory, immune and performance responses to three football games in 1 week in competitive male players. *Eur J Appl Physiol,* 2016. **116**: p. 179-193.

16. Coutts, A.J., L. Wallace, and K. Slattery, Monitoring training load. *Sports Coach,* 2004. **27**(1): p. 12-14.

17. Doguet, V. and M. Jubeau, Reliability of H-reflex in vastus lateralis and vastus medialis muscles during passive and active isometric conditions. *Eur J Appl Physiol,* 2014. **114**: p. 2509-2519.

18. Baudry, S., A.H. Maerz, J.R. Gould, et al., Task- and time-dependent modulation of Ia presynaptic inhibition during fatiguing contractions performed by humans. *J Neurophysiol,* 2011. **106**: p. 265-273.

19. Vila-Cha, C., D. Falla, M.V. Correia, et al., Changes in H reflex and V wave following short-term endurance and strength training. *J Appl Physiol,* 2012. **112**: p. 54-63.

20. Jones, T.W., A. Smith, L.S. MacNaughton, et al., Strength and conditioning and concurrent training practices in elite rugby union. . *J Strength Cond Res,* 2016. **30**(12): p. 3354-3366.

21. Strojnik, V. and P.V. Komi, Neuromuscular fatigue after maximal stretch-shortening cycle exercise. *J Appl Physiol*, 1998. **84**: p. 344-350.

22. Marshall, P.W.M., M. McEwen, and D.W. Robbins, Strength and neuromuscular adaptation following one, four, and eight sets of high intensity resistance exercise in trained males. *Eur J Appl Physiol*, 2011. **111**(12): p. 3007-3016.

23. Morton, R.W., S.Y. Oikawa, C.G. Wavell, et al., Neither load nor systemic hormones determine resistance training-mediated hypertrpohy or strength gains in resistance-trained young men. *J Appl Physiol*, 2016. **121**(1): p. 129-138.

24. Mangine, G.T., J.R. Hoffman, A.M. Gonzalez, et al., The effect of training volume and intensity on improvements in muscular strength and size in resistance-trained men. *Physiol Rep*, 2015. **3**(8): p. e12472.

25. Proske, U. and D.L. Morgan, Muscle damage from eccentric exercise: mechanism, mechanical signs, adaptation and clinical applications. *J Physiol*, 2001. **537**: p. 333-345.

26. Marshall, P.W.M., A. Cashman, and B.S. Cheema, A randomized controlled trial for the effect of passive stretching on measures of hamstring extensibility, passive stiffness, strength, and stretch tolerance. *J Sci Med Sport*, 2011. **14**(6): p. 535-540.

27. Van Cutsem, M., J. Duchateau, and K. Hainaut, Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. . *J Physiol*, 1998. **513**: p. 295-305.

28. Johnson, S.T., K. Kipp, M.F. Norcross, et al., Spinal and supraspinal motro contorl predictors of rate of torque development. *Scand J Med Sci Sports*, 2015. **25**(5): p. 623-629.

Figure Legends

Figure 1. Changes in voluntary and evoked quadriceps measures during the study. Box A, maximal voluntary torque (MVT), quadriceps potentiated twitch (Q.pot.tw), voluntary activation (VA). 48H is p=0.008 between IP and 48H, * is p<0.05 and ** is p<0.001 from all other time-points. Box B, rate of torque development (RTD) in time intervals from contraction onset. Box C and D are vastus lateralis (VL) and medialis (VM) rate of EMG rise during voluntary contractions. Data are mean and SD.

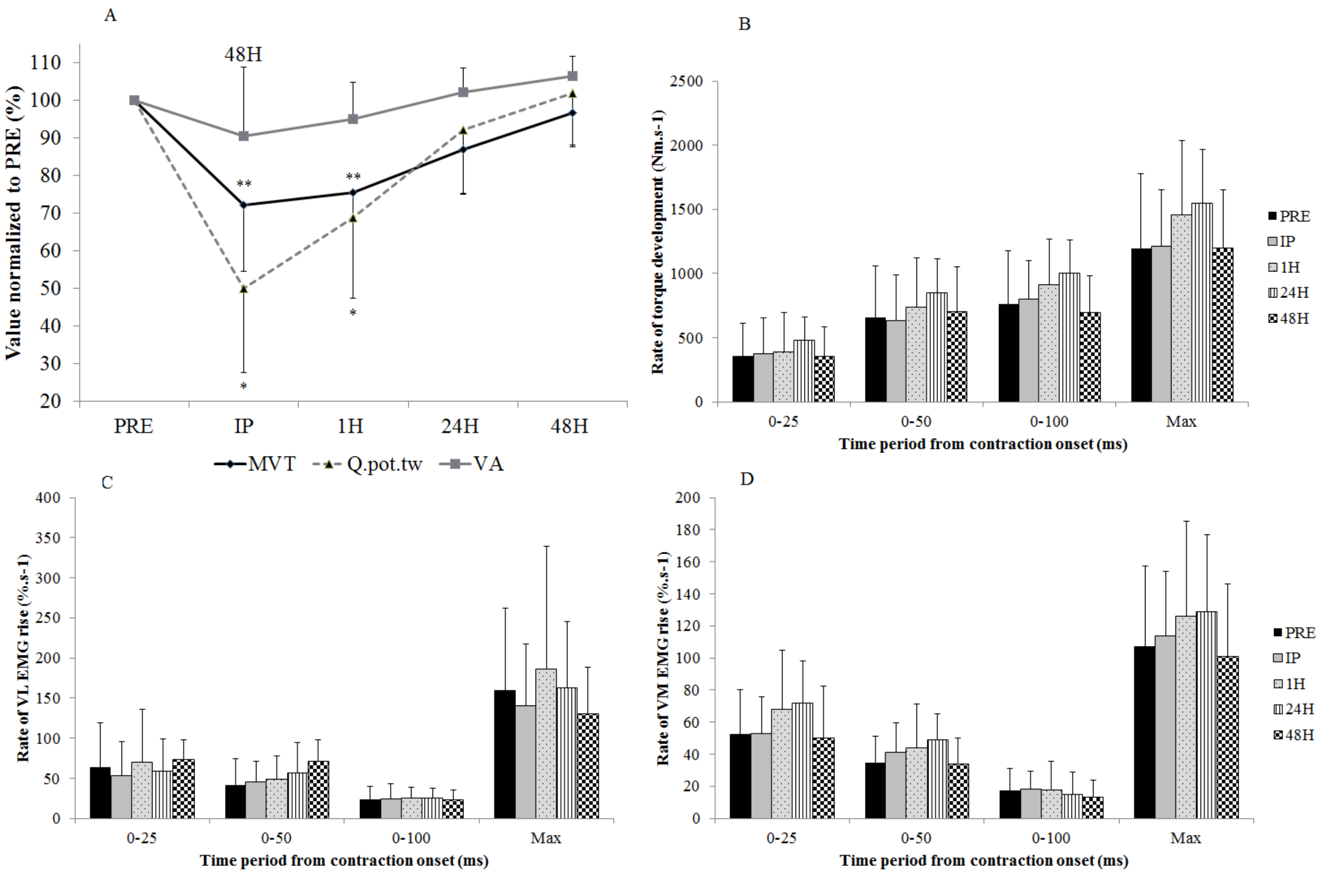

Table 1. Resistance exercise session used in this study, including actual average load across the sets (mean ± SD; relative to bodyweight) lifted for each exercise by participants in this study. Inter-set rest periods (ISRP), total set volume, and prescribed relative intensity (RI) (repetition maximum (RM) loading or percentage bodyweight (BW)) are designated for each exercise.

Exercise	ISRP	Volume	RI	Average load per set
90° knee flexion pin squats	1.5 to 2.0 mins	4 sets	4-6 RM	2.0 ± 0.4
Barbell bench press	1.5 to 2.0 mins	4 sets	4-6 RM	1.1 ± 0.1
Pendlay Rows	1.5 to 2.0 mins	4 sets	4-6 RM	1.0 ± 0.1
Dumb-bell (DB) Snatch	1.0 to 1.5 mins	4 sets	25% BW x 6 reps each arm	[redacted]
Pull-Ups	1.0 to 1.5 mins	3 sets	10-12 RM	BW only
Barbell Hang Cleans	1.0 to 1.5 mins	4 sets	50% BW x 6 reps	[redacted]
Full depth barbell back squats (below parallel)	1.0 to 1.5 mins	4 sets	10-12 RM	0.9 ± 0.1

*note the average total duration of the training session was 60.4 ± 4.5 mins, range 57.5 mins to 69.5 mins. The first three exercises were typically completed within 27.5 to 30 mins. Session training load (RPE x mins) was 465.2 ± 7.6AUs.

Table 2. Measures of fatigue and pain collected during the study, with lower scores indicating poor self-perception. VAS is visual analog pain scale (rest is while sitting, squat is after performing a bodyweight only squat), with higher scores indicate worse perceived pain. * is p<0.05, ** is p<0.01, and * is p<0.001 from PRE. Data are mean ± SD.**

	PRE	IP	1H	24H	48H
Fatigue (0-5)	3.6 ± 0.7			3.1 ± 0.6*	3.6 ± 0.5
Sleep Quality (0-5)	4.1 ± 0.4			4.3 ± 0.7	4.4 ± 0.5
General Soreness (0-5)	3.6 ± 0.7			2.0 ± 0.5***	2.6 ± 1.1
Stress Levels (0-5)	3.4 ± 0.5			3.5 ± 0.5	3.6 ± 0.5
Mood (0-5)	4.1 ± 0.4			4.3 ± 0.5	4.0 ± 0.5
VAS_{rest} (0-10cm)	0.6 ± 1.1	3.8 ± 3.4***	3.4 ± 3.0***	1.9 ± 1.9**	1.0 ± 1.6
VAS_{squat} (0-10cm)	0.8 ± 1.2	5.8 ± 2.6***	5.2 ± 2.3***	3.8 ± 1.5***	2.8 ± 2.7