Neuromuscular fatigue and recovery after heavy resistance, jump, and sprint training

Kevin Thomas[1] Callum George Brownstein[1], Jack Dent[1], Paul Parker[1], Stuart Goodall[1], Glyn Howatson[1,2]

[1]Faculty of Health and Life Sciences, Northumbria University, Newcastle-upon-Tyne, United Kingdom; [2]Water Research Group, School of Environmental Sciences and Development, Northwest University, Potchefstroom, South Africa

Short title:

Neuromuscular fatigue after training

Address for correspondence:

Glyn Howatson,

Faculty of Health and Life Science,

Department of Sport, Exercise and Rehabilitation,

Northumbria University,

Newcastle-upon-Tyne,

NE1 8ST,

UK.

Tel: +44 191 227 4863,

Fax: +44 191 227 4713

Email: glyn.howatson@northumbria.ac.uk

Abstract

Purpose. Training methods that require maximal intensity efforts against light- and heavy-resistance are commonly used for athletic development. Typically these sessions are separated by at least 48 hours recovery on the assumption that such efforts elicit marked fatigue of the central nervous system (CNS), but this posit has not been well-studied. The aim of the study was to assess the aetiology and recovery of fatigue after heavy-resistance (strength), jump, and sprint training methods. **Methods.** Ten male athletes completed three training sessions requiring maximal efforts that varied in their loading characteristics; i) heavy resistance exercise (10 × 5 back squats at 80% 1RM) (STR); ii) jumping exercise (10 × 5 jump squats) (JUMP); iii) maximal sprinting (15 × 30 m) (SPR). Pre-, post- and at 24, 48 and 72 h post- participants completed a battery of tests to measure neuromuscular function using electrical stimulation of the femoral nerve, and single- and paired-pulse magnetic stimulation of the motor cortex, with evoked responses recorded from the knee extensors. Fatigue was self-reported at each time point using a visual analogue scale. **Results**. Each intervention elicited fatigue that resolved by 48 (JUMP) and 72 h (STR & SPR). Decrements in muscle function (reductions in the potentiated quadriceps twitch force) persisted for 48 h after all exercise. Reductions in voluntary activation were present for 24 h after JUMP and SPRINT, and 48 h after STR. No other differences in CNS function were observed as a consequence of training. **Conclusion**. Strength, jump, and sprint training requiring repeated maximum efforts elicits fatigue that requires up to 72 h to fully resolve, but this fatigue is not primarily underpinned by decrements in CNS function.

Key words. Neurophysiology; brain; muscle; transcranial magnetic stimulation; central nervous system

Introduction

Athletic development in a range of sports is characterized by the application of various training means and methods in order to target specific adaptations. Resistance training is a key training means employed by coaches and athletes to improve the strength, impulse and speed qualities necessary for success in sports requiring movements underpinned by high force and/or velocity. The methods by which resistance training can be employed in an athlete's training programme can vary depending on the desired adaptive outcome. For example, to target maximum strength, coaches will typically utilize heavier loads (80-95% of 1 repetition maximum (RM)) with consequent slower velocities of movement (1). Conversely, to target the ability to produce high levels of force rapidly, submaximal loads are required in order to accrue impulse quickly (2). To train acceleration and maximum velocity running characteristics, the most effective training means is practice of sprinting itself (3). Each of these training stimuli impose distinct demands on the athlete, but their specific consequences are not well-studied or understood.

Heavy resistance and high velocity training methods typically require athletes to repeatedly produce maximal efforts in order to stimulate adaptation. An inevitable consequence of this is fatigue, a symptom or percept characterised by sensations of tiredness and weakness (4). Fatigue is a complex phenomenon, and while likely underpinned by a range of physiological and psychological mediators, an often-cited posit amongst athletic development professionals is that repeated maximal efforts elicit a high degree of “neuromuscular” or “central” fatigue, requiring prolonged (>48 hours) recovery. Such a postulate has also recently been cited in the academic literature (5), further propagating this idea, despite a lack of peer-reviewed evidence.

Neuromuscular fatigue could feasibly relate to any alteration in the physiological processes governing central nervous system (CNS) or muscle function, but is typically quantified by examining voluntary and artificially-evoked forces during an isometric muscle action. Peripheral neuromuscular fatigue refers to impairments in muscle distal to the neuromuscular junction, quantified as a reduction in the resting involuntary twitch response to nervous tissue stimulation (6). Central neuromuscular fatigue is attributable to the central nervous system inadequately being able to activate muscle to the required level, quantified as a reduction in voluntary activation (6). Adjustments in CNS function can also be quantified via studying the evoked responses to motor cortical stimulation (7). Single- and paired-pulse magnetic stimulation of the motor cortex has been previously applied to understand acute and chronic adjustments in CNS function in response to strength training (8-12) and fatiguing single-limb (13-15) and locomotor exercise (16). In concert, the application of these techniques to study adjustments in neuromuscular function after athletic training could help explain the etiology of fatigue, and aid practitioners in the appropriate scheduling of, and recovery from, different training methods.

While decrements in neuromuscular function, particularly of the CNS, are widely considered when programming training stimuli, the evidence underpinning the idea that heavy strength and power sessions require >48 h recovery is incomplete. Previous studies recently demonstrated that heavy resistance exercise elicited greater acute reductions in voluntary force than a similar low-resistance, high-velocity "power" session (17), and that these heavy resistance exercise induced decrements persisted at 24 h post-exercise in elite athletes (18). Bartolomei *et al*. (19) recently demonstrated greater and more prolonged strength and jump performance impairments after

"hypertrophy" style training (higher volume, lower load, shorter rest periods) compared to a training stimulus targeting strength development (lower volume, higher intensity, longer rest periods). Collectively these findings suggest the acute and prolonged adjustments underpinning the fatigue experienced after resistance exercise varies between training methods, but these studies were limited by both the range of outcome measures studied, and/or a limited profile of the time-course recovery of neuromuscular function. Further study is warranted to comprehensively assess the acute and prolonged neuromuscular adjustments induced by the typical training means and methods commonly employed in the physical preparation of athletes. Such information will be of high value to practitioners when prescribing training stimuli.

The aim of the study was to assess the etiology and recovery of neuromuscular fatigue in response to heavy resistance, jumping, and sprinting exercise. It was hypothesised that the maximal nature of all exercise interventions would induce marked neuromuscular fatigue that would require >48 hours to resolve, and that the time-course of recovery would be similar between interventions.

Methods

Participants

Ten male participants (age 21 ± 2 years, stature, 1.82 ± 0.05 m, mass, 85 ± 12 kg) gave their written, informed consent to participate in the study, which was approved by the Northumbria University Faculty of Health & Life Sciences Ethics Committee. All participants had >3 years history of training experience utilising resistance and maximal speed methods, and were currently competing in intermittent (n = 6), or track and field (n = 4) sports at University or national standard.

Design

Participants initially visited the laboratory on two separate occasions for preliminary assessments and to habituate to the measurement tools of the study. Subsequent to this participants completed three experimental trials, each spanning four consecutive days and separated by one week, in a randomised, counterbalanced order. On the first day of each experimental trial, participants completed one of three interventions as follows: i) a heavy resistance exercise session consisting of repeated sets of back squats (STR); ii) a low-load, high-velocity exercise session consisting of repeated sets of jump squats (JUMP); iii) a maximal speed training session consisting of repeated 30 m sprints (SPR). Pre-, immediately post-, and at 24, 48 and 72 h post- a battery of assessments to measure fatigue and neuromuscular function were administered. Prior to all visits participants were instructed to refrain from caffeine (24 hours), alcohol (48 hours), and to arrive 2 h post-prandial in a fully rested, hydrated state. Participants were also instructed not to perform any exercise other than that required by the study for the duration of their participation. To account for any potential detraining-induced changes in physical fitness, a "refresh" session consisting of maintenance loads for the physical qualities under study was employed between experimental trials. An overview of the experimental trials can be viewed in Supplemental Digital Content 1.

Procedures

Practice trial

Prior to the experimental trials, participants visited the laboratory on two occasions for habituation to the measurement tools of the study (on both visits), and an assessment of 1 repetition maximum (1RM) back squat strength or jump squat

performance (on separate visits). Prior to all exercise (practice & experimental trials) participants completed a structured ten-minute warm-up, which incorporated jogging, dynamic flexibility movements, mobility exercises specific to squatting, jumping, and sprinting, and 3 × 30 m progressive strides at 70, 80 and 90% of perceived maximum sprint speed. For the assessment of maximum isoinertial strength, participants first completed warm-up sets of 3-5 repetitions of back squats (high bar position), beginning with an unloaded barbell and progressing to 50%, 70%, 80% and 90% of their estimated 1RM. The load on the bar was then incremented by 2-5% until participants could not complete 1 repetition. The technical execution of each lift required participants to descend under control (2 s tempo) to a depth where the femur was parallel to the floor. Participants then immediately reversed the movement and were instructed to maximally accelerate the bar during the concentric phase. A repetition was deemed unsuccessful if participants could not complete the concentric phase in ≤ 2 s. Maximum isoinertial strength was 126 ± 14 kg, or 150 ± 15% body mass. For jump squats, participants completed vertical jumps for maximum height, beginning with body mass (plus a wooden dowel) and incrementing by 5 kg; the first increment was achieved by replacing the dowel with a lightweight training barbell with a mass of 5 kg. Each repetition required participants to squat to a self-selected depth (approximating a half squat) and jump for maximum height. Jump height was recorded using photoelectronic timing gates (Optojump Next, Microgate, Milan, Italy) for 2 to 3 efforts at each load. When participants were unable to maintain performance within 5% of their unloaded jump height because of added resistance, the test was terminated and the highest applied load where squat jump height was maintained was used for experimental trials (mean, SD 10 ± 5 kg, with a range of 0 to 20 kg, additional load).

176

177 *Experimental trials; exercise intervention*

178 On the first day of each experimental trial, subsequent to pre-test assessment,
179 participants completed one of three exercise prescriptions; i) heavy resistance training
180 consisting of 10 × 5 repetitions of the high bar back squat at 80% 1RM, with 3 min
181 recovery (STR); ii) 10 × 5 repetitions of jump squats, with 3 min recovery (JUMP);
182 iii) 15 × 30 m maximum sprints, with 2 min recovery (SPR). For STR and JUMP
183 participants were encouraged to maximally accelerate the load, and the velocity of
184 each repetition was monitored using a wearable linear position transducer (PushBand,
185 Heap Analytics, Toronto, Canada). For SPR participants began each sprint 0.5 m
186 behind the first timing gate, and were encouraged to sprint maximally through the
187 timing gate at 30 m. Each sprint was measured using photocell technology (TC
188 Timing system, Brower Timing Systems, Draper, Utah, USA). For all trials
189 participants were provided feedback on the execution of each repetition to promote a
190 maximum effort. Post-training, participants were asked for a whole trial session rating
191 of perceived exertion (RPE) using the 0-10 category ratio scale. While it was
192 impossible to equate training load between the experimental trials, the configurations
193 for STR, JUMP and SPR were designed in consultation with experienced strength and
194 conditioning coaches to represent a "heavy" stimulus for the physical quality under
195 stress, and were similar in duration (approximately 45 min, including the standardised
196 warm-up).

197

198 *Experimental trials; outcome measures*

On each occasion participants completed a battery of assessments to measure fatigue and neuromuscular function. All outcome measures were assessed pre-, post-, and at 24, 48 and 72 h post-exercise, unless otherwise stated.

Visual analogue scales & creatine kinase

Upon arrival, and post-exercise after assessment of neuromuscular function, participants completed visual analogue scales (VAS, 100 mm scale) to record fatigue and perceptions of muscle soreness. For fatigue the VAS was anchored with the verbal descriptors "not fatigued at all" to "extremely fatigued"; participants were asked to rate their general feeling of "fatigue, tiredness, weakness and lethargy". For muscle soreness the VAS was anchored with "no soreness" to "extremely sore"; participants preceded their rating with three repetitions of a body weight squat and were asked to rate their "muscle soreness and pain". Subsequent to this fingertip samples of capillary blood were obtained and immediately assayed for creatine kinase (CK) concentration (Reflotron, Roche Diagnostics, Germany).

Assessment of neuromuscular function

The evoked force and electromyographic (EMG) responses of the *rectus femoris* (RF) to transcranial magnetic stimulation (TMS) of the primary motor cortex, and electrical stimulation of the femoral nerve, were used to assess neuromuscular fatigue, corticospinal excitability, and the status of inhibitory intracortical networks. The assessment of neuromuscular function took place subsequent to perceptual assessments and capillary blood sampling at all time points except for post-exercise, where it was conducted first in order to capture the extent of neuromuscular fatigue elicited by the exercise intervention.

A calibrated load cell (MuscleLab force sensor 300, Ergotest technology, Norway) recorded muscle force (N) during an isometric maximal voluntary contraction (iMVC) of the knee extensors. During contractions, participants sat with hips and knees at 90° flexion, with a load cell fixed to a custom-built chair and attached to the participants right leg, superior to the ankle malleoli, with a noncompliant cuff. Electrical activity from the RF and *bicep femoris* (BF) were recorded from surface electrodes (Ag/AgCl; Kendall H87PG/F, Covidien, Mansfield, MA, USA) placed 2 cm apart over the belly of each muscle, with a reference electrode placed on the patella. Electrode placement was marked with indelible ink to ensure consistent placement throughout the study, with the areas cleaned and shaved prior to electrode placement. The electrodes recorded the root-mean-square (RMS) amplitude for sub-maximal and maximal voluntary contractions, the compound muscle action potential (M-wave) from the electrical stimulation of the femoral nerve, and the motor evoked potential (MEP) elicited by TMS. Signals were amplified: gain ×1000 for EMG and ×300 for force (CED 1902; Cambridge Electronic Design, Cambridge, UK), band-pass filtered (EMG only: 20-2000 Hz), digitized (4 kHz; CED 1401, Cambridge Electronic Design) and analysed offline. Further details on these methods are provided below.

Motor nerve stimulation

Motor nerve stimulation was used for the measurement of contractile function, muscle membrane excitability and voluntary activation (VA). Single electrical stimuli were administered using square wave pulses (200 μs) via a constant-current stimulator (DS7AH, Digitimer Ltd., Hertfordshire, UK) using self-adhesive surface electrodes

(Nidd Valley Medical Ltd., North Yorkshire, UK). Electrical stimuli were first administered to the motor nerve at rest in 20 mA step-wise increments from 20 mA until the maximum quadriceps twitch amplitude (Q_{tw}, N) and muscle compound action potential (M_{max}, mV) were elicited. To ensure a consistent, supramaximal stimulus and account for any activity-induced changes in axonal excitability, the resulting stimulation intensity was increased by 30% for all subsequent stimulus .The peak-to-peak amplitude and area of the electrically evoked maximal compound action potential (M_{max}) was used as a measure of membrane excitability. Participants subsequently completed six iMVCs (3-5 s duration) of the knee extensors, separated by 60 s rest. For the final three iMVCs, electrical stimuli were delivered during and 2 s post contraction to assess VA and potentiated quadriceps twitch force ($Q_{tw,pot}$) respectively.

Motor cortical stimulation

Single- and paired-pulse TMS of 1 ms duration were delivered using a concave double cone coil using two linked monopulse magnetic stimulators (Magstim 200, The Magstim Company Ltd, Whitland, UK). The junction of the double cone coil was aligned tangentially to the sagittal plane, with its centre 1-2 cm to the left of the vertex. The optimal coil placement was determined at the start of each trial as the position that elicited the largest MEP in the RF, with a concomitant small MEP in the BF. The position was marked with indelible ink for consistent placement during subsequent trials. The stimulator intensity was based on active motor threshold (AMT) measured during a 10% iMVC. In order to determine AMT, the stimulator intensity was increased in 5% steps beginning at 35% of stimulator output until a consistent MEP with peak-to-peak amplitudes of >200 μV was found. Thereafter,

274 stimulus intensity was reduced in 1% step until an MEP of >200 μV was found in
275 50% of stimulations.
276
277 *Corticospinal excitability & Short-interval intracortical inhibition (SICI)*
278 Once AMT was established, the stimulator intensities required to assess the MEP
279 response to varying TMS intensities (stimulus-response curve) were determined in
280 order to assess corticospinal excitability. Participants held a submaximal voluntary
281 contraction (10% iMVC) with one set of five stimuli delivered at each of 90%, 100%,
282 110%, 120%, 130%, 140%, 150% and 160% of AMT in a randomized and
283 counterbalanced order, with 4-6 s between each stimuli and 15 s between each set.
284 For SICI, ten single and ten paired-pulse TMS stimuli were administered in two sets
285 of 10 stimuli during a 10% iMVC, for measurement of unconditioned and conditioned
286 MEP amplitude respectively. Paired-pulse TMS consisted of a subthreshold
287 conditioning pulse at 70% of AMT, and a suprathreshold test pulse at 120% AMT,
288 with an inter-stimulus interval (ISI) of 2 ms. Single- and paired-pulses (× 10 each)
289 were delivered in a pre-determined randomised order, with 4-6 s between each
290 stimulation and a short rest between each set. This assessment was conducted pre-
291 exercise, and at 24 hour intervals thereafter until 72 h post.
292
293 *Voluntary activation with TMS*
294 Single pulse TMS was delivered during brief (3-5 s) contractions at 100%, 75% and
295 50% iMVC, separated by 5 s of rest, for determination of voluntary activation with
296 TMS (VA_{TMS}). This procedure was repeated 3 times with 15 s rest between each set.
297 The stimulation intensity was set at the stimulator output that elicited the maximum
298 superimposed twitch force (SIT) during a 50% iMVC. The SIT force elicited from

299 contractions at 100%, 75%, and 50% were used to determine VA_{TMS} (see data
300 analysis section for details).
301
302 *Experimental trials: "refresh session"*
303 On the final day of each experimental trial, after all outcome measures had been
304 completed, a "refresh" session designed to maintain the physical qualities under study
305 over the course of the experimental period was employed. This consisted of a low-
306 volume, high-intensity stimulus for each physical quality in a single session (3 × 5
307 sets of back squats at 80% 1RM, 3 × 5 maximal effort jump squats, 3 × 30 m maximal
308 effort sprints). Previous research has demonstrated that strength qualities can be
309 adequately maintained for prolonged periods using low doses provided the intensity
310 of exercise remains close to maximal (20, 21).
311
312 **Data analysis**
313 Voluntary activation assessed through the interpolated twitch technique (22) was
314 quantified by comparing the amplitude of the superimposed twitch force to the
315 potentiated twitch (100 Hz) delivered 2 s following the iMVC at rest using the
316 following equation: Motor point VA (%) = [1- ($SIT/Q_{tw,\ pot}$) × 100]. Voluntary
317 activation using TMS (VA_{TMS}) was assessed during contractions at 50%, 75% and
318 100% iMVC using linear regression of the superimposed twitch force evoked by TMS
319 (23), with the regression analysis confirming a linear relationship at each time-point
320 (r^2 range = 0.89 ± 0.03 to 0.95 ± 0.04). The estimated resting twitch (ERT) was
321 calculated as the y-intercept of the linear regression between the mean amplitude of
322 the SIT force evoked by TMS at each contraction intensity. Subsequently, VA_{TMS} was
323 quantified using the equation [1 – (SIT/ERT) × 100]. To quantify SICI, the ratio of

the average conditioned paired-pulse MEP was expressed relative to the average unconditioned MEP at 120% AMT. Recruitment curves were constructed by plotting the TMS stimulation intensity relative to AMT against the MEP amplitude averaged from the five stimulations at each intensity, expressed relative to M_{max}. The ratio of the MEP amplitude to the maximum M-wave was used as an index of corticospinal excitability. In order to provide a summary measure of corticospinal excitability, the summated area under the stimulus-response curve was calculated for each participant at each time point using the trapezoid integration method (24). The root mean square EMG amplitude (RMS_{EMG}) and average force was calculated in the 80 ms prior to each TMS to ensure a similar level of background muscle activity was present during the stimulus-response curve and SICI measurements. The peak-to-peak amplitude of evoked MEP and M_{max} were measured offline.

Statistical analysis

Data are presented as mean ± SD. To ascertain the time-course recovery of neuromuscular fatigue within-trial, one-way repeated measures ANOVA across time were employed for STR, JUMP and SPR data. Significant main effects were followed up with Dunnett's multiple comparison procedure, with the pre-exercise score used as the control category. To assess between-trial differences in the magnitude of neuromuscular fatigue induced by STR, JUMP and SPR, two-way (trial × time) factorial repeated measures ANOVA analysis was employed. As baseline scores did not differ between trials for any outcome measure, significant trial × time interaction effects were followed up with one-way repeated measures ANOVA, and *post-hoc* Tukey-adjusted pairwise comparisons at each time point to locate statistically significant between-trial differences. The assumptions underpinning these statistical

procedures were verified as per the guidelines outlined by Newell *et al.* (25). Data were analysed using GraphPad Prism (version 7, GraphPad Software Inc., La Jolla, CA). Statistical significance was accepted at $P < 0.05$.

Results

Exercise responses. All participants successfully completed the prescribed training interventions. For STR, the load lifted was 101 ± 11 kg. Repetition velocity decreased from 0.53 $m \cdot s^{-1}$ in set 1, to 0.44 $m \cdot s^{-1}$ in set 10 ($P < 0.05$), with a best of 0.54 ± 0.07 $m \cdot s^{-1}$ and worst of 0.41 ± 0.07 $m \cdot s^{-1}$ independent of set. Session RPE averaged 8 ± 2 for STR. For JUMP, mean repetition velocity was successfully maintained throughout the exercise (1.61 ± 0.17 $m \cdot s^{-1}$ in set 1 vs. 1.56 ± 0.14 $m \cdot s^{-1}$ in set ten, $P = 0.31$, best score of 1.69 ± 0.11 $m \cdot s^{-1}$, worst of 1.48 ± 0.10 $m \cdot s^{-1}$) and session RPE was lower (5 ± 1) than STR ($P = 0.001$). For SPR, 40 m sprint time declined from 4.40 ± 0.14 s in set 1 to 4.55 ± 0.22 s in set fifteen ($P = 0.04$), with a fastest sprint of 4.36 ± 0.16 s and a slowest of 4.61 ± 0.24 s. Session RPE after SPR (6 ± 2) was not different to STR ($P = 0.18$) or JUMP ($P = 0.33$)

Perceived fatigue & muscle damage responses. All exercise interventions elicited significant perceived fatigue (Table 1) that persisted for 48 h after STR (48 h, $P = 0.002$) and SPR training (48 h, $P = 0.008$), and 24 h after JUMP training (24 h, $P = 0.02$). Between trials, both STR and SPR training resulted in greater perceived fatigue than JUMP training for up to 48 h (Figure 1, panel A). Similar patterns were also evident for perceptions of muscle soreness; all training resulted in increases in muscle soreness that were different to baseline for 48 h, and between trials - both STR (for up

374 to 72 h, $P = 0.0006$) and SPR (for up to 48 h, $P = 0.0008$) elicited a greater magnitude
375 of soreness in comparison to JUMP (Figure 1, panel B). Creatine kinase peaked at 24
376 h in all trials and was different to baseline for 24, 48 and 72 h for STR, JUMP and
377 SPR respectively (Table 1). Between trials, CK was lower at 24 h in JUMP compared
378 to both STR ($P = 0.001$) and SPR ($P = 0.002$) (Figure 1, panel C).
379
380 **Neuromuscular fatigue.** All exercise interventions resulted in declines in iMVC
381 force that took until 72 h to fully resolve in all trials (Table 2). The magnitude of the
382 reduction in iMVC force immediately post-exercise was higher after STR compared
383 to JUMP ($P < 0.001$) and SPR ($P < 0.001$), a difference that persisted at 24 hours (P
384 $= 0.02$ and 0.05 respectively, Figure 2, panel A). Reductions in VA were also evident
385 immediately post-exercise for all trials, and persisted for 48 h after STR ($P = 0.004$),
386 and 24 h after JUMP ($P = 0.015$) and SPR ($P = 0.023$, Table 2). Significant reductions
387 in VA_{TMS} were also evident post-exercise in all trials (all $P < 0.05$), but returned to
388 baseline quicker than VA; by 48 h in STR and 24 h in JUMP and SPR (Table 2). The
389 magnitude of reductions in VA, measured with both motor nerve and motor cortical
390 stimulation, was not different between exercise interventions (Figure 2, panel B & C).
391 All trials resulted in reductions in $Q_{tw,pot,}$, that took 72 h to fully resolve (Table 2).
392 Between trials there were larger reductions in $Q_{tw,pot}$ immediately-post STR compared
393 to both JUMP and SPR (both $P < 0.001$), with no differences between trials thereafter
394 (Figure 2, panel D).
395
396 **Corticospinal excitability and SICI.** Exercise resulted in no modulation of
397 corticospinal excitability (Figure 3, stimulus-response curves) or SICI (Figure 4), both
398 within and between trials (all $P > 0.05$). The EMG_{RMS} was also not different within

and between trials (supplementary material, Table 3). For a full list of surface EMG responses to TMS and electrical stimulation please see supplementary material, Table 3.

Discussion

The aim of the study was to assess the effect of strength, jump and sprint training, performed with maximal intent, on the etiology and time-course of neuromuscular fatigue and recovery. In accordance with our hypothesis, all training stimuli resulted in neuromuscular adjustments that took up to 72 h to fully resolve. For twitch force, indicative of peripheral fatigue, strength training resulted in larger post-exercise reductions compared to jump and sprint training, but the time-course recovery was similar thereafter, with marked decrements still evident at 48 h post-exercise in all trials. Reductions in voluntary activation, an indicator of central fatigue, persisted for 24 h after jump and sprint training, and 48 h after strength training, with no difference between trials in the magnitude of these reductions. Measures of CNS responsiveness and inhibition were not modulated in response to the training stimuli at any time point. Perceptual indicators of fatigue and soreness followed a similar time-course of recovery to measures of neuromuscular function, requiring up to 72 h to return to baseline, with a tendency for jump training to be less fatiguing compared to strength and sprint training. Collectively these data indicate that maximal intent, relatively high volume, strength, jump and sprint training methods elicit neuromuscular fatigue, mediated by both central and peripheral mechanisms, that requires up to 72 h to fully resolve.

Time-course of recovery of neuromuscular fatigue after training. An often-cited posit in strength and conditioning is the idea that training methods performed with maximal intent, such as those studied here, result in central fatigue, or are CNS intensive, and require 48-72 h recovery before similarly intense stimuli are imposed (26, 5, 27). To date however, the formal study of neuromuscular fatigue in the days post-training has been limited (19, 17, 18, 28, 29). Here we show that strength, jump and sprint training elicits marked neuromuscular central and peripheral fatigue, that can require up to 72 h to fully resolve, which provides some support to these previous assertions. The capacity to produce voluntary force was impaired for 48 h after all training, with decrements in MVC force of 8%, 7% and 6% on average for strength, jump and sprint training. Similarly, twitch force was reduced compared to baseline for 48 h in all trials, indicating a prolonged decrement in muscle function, with values remaining depressed by 5-6% on average at 48 h. Reductions in voluntary activation persisted for 48 h after strength training, and 24 h after jump and sprint training, suggesting heavy resistance training elicited more prolonged central fatigue than the other methods studied. At the 48 h time point the decrement in voluntary activation averaged 5%, 2% and 3% for strength, jump and sprint training respectively. Collectively, these data suggest that neuromuscular fatigue after training methods that emphasise maximal intent is persistent, and multi-factorial. This underscores the need for appropriate recovery between such sessions, alongside interventions that address the multi-factorial nature of fatigue. The data also provide some support to the assertion that training sessions that emphasise maximal intent should be separated by at least 48 h if peak performance is a priority, as the majority of variables under study took 72 h to fully resolve.

"Central" fatigue after training. Fatigue of the CNS is often implicated as a primary consideration after training modes that emphasise maximal intent, and recent reviews have called for an increased emphasis on the recovery of central and "brain" fatigue after exercise (30, 31). However, the formal study, and precise definition, of what constitutes central fatigue is limited. Here we specifically measured central fatigue as a reduction in the ability of the CNS to activate skeletal muscle. This activation deficit was evident post-training for up to 24 h after jump and sprint training, and up to 48 h after heavy resistance training. We also measured variables purported to reflect CNS excitability and inhibition, but these did not modulate with training. In contrast, the capacity to produce voluntary force was impaired for 48 h in all trials, decrements in muscle function (indicative of peripheral fatigue) persisted for 48 h in all trials, and sensory perceptions of fatigue and soreness persisted for 48-72 h post. The magnitude of central fatigue was also modest, with voluntary activation returning to within 5% of baseline in the majority of cases (n = 6, 8 & 6 respectively for strength, jump and sprint training) by 24 h post. Additionally, the magnitude of the decrement post-trial was similar to that previously observed in our lab for prolonged cycling exercise (32, 33), repeated-sprint exercise (34) and simulated intermittent-sprint exercise (35). The recovery of central neuromuscular fatigue in the days post- was also similar to that observed after simulated intermittent-sprint exercise (35). Therefore, the idea that recovery of the CNS should be prioritised after methods of training that emphasise maximal intent is debatable, but perhaps simply reflects an imprecise definition of terms. Fatigue is a symptom, or percept, characterised by sensations of tiredness and weakness (4), underpinned by a myriad of physiological and psychological mechanisms; what is commonly perceived as central fatigue by athletes and coaches is likely more accurately interpreted as fatigue *per se*. That is,

474 the feelings of tiredness and weakness that athletes experience in the days post-
475 exercise are likely underpinned by a range of mechanisms relating to both central and
476 peripheral function, and not primarily attributable to "CNS" fatigue. A caveat to this
477 conclusion is the acknowledgement that our ability to measure aspects of CNS
478 function, and thus infer the impact of exercise, is limited by the available
479 measurement tools. For example, even the most widely acknowledged measure of
480 central fatigue - a reduction in voluntary activation of skeletal muscle – has
481 questionable validity (36). This notwithstanding, our data suggest that the fatigue
482 experienced after the training methods under study is multi-factorial and not primarily
483 underpinned by central mechanisms.
484
485 **Differential effect of strength, jump and sprint training.** A number of differences
486 were observed between trials that indicated the jumping training stimulus elicited less
487 fatigue, and took less time to recover from. These included differential effects on
488 iMVC and twitch force, the creatine kinase response, and perceptions of fatigue and
489 muscle soreness, in comparison to heavy resistance exercise and sprinting. However,
490 whether these differences could be primarily attributed to differences in the force-
491 velocity requirements of the differing sessions is debatable. Both the heavy resistance
492 (back squat to parallel depth) and sprinting stimuli required greater displacement of
493 load (external or body mass) in comparison to power training (jumping from a half
494 squat). The ostensibly increased work required during STR and SPR (and associated
495 metabolic demand), and the increased potential for muscle damage at longer muscle
496 lengths, could explain the differences observed between trials independent of
497 differences in the force-velocity demands of the exercise. Equating the training
498 stimulus between trials is an impossible endeavour, and therefore any between-trial

comparisons should be interpreted with caution. However, the relatively lower stress and quicker recovery observed after jumping compared to heavy resistance training is not without precedent. Howatson *et al*. (18) previously observed strength training (consisting of 4 × 5 heavy back squat, split squat and push press) elicited reductions in iMVC for up to 24 h, whereas the same session conducted with lower loads and higher repetition velocities elicited no reduction in iMVC. Additionally, Linnamo *et al.* (29) previously demonstrated a higher degree of acute neuromuscular fatigue following heavy load vs. light load "explosive" bilateral leg extension resistance training. These previous data, and the current study, indicate that training methods that emphasise the ability to generate impulse to accelerate relatively light loads might require less recovery time than heavy resistance or maximal sprint training, a finding that has implications for the scheduling of such activities.

Corticospinal excitability and short intracortical inhibition. There were no discernible adjustments in corticospinal excitability nor short intracortical inhibition at any time point in response to all exercise interventions. Corticospinal excitability has been shown to modulate acutely with single limb fatiguing exercise (13-15) and ballistic isometric exercise (9), and chronically after single limb (8, 12) and whole body (10) resistance training programmes. Short intracortical inhibition has similarly been demonstrated to be modulated after a period of resistance training (10), and acutely during locomotor exercise (16) and after fatiguing isometric knee extensor exercise (37). Of importance, these acute adjustments seem to quickly resolve upon exercise cessation (37, 16); this could explain why, in the present study, we did not observe any differences post-exercise as the measurement of these variables was delayed in comparison to previous work. The finding that neither corticospinal

524 excitability nor short intracortical inhibition were modulated with recovery in the days
525 post-exercise concurs with previous studies from our laboratory studying the etiology
526 and recovery of neuromuscular fatigue after simulated and competitive intermittent-
527 sprint exercise (38, 35). Thus, while measures of CNS excitability and inhibition
528 might be modulated during and immediately post-exercise, or chronically in response
529 to longer-term training, they do not systematically differ from baseline in the days
530 post-fatiguing exercise.
531
532 In addition to an inability to match training stimuli between trials, the ecological
533 validity of both the imposed sessions, and the measurement protocols, could also be
534 questioned. Considering the primary variables under study (i.e. indicators of
535 neuromuscular fatigue), we deliberately chose to study a high volume of exercise for
536 each training stimulus, and limited each to a single exercise that required a significant
537 contribution from the quadriceps muscle group, and where possible were
538 biomechanically similar (e.g. back squats vs. jump squats). For these reasons, the
539 applicability of the results to regular athletic development training, which typically
540 involves lower volumes and higher variation of exercises within sessions, is
541 questionable. There are of course unlimited configurations of exercise selection, sets,
542 repetitions and recovery durations that could be manipulated, and consequently any
543 decisions on the exercise intervention employed in a study of this nature could be
544 questioned. Additionally, adjustments in neuromuscular function as a consequence of
545 exercise were studied during single-limb, isometric knee extensor muscle actions.
546 This assessment set-up is required to measure neuromuscular fatigue, however these
547 adjustments might not fully reflect decrements in the type of dynamic knee extensor
548 function required of the exercise modes under study, and athletic performance more

generally. These limitations notwithstanding, the data do provide new information on the nature of fatigue and recovery after resistance and speed training; an area of research that is under-studied, and in need of further investigation.

In conclusion, this study has demonstrated that training methods requiring repeated maximal intensity efforts elicit marked neuromuscular fatigue that requires up to 72 h to fully resolve. The observed neuromuscular fatigue was of both a central and peripheral origin, with a faster recovery of central, compared to peripheral, neuromuscular fatigue. The data provide partial support for the idea that training methods that emphasise maximal intent to express force or velocity should be separated by at least 48 h, but the recovery of central nervous system function is not necessarily the primary aim of this period. Rather, the residual fatigue experienced by athletes after such training is multi-factorial, and thus development of appropriate monitoring and rest/recovery strategies that reflect this is warranted. Further research is required to further probe the consequences of maximal intensity training using novel measurement tools, and stimuli that more accurately reflect the day-to-day practice of different athletic groups.

Acknowledgements

Support for the study was provided by the United Kingdom Strength & Conditioning Association research grants programme. The authors would like to thank Mr Joe Kupusarevic, Mr Sam Orange, Mr Alan Toward, and Mr Sam White for their assistance with data collection.

Conflict of Interest

The authors have no conflict of interest to declare. The results of the study do not constitute endorsement by ACSM. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation

References

1. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol (1985)*. 2002;93(4):1318-1326.

2. Cronin JB, McNair PJ, Marshall RN. Force-velocity analysis of strength-training techniques and load: implications for training strategy and research. *J Strength Cond Res*. 2003;17(1):148-155.

3. Rumpf MC, Lockie RG, Cronin JB, Jalilvand F. Effect of Different Sprint Training Methods on Sprint Performance Over Various Distances: A Brief Review. *J Strength Cond Res*. 2016;30(6):1767-1785.

4. Enoka RM, Duchateau J. Translating Fatigue to Human Performance. *Med Sci Sports Exerc*. 2016;48(11):2228-2238.

5. Hartmann H, Wirth K, Keiner M, Mickel C, Sander A, Szilvas E. Short-term Periodization Models: Effects on Strength and Speed-strength Performance. *Sports Med*. 2015;45(10):1373-1386.

6. Carroll TJ, Taylor JL, Gandevia SC. Recovery of central and peripheral neuromuscular fatigue after exercise. *J Appl Physiol (1985)*. 2017;122(5):1068-1076.

7. Goodall S, Howatson G, Romer L, Ross E. Transcranial magnetic stimulation in sport science: A commentary. *Eur J Sport Sci*. 2014;14(sup1):S332-S340.

8. Griffin L, Cafarelli E. Transcranial magnetic stimulation during resistance training of the tibialis anterior muscle. *J Electromyogr Kinesiol*. 2007;17(4):446-452.

9. Nuzzo JL, Barry BK, Gandevia SC, Taylor JL. Acute Strength Training Increases Responses to Stimulation of Corticospinal Axons. *Med Sci Sports Exerc*. 2016;48(1):139-150.

10. Weier AT, Pearce AJ, Kidgell DJ. Strength training reduces intracortical inhibition. *Acta Physiol (Oxf)*. 2012;206(2):109-119.

11. Zult T, Goodall S, Thomas K, Hortobágyi T, Howatson G. Mirror illusion reduces motor cortical inhibition in the ipsilateral primary motor cortex during forceful unilateral muscle contractions. *J Neurophysiol*. 2015;113(7):2262-2270.

12. Zult T, Goodall S, Thomas K, Solnik S, Hortobagyi T, Howatson G. Mirror Training Augments the Cross-education of Strength and Affects Inhibitory Paths. *Med Sci Sports Exerc*. 2016;48(6):1001-1013.

13. Goodall S, Howatson G, Thomas K. Modulation of specific inhibitory networks in fatigued locomotor muscles of healthy males. *Exp Brain Res*. 2018;236(2):463-473.

14. Takahashi K, Maruyama A, Hirakoba K et al. Fatiguing intermittent lower limb exercise influences corticospinal and corticocortical excitability in the nonexercised upper limb. *Brain Stimul*. 2011;4(2):90-96.

15. Williams PS, Hoffman RL, Clark BC. Cortical and spinal mechanisms of task failure of sustained submaximal fatiguing contractions. *PLoS One*. 2014;9(3):e93284.

16. Sidhu SK, Lauber B, Cresswell AG, Carroll TJ. Sustained cycling exercise increases intracortical inhibition. *Med Sci Sports Exerc*. 2013;45(4):654-662.

17. Brandon R, Howatson G, Strachan F, Hunter AM. Neuromuscular response differences to power vs strength back squat exercise in elite athletes. *Scand J Med Sci Sports*. 2015;25(5):630-639.

18. Howatson G, Brandon R, Hunter AM. The Response to and Recovery From Maximum-Strength and -Power Training in Elite Track and Field Athletes. *Int J Sports Physiol Perform*. 2016;11(3):356-362.

19. Bartolomei S, Sadres E, Church DD et al. Comparison of the recovery response from high-intensity and high-volume resistance exercise in trained men. *Eur J Appl Physiol*. 2017;117(7):1287-1298.

20. Bickel CS, Cross JM, Bamman MM. Exercise dosing to retain resistance training adaptations in young and older adults. *Med Sci Sports Exerc*. 2011;43(7):1177-1187.

21. Ronnestad BR, Nymark BS, Raastad T. Effects of in-season strength maintenance training frequency in professional soccer players. *J Strength Cond Res*. 2011;25(10):2653-2660.

22. Merton PA. Voluntary strength and fatigue. *J Physiol*. 1954;123(3):553-564.

23. Todd G, Taylor JL, Gandevia SC. Measurement of voluntary activation of fresh and fatigued human muscles using transcranial magnetic stimulation. *J Physiol*. 2003;551(Pt 2):661-671.

24. Carson RG, Nelson BD, Buick AR, Carroll TJ, Kennedy NC, Cann RM. Characterizing changes in the excitability of corticospinal projections to proximal muscles of the upper limb. *Brain Stimul*. 2013;6(5):760-768.

25. Newell J, Aitchison T, Grant S. *Statistics for Sports and Exercise Science: A practical approach*. Harlow: Pearson Education; 2010. 427

26. Gambetta V. *Athletic development: The art & science of functional sports conditioning*. New World Library; 2007. p. 71

27. Olbrecht J. *The science of winning: planning, periodizing and optimizing swim training*. F&G Partners; 2000. p. 5-15

28. Johnston M, Cook CJ, Crewther BT, Drake D, Kilduff LP. Neuromuscular, physiological and endocrine responses to a maximal speed training session in elite games players. *Eur J Sport Sci*. 2015;15(6):550-556.

29. Linnamo V, Hakkinen K, Komi PV. Neuromuscular fatigue and recovery in maximal compared to explosive strength loading. *Eur J Appl Physiol Occup Physiol*. 1998;77(1-2):176-181.

30. Minett GM, Duffield R. Is recovery driven by central or peripheral factors? A role for the brain in recovery following intermittent-sprint exercise. *Front Physiol*. 2014;5:24.

31. Rattray B, Argus C, Martin K, Northey J, Driller M. Is it time to turn our attention toward central mechanisms for post-exertional recovery strategies and performance? *Front Physiol*. 2015;6:79.

32. Thomas K, Elmeua M, Howatson G, Goodall S. Intensity-Dependent Contribution of Neuromuscular Fatigue after Constant-Load Cycling. *Med Sci Sports Exerc*. 2016;48(9):1751-1760.

33. Thomas K, Goodall S, Stone M, Howatson G, St Clair Gibson A, Ansley L. Central and peripheral fatigue in male cyclists after 4-, 20-, and 40-km time trials. *Med Sci Sports Exerc*. 2015;47(3):537-546.

34. Goodall S, Charlton K, Howatson G, Thomas K. Neuromuscular fatigability during repeated-sprint exercise in male athletes. *Med Sci Sports Exerc*. 2015;47(3):528-536.

35. Thomas K, Dent J, Howatson G, Goodall S. Etiology and Recovery of Neuromuscular Fatigue after Simulated Soccer Match Play. *Med Sci Sports Exerc*. 2017;49(5):955-964.

36. Contessa P, Puleo A, De Luca CJ. Is the notion of central fatigue based on a solid foundation? *J Neurophysiol*. 2016;115(2):967-977.

37. Hunter SK, McNeil CJ, Butler JE, Gandevia SC, Taylor JL. Short-interval cortical inhibition and intracortical facilitation during submaximal voluntary contractions changes with fatigue. *Exp Brain Res*. 2016;234(9):2541-2551.

38. Brownstein CG, Dent JP, Parker P et al. Etiology and Recovery of Neuromuscular Fatigue following Competitive Soccer Match-Play. *Front Physiol*. 2017;8:831.

Tables & Figures

Table 1. Within-trial differences in fatigue and perceptions of muscle soreness measured using visual analogue scales (100 mm scale), and creatine kinase (CK), measured pre- and in the 72 h post-strength, jump, and sprint training. Values are mean ± SD. * = significant difference witin-trial from pre-test score.

Table 2. Within-trial differences in isometric maximum voluntary contraction strength and measures of neuromuscular fatigue pre-, post, and 24, 48, and 72 hours post-strength, jump and sprint training. Values are mean ± SD. * = significant difference from pre-test score within trial.

Figure 1. Between-trial differences in fatigue (A), muscle soreness (B) and creatine kinase (C) measured pre-, post- and 24, 48 and 72 hours post- strength, jump, and sprint training. Between trial differences indicated by * = difference between strength and jump; # = difference between jump and sprint; ^ = difference between strength and sprint (all $P > 0.05$). Individual responses are plotted, with lines representing the mean score.

Figure 2. Between-trial differences in isometric maximum voluntary contraction force (A), voluntary activation measured with motor nerve (B) and motor cortical (C) stimulation, and quadriceps potentiated twitch force (D) Between trial differences indicated by * = difference between strength and jump; # = difference between jump and sprint; ^ = difference between strength and sprint (all $P > 0.05$). Individual responses are plotted, with lines representing the mean score.

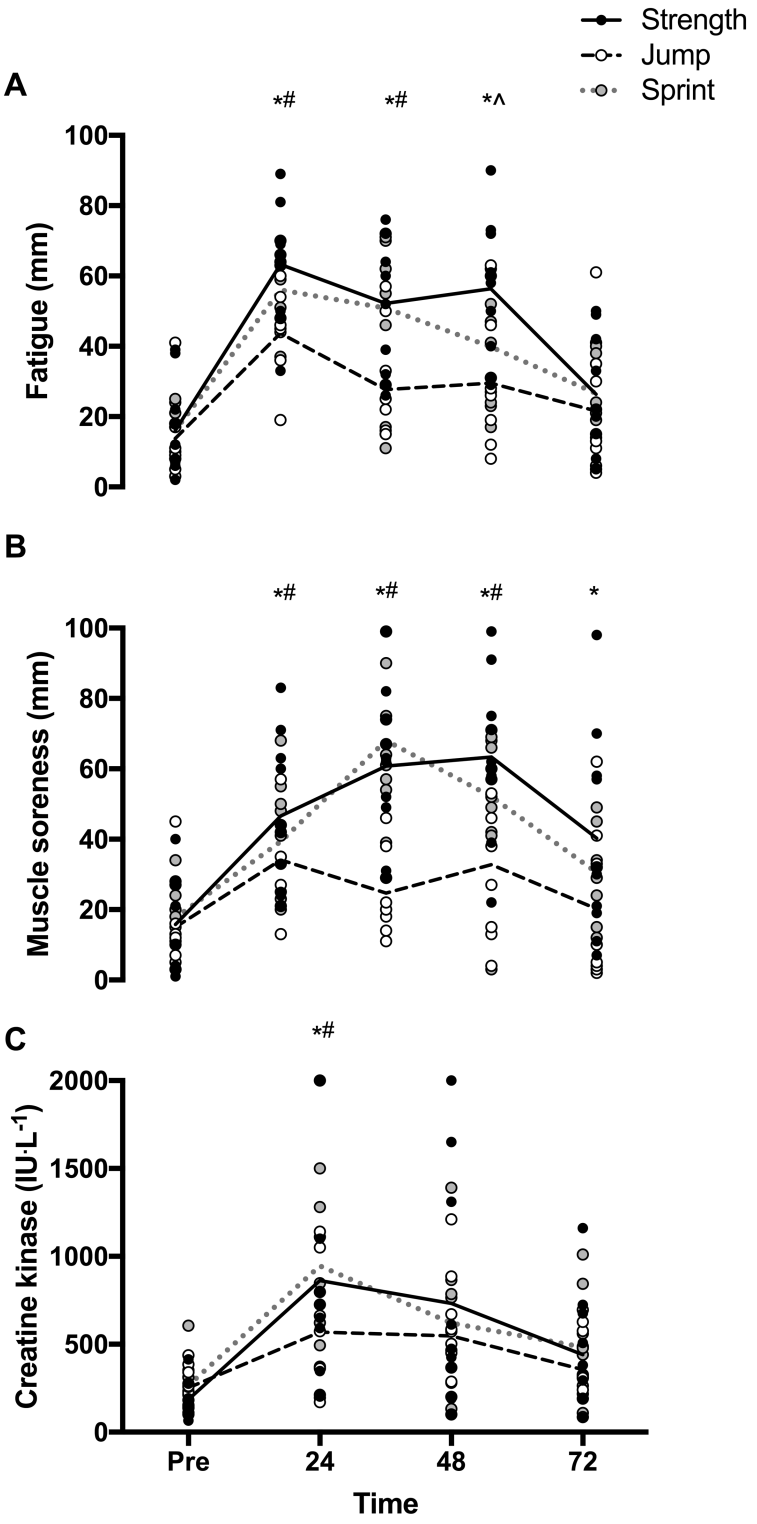
Figure 3. Motor evoked potential (expressed relative to Maximum M-wave) stimulus-response curves measured above and below active motor threshold (AMT, 100%) pre-, and 24, 48 and 72 hours post- strength (A), jump (B) and sprint (C) training. Values are mean ± SD. A reference line is included at 60% to assist comparison between trials.

Figure 4. Short intracortical inhibition (SICI) expressed as the ratio between conditioned and unconditioned motor evoked potentials pre-, and 24, 48 and 72 hours post- strength, jump and sprint training. Individual responses are plotted, with lines representing the mean score.

Supplemental digital content

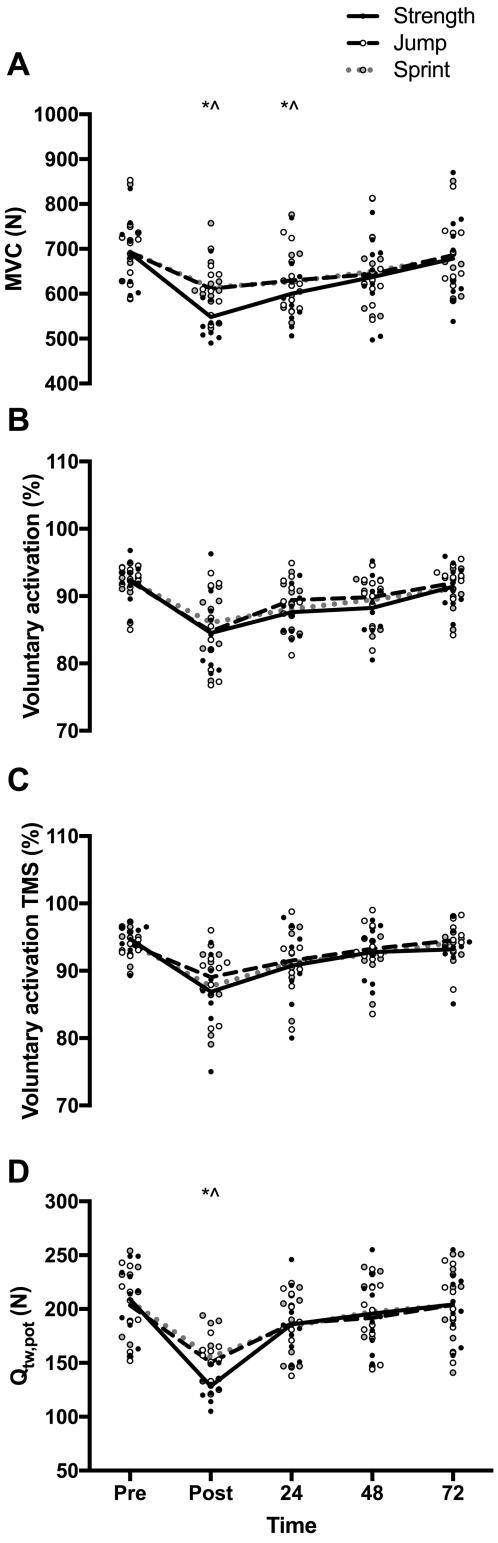
Supplemental digital content 1.pdf. Schematic of experimental protocol. Pre-exercise and at 24, 48 and 72 h post participants completed the battery of assessments in the same order. After the pre-exercise assessment participants completed one of three exercise interventions: i) heavy resistance training consisting of 10 × 5 repetitions of the high bar back squat at 80% 1RM, with 3 min recovery (STR); ii) 10 × 5 repetitions of a jump squat, with 3 min recovery (JUMP); iii) 15 × 30 m maximum sprints, with 2 min recovery (SPR). Participants were encouraged to complete every repetition with maximal intensity. Immediately post-exercise, central and peripheral neuromuscular fatigue were evaluated within 2 min of exercise cessation. Pre-exercise and at 24 h intervals thereafter, single-pulse transcranial magnetic stimulation (TMS) were administered during a submaximal isometric contraction at various percentages (90 to 160%) of active motor threshold (AMT) for

774 the assessment of corticospinal excitability. Paired-pulse TMS were administered
775 during submaximal contraction for assessment of short intracortical inhibition.
776
777



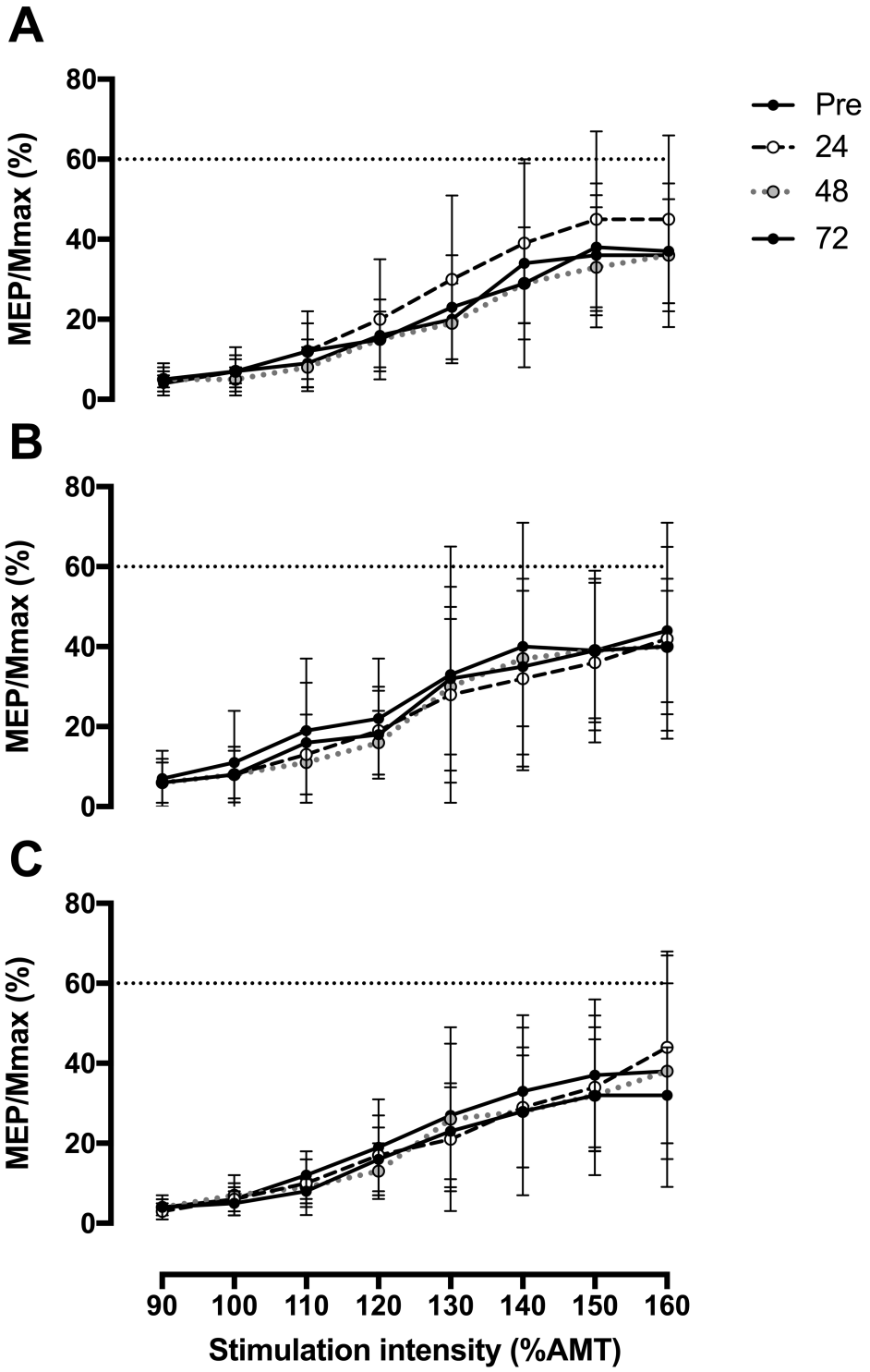
778

779 Figure 1.



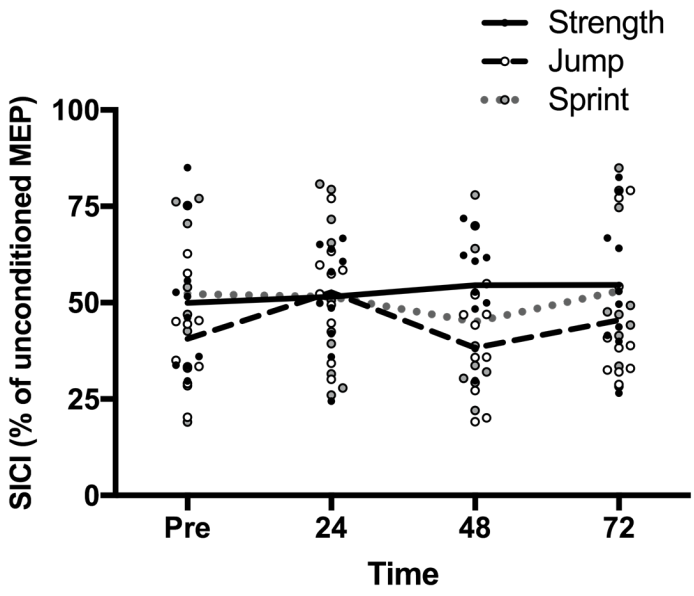
780

781 Figure 2



782

783 Figure 3



784

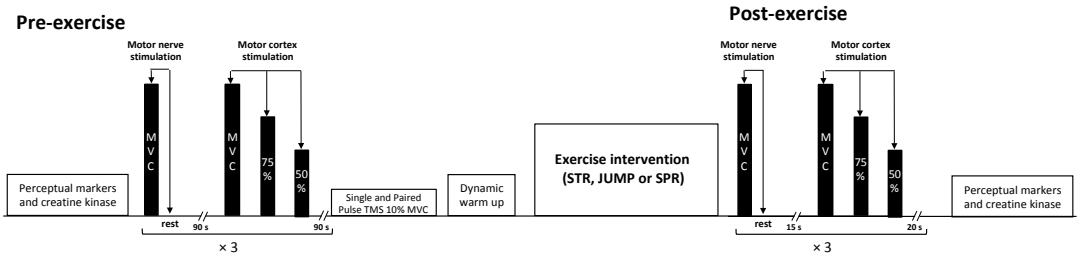
785 Figure 4

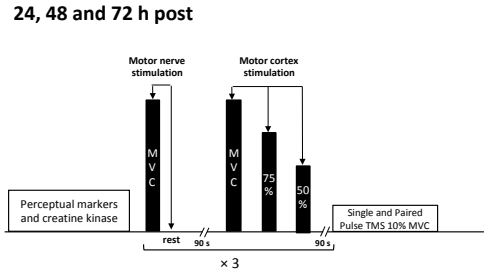
Table 1. Within-trial differences in fatigue and perceptions of muscle soreness measured using visual analogue scales (100 mm scale), and creatine kinase (CK), measured pre- and in the 72 h post-strength, jump, and sprint training. Values are mean ± SD. * = significant difference within-trial from pre-test score.

	Strength	Jump	Sprint
Fatigue (mm)			
Pre-	16 ± 13	14 ± 11	16 ± 6
Post-	63 ± 16*	44 ± 15*	56 ± 11*
24 h	52 ± 19*	28 ± 15*	51 ± 21*
48 h	56 ± 19*	30 ± 16	40 ± 16*
72 h	26 ± 16	22 ± 17	27 ± 13
Muscle soreness (mm)			
Pre-	16 ± 13	15 ± 13	18 ± 9
Post-	47 ± 22*	34 ± 10*	39 ± 17*
24 h	61 ± 22*	25 ± 11*	68 ± 17*
48 h	63 ± 23*	33 ± 21*	52 ± 21*
72 h	40 ± 29	20 ± 21	31 ± 18
CK ($IU \cdot L^{-1}$)			
Pre-	185 ± 98	253 ± 114	265 ± 142
24 h	863 ± 659*	569 ± 340*	946 ± 531*
48 h	733 ± 673	547 ± 328*	622 ± 357*
72 h	440 ± 333	356 ± 205	484 ± 270*

Table 2. Within-trial differences in isometric maximum voluntary contraction strength and measures of neuromuscular fatigue pre-, post, and 24, 48, and 72 hours post-strength, jump and sprint training. Values are mean ± SD. * = significant difference from pre-test score within trial.

	Strength	Jump	Sprint
iMVC (N)			
Pre-	691 ± 78	693 ± 78	693 ± 74
Post-	548 ± 61*	611 ± 52*	614 ± 66*
24	600 ± 78*	630 ± 63*	627 ± 72*
48	637 ± 90*	644 ± 77*	650 ± 83*
72	678 ± 102	686 ± 77	682 ± 78
VA (%)			
Pre-	92.4 ± 2.9	92.2 ± 2.7	92.3 ± 2.6
Post-	84.5 ± 5.8*	84.8 ± 6.1*	86.1 ± 4.7*
24	87.6 ± 3.3*	89.4 ± 3.8*	88.1 ± 3.5*
48	88.2 ± 4.4*	89.9 ± 3.8	89.5 ± 3.3
72	91.4 ± 3.2	92.0 ± 3.2	91.1 ± 2.9
VA_{TMS} (%)			
Pre-	94.7 ± 2.5	94.0 ± 2.4	94.2 ± 2.0
Post-	86.9 ± 5.7*	89.1 ± 4.7*	87.7 ± 5.3*
24	90.7 ± 5.7*	91.5 ± 5.1	91.2 ± 4.0*
48	92.8 ± 4.1	93.3 ± 4.4	92.5 ± 3.4
72	93.2 ± 3.5	94.5 ± 3.3	94.2 ± 2.0





Supplemental digital content 1. Schematic of experimental protocol. Pre-exercise and at 24, 48 and 72 h post participants completed the battery of assessments in the same order. After the pre-exercise assessment participants completed one of three exercise interventions: i) heavy resistance training consisting of 10 × 5 repetitions of the high bar back squat at 80% 1RM, with 3 min recovery (STR); ii) 10 × 5 repetitions of a jump squat, with 3 min recovery (JUMP); iii) 15 × 30 m maximum sprints, with 2 min recovery (SPR). Participants were encouraged to complete every repetition with maximal intensity. Immediately post-exercise, central and peripheral neuromuscular function were evaluated within 2 min of exercise cessation. Pre-exercise and at 24 h intervals thereafter, single-pulse transcranial magnetic stimulation (TMS) were administered during a submaximal isometric contraction at various percentages (90 to 160%) of active motor threshold (AMT) for the assessment of corticospinal excitability. Paired-pulse TMS were administered during submaximal contraction for assessment of short intracortical inhibition.

788