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Optimising player performance and readiness to train: fatigue and recovery of neuromuscular function following football match-play

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Executive Summary

Association football is an intermittent-sprint sport that places significant physical demand on players (Rampinini *et al.*, 2007; Akenhead *et al.*, 2013). An inevitable consequence of this physical demand is fatigue, which can manifest in acute and residual impairments to performance (Minnet & Duffield, 2014). While the presence of fatigue during and post-football-match-play is well-established, the aetiology of this is not well-studied. The consequences of fatigue after match-play have typically been studied from a peripheral viewpoint, with recovery of skeletal muscle function the target of intervention strategies. Less is known regarding the recovery of central nervous system function following intermittent sprint exercise, despite an apparent disconnect in the temporal pattern of recovery of physical function, and markers of peripheral physiology and muscle damage following intermittent-sprint exercise (Pointon *et al.*, 2012; Minnet *et al.*, 2013). This study assessed the fatigue and recovery of neuromuscular function, using electrical and magnetic stimulation of nervous tissue, following simulated football match-play. Additionally, we concurrently assessed a range of simple functional and perceptual assessments in order to ascertain their utility as monitoring tools for practitioners. The results of the study demonstrate that simulated football match-play induces significant fatigue, both central and peripheral in origin, that persists for up to 72 h post-match. Central fatigue is manifest in large reductions in voluntary activation post-exercise, which recovers markedly by 24 h but remains different to baseline values for 48 h post-match. Supraspinal fatigue, a subset of central fatigue attributable to a suboptimal output from motor cortical cells, contributes to the observed fatigue for up to 24 h post-match but is recovered thereafter. The magnitude and prolonged reduction in the quadriceps potentiated twitch force (a measure of peripheral fatigue) indicates that changes in skeletal muscle primarily explain the resolution of fatigue in the days post-football-match-play. A similar decline and subsequent time-course recovery of jumping performance and perceptual function was also observed, suggesting these might be appropriate tools to indirectly assess the recovery of neuromuscular function following football match-play. These data suggest that full recovery from football match-play can require over 72 h, and therefore those responsible for managing the training process and scheduling fixtures should consider strategies to reduce the potential maladaptive responses that are concurrent with the prolonged compromised neuromuscular function post-football-match-play.

Background to the problem

Association football match-play imposes a significant physical demand on players; a typical 90 minute game requires numerous high-intensity actions, including sprinting, accelerating, jumping, kicking and changing direction, while average heart rates of 80-90% of maximum are attained (Bush *et al.*, 2015; Akenhead *et al.*, 2013; Di Salvo *et al.*, 2009; Rampinini *et al.*, 2007; Mohr *et al.*, 2003). An inevitable consequence of this high physical demand is fatigue, which acutely effects physical performance and persists in the days post-match (Minett & Duffield, 2014). The competitive schedule of the modern day footballer includes frequent demanding periods during the season where multiple games per week are played, often separated by as little as 48 hours. The accumulation of fatigue during these demanding periods has been linked with an increased incidence of injury (Carling *et al.*, 2015; Dellal *et al.*, 2015; Bengtsson *et al.* 2014; Dupont *et al.*, 2010; Ekstrand *et al.*, 2004), and numerous high profile football coaches and managers have called for more flexible scheduling to afford a more complete recovery between games. In England, this debate is particularly prominent, highlighted by a number of recent high profile examples. These include Chelsea FC manager Guus Hiddink calling for medical professionals to challenge fixture scheduling after his team were scheduled to play 4 games in 12 days (<http://www.bbc.co.uk/sport/football/35683605>); Liverpool FC manager Jurgen Klopp attributing an increased incidence of hamstring injuries to a busy fixture schedule (<http://www.bbc.co.uk/programmes/p03dnyrk>) and subsequently selecting a reserve team for a Football Association (FA) Cup fixture (<http://www.bbc.co.uk/sport/football/35155398>); and Manchester City FC Manuel Pellegrini openly criticising the scheduling of an FA Cup fixture in close proximity to an away European fixture (<http://www.bbc.co.uk/sport/football/35572091>). The issue of fixture congestion and fatigue also permeates the England national team, and there are annual debates on the utility or otherwise of a mid-season Winter break as a potential strategy to aid international tournament performance (<http://www.bbc.co.uk/sport/football/35171607>). These examples serve to highlight the extent to which this issue affects a range of stakeholders in football, and its current position within the public eye. Consequently, research that could inform the optimal management of fatigue and recovery in football players can have important implications, not just for the players themselves, but also for competition organisers, coaches, managers and fans.

Introduction

Fatigue is a universal and daily phenomena underpinned by a myriad of complex mechanisms. In the exercise sciences, fatigue is typically defined as an exercise-induced impairment in the ability to produce force (Gandevia, 2001) in the presence of an increased perception of effort (Enoka & Stuart, 1992). Such a definition recognises that fatigue induced by exercise has both functional and perceptual consequences, and provides a means to operationalize the measurement of fatigue. The functional consequences of fatigue can be assessed through measurement of voluntary force production, and through the involuntary response to stimulation of nervous tissue. Such stimulation also permits the attribution of fatigue to various processes along the motor pathway that can be broadly split in to central and peripheral origins (Gandevia, 2001). Peripheral fatigue attributes the decline in force to processes at, or distal to, the neuromuscular junction, in the muscle group under study (Gandevia, 2001). Central fatigue attributes the decline in voluntary force production to processes residing within the central nervous system, commonly assessed by supramaximally stimulating the peripheral motor nerve during an isometric maximum voluntary contraction, and calculating the degree of voluntary activation of muscle via twitch interpolation (Merton, 1954). A subset of central fatigue is supraspinal fatigue, which attributes the decline in force to a sub-optimal output from the motor cortex and can be measured through transcranial magnetic stimulation (TMS) of the brain (Todd *et al.*, 2003). These techniques have been used to demonstrate the presence of central and peripheral fatigue in a range of exercise paradigms (Sidhu *et al.*, 2012; Goodall *et al.*, 2012; 2015; Thomas *et al.*, 2015), and used in concert can provide a deeper understanding of the processes underpinning exercise-induced fatigue.

In football, the nature of fatigue is primarily dependent on the physical demands of match-play, which have been characterised extensively in male participants. Time-motion analyses have demonstrated that elite male footballers will typically cover a total distance of 9-12 km in a 90 min game, with mean heart rate and oxygen uptake values equating to 80-90% and 70% of maximum, respectively (Bush *et al.*, 2015; Akenhead *et al.*, 2013; Di Salvo *et al.*, 2009; Rampinini *et al.*, 2007; Mohr *et al.*, 2003). The activity profile of football is intermittent and varied in nature, and includes frequent and random occurrences of high intensity sprinting, jumping, kicking and changing direction, often with incomplete recovery. More recent advances in technology have further highlighted the extent of the demands of

football match-play, demonstrating the significant requirement for acceleration movements within football that were previously undetectable with less sensitive measurement tools (Osgnach *et al.*, 2010; Akenhead *et al.*, 2013). Collectively these data indicate that association football match-play relies heavily on aerobic endurance, coupled with frequent short-term, high-intensity intermittent actions, and therefore the fatigue induced by football match-play is both metabolic and mechanical in nature.

During football match-play, the occurrence of fatigue is reflected in transient reductions in work rate after intense periods, and cumulative declines in speeds/distance covered as the match progresses (Akenhead *et al.*, 2013). After football match-play, the consequences of fatigue have typically been studied from a peripheral viewpoint, with recovery of skeletal muscle function the target of intervention strategies. For example, significant glycogen depletion has been observed post-match-play (Krustrup *et al.*, 2006) and requires up to 48-72 h to recover (Nedelec *et al.*, 2012). Marked changes in biochemical factors indicative of exercise-induced muscle damage (EIMD) have also been observed, persisting for at least 72 h post-game (Nedelec *et al.*, 2012; Ispirlidis *et al.*, 2008). These physiological changes have been associated with reductions in physical function (maximum voluntary contraction (MVC), countermovement jump height (CMJ) and sprint speed) for a similar time-period (Nedelec *et al.*, 2012; Andersson *et al.*, 2008; Rampinini *et al.*, 2011). There remains however an apparent disconnect in the temporal pattern of recovery of physical function, and markers of peripheral physiology and muscle damage following intermittent-sprint exercise (Pointon *et al.*, 2012; Minnet *et al.*, 2013). This disconnect has led some to speculate that processes within the central nervous system (CNS), specifically the brain, could be making significant contributions to the prolonged fatigue experienced after football match-play (Minnet & Duffield, 2014; Rattray *et al.*, 2015).

In contrast to the study of peripheral physiology, the recovery of CNS function post-intermittent-sprint exercise has not been well researched. As previously described, the neuromuscular mechanisms contributing to fatigue can be central (i.e. residing in the CNS) as well as peripheral in origin (Gandevia, 2001). The significant and prolonged reduction in performance measures that are thought to reflect neuromuscular function (e.g. MVC, CMJ, sprint speed) suggests a potential contribution of impaired CNS function to the observed fatigue post football match-play (Nedelec *et al.*, 2012; Andersson *et al.*, 2008; Rampinini *et*

al., 2011). Although the evidence supporting this posit is limited, one study has demonstrated reductions in voluntary activation measured using motor nerve stimulation (a measure of central fatigue) for up to 48 h post-football match-play (Rampinini *et al.*, 2011). We have also previously shown that voluntary activation is depressed after just two repetitions of a 12 × 30 m repeat-sprint running protocol, and reaches a nadir after sprint ten (Goodall *et al.*, 2015). These data suggest that resolution of the impairments in CNS function are likely to contribute to the recovery of physical performance after football match-play, but there remains a paucity of data to substantiate this claim (Minnet & Duffield, 2014). Accordingly, the primary aim of the present study was to profile the fatigue and recovery of neuromuscular function following football match-play. A secondary aim of the study was to study the time-course recovery of a range of simple measures of physical and perceptual function, in order to provide information on the appropriateness of these tools as markers of a players readiness to train and compete.

Methods

Participants

Following ethical approval from the Northumbria University Faculty of Health & Life Sciences Ethics committee, 16 male semi-professional footballers gave written informed consent to participate. One participant incurred an injury on their penultimate trial and was removed from the study, giving a final sample size of 15 (age, 21 ± 1 ; stature, 1.83 ± 0.07 m; mass, 77 ± 9 kg; predicted maximum oxygen uptake, 55.0 ± 2.9 mL·kg⁻¹·min⁻¹). All participants were current players with teams at Level 9 of the English football league system. Testing took place in the late off-season to early pre-season phase of the players training year (n = 12) and mid-season (n = 3).

Design

Participants first completed two practice trials for habituation to the measurement tools of the study, and a preliminary assessment of aerobic fitness. The experimental trial required participants to visit the laboratory on four consecutive days, separated by 24 h. On the first day participants completed a simulated football match protocol on an indoor synthetic track, in a temperature controlled environment. Pre-, immediately post- and on subsequent days at 24, 48 and 72 h post-match, participants completed a series of assessments to measure neuromuscular, physical and perceptual function to ascertain the fatigue and time-course recovery of these variables after a simulated match. Participants were instructed to avoid food (>2 h), caffeine and alcohol (>24 h), and strenuous exercise (>48 h) prior to the first visit, and were instructed to refrain from caffeine, alcohol and any exercise other than that completed for the study for the duration of their participation.

Procedures

Practice trials

Participants visited the laboratory on two separate occasions for practice trials. On both occasions, after a standardised ten-minute warm-up, participants were habituated to all of the neuromuscular, functional and perceptual measures employed in the study (described below). Subsequent to this on the first practice trial, participants completed the multi-stage fitness test to measure aerobic fitness, and to determine appropriate intensities for the simulated football match protocol. On the second practice trial participants completed fifteen minutes of the simulated football match (described below) to habituate to the demands of the test.

Experimental trials

Simulated football match

On the first day of the experimental trial, participants completed a modified version of the Loughborough Intermittent Shuttle Test (LIST). This simulated football match consisted of 2 × 45 min halves of varying intensity exercise requiring walking, jogging (55% $\dot{V}O_{2max}$), back-peddalling, and running (95% $\dot{V}O_{2max}$) 20 m shuttles in time to an audible beep, interspersed with maximum effort 20 m sprints. This protocol has been previously demonstrated to induce a physical demand and associated metabolic response consistent with a 90 min football match (Nicholas *et al.*, 2000; Magalhaes *et al.*, 2010; Russell *et al.*, 2011). After each 20 m sprint participants were required to forcibly decelerate to a target line situated 5 m from the finish. This procedure was included to more accurately reflect the demands of football match play (Akenhead *et al.*, 2013) and to induce muscle damage consistent with the mechanical demands of football (Howatson & Milak, 2009; Leeder *et al.*, 2013). In total participants completed 42 maximal sprints with forced deceleration across the 90 min. Sprint performance (15 and 20 m) and rating of perceived exertion (RPE, category ratio 0-10 scale) were recorded throughout the simulated match, a schematic of which can be viewed in Figure 1.

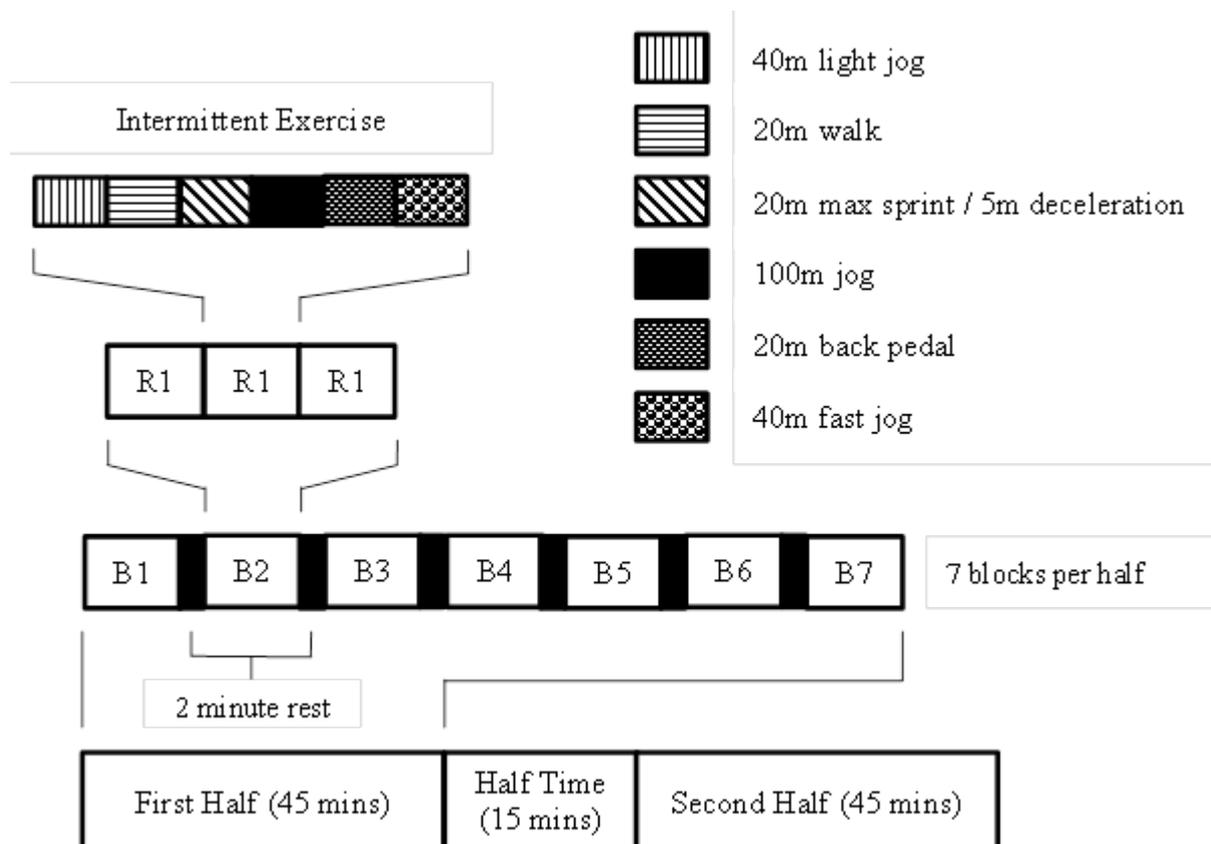


Figure 1. Schematic representation of the simulated football match protocol. Participants were required to complete “rounds” of intermittent exercise consisting of walking, sprinting, jogging, back pedalling and fast jogging. A round of exercise was repeated three times to make a “block” of activity. Seven blocks of activity, each separated by two min rest, equated to a 45 min half. B = block of intermittent exercise, R = round of intermittent exercise per block.

Measures of fatigue and recovery

A range of neuromuscular, physiological, physical and perceptual measures were assessed pre- and post- simulated football match-play, and at 24 h intervals for 72 h post-match, in order to ascertain the fatigue and time-course recovery of these variables. Details of each are outlined below.

Assessment of neuromuscular function

The evoked force and electromyographic (EMG) responses of the quadriceps musculature to TMS of the motor cortex and electrical stimulation of the femoral nerve were assessed to profile fatigue and recovery of CNS and muscle function. A calibrated load cell (MuscleLab force sensor 300, Ergotest technology, Norway), attached via a non-compliant strap and positioned superior to the ankle malleoli of the participants’ dominant leg recorded muscle force (N) during isometric knee-extensor contractions. Surface EMG activity of the *rectus femoris* (RF) and *biceps femoris* (BF) was recorded from surface electrodes (Ag/AgCl;

Kendall H87PG/F, Covidien, Mansfield, MA, USA) placed 2 cm apart over the muscle bellies, with a reference electrode placed on the patella. Electrodes were used to record the root-mean-square (RMS) amplitude for sub-maximal and maximal voluntary contractions, the compound muscle action potential (M-wave) from electrical stimulation of the femoral nerve, and the motor evoked potential (MEP) elicited by TMS. Further detail on these methods is provided below.

Motor nerve stimulation

Single electrical stimuli (200 μ s) were delivered via a constant-current stimulator (DS7AH, Digitimer Ltd., Hertfordshire, UK) using self-adhesive surface electrodes (Nidd Valley Medical Ltd., North Yorkshire, UK) positioned superficially on the skin over the femoral nerve. Electrical stimuli were administered at rest in 20 mA step-wise increments from 100 mA until the maximum quadriceps twitch amplitude (Q_{tw} , N) and muscle compound action potential (M_{max} , mV) was elicited. To ensure a consistent, supramaximal stimulus and account for any fatigue-induced changes in axonal excitability, the resulting stimulation intensity was increased by 30%. Participants subsequently completed six isometric maximum voluntary contractions (MVC) of the knee extensors, separated by 60 s rest. For the final three MVCs, electrical stimuli were delivered during and 2 s post to assess voluntary activation (VA) and potentiated quadriceps twitch force ($Q_{tw,pot}$), respectively.

Motor cortical stimulation

Single and paired pulse TMS of 1 ms duration were delivered to the left motor cortex over Brodmann Area 4 (postero-anterior intracranial current flow) using a concave double cone coil (110 mm diameter, maximum output 1.4 T) powered by two linked monopulse magnetic stimulators (Magstim 200, The Magstim Company Ltd., Whitland, UK). The coil position that elicited a large MEP in the knee extensors and concurrent small MEP in the antagonist muscle was marked with indelible ink. Active motor threshold (AMT) was determined prior to each trial as the stimulus intensity required to elicit an MEP of at least 0.2 mV in the *rectus femoris* in three of five consecutive stimulations during a submaximal (10% MVC) contraction.

Central nervous system excitability and inhibition

Single- and paired-pulse TMS were delivered during sub-maximal contraction (10% MVC) to elicit unconditioned (single pulse) and conditioned (paired-pulse) MEPs at each time point. The ratio of the unconditioned MEP to the maximum M-wave was used as an index of corticospinal excitability. The ratio of the unconditioned to conditioned MEP was used as an index of short-intracortical inhibition (SICI). Ten unconditioned and ten conditioned MEPs were elicited in two sets of ten stimuli, delivered in random order, with each stimuli separated by 4-6 s, and each set separated by 60 s. Single-pulse TMS was delivered at $1.2 \times \text{AMT}$. Paired stimuli, to induce SICI, consisted of a sub-threshold ($0.7 \times \text{AMT}$) conditioning stimulus followed by a supra-threshold ($1.2 \times \text{AMT}$) test stimulus, with an inter-stimulus interval of 3 ms. Post-exercise and at 24, 48 and 72 h if MVC force differed from baseline by $>10\%$ responses were elicited at two contraction strengths; i) at 10% of the non-fatigued MVC recorded at baseline (absolute) and ii) at 10% of the fatigued MVC recorded on the day of the test (relative).

Voluntary activation with TMS

Single pulse TMS was delivered during brief (3-5 s) contractions at 100%, 75% and 50% MVC, separated by 5 s of rest, for determination of voluntary activation with TMS (VA_{TMS}). This procedure was repeated 3 times with 15 s rest between each set. The stimulation intensity was set at the stimulator output that elicited the maximum superimposed twitch force during a 50% MVC (Sidhu *et al.*, 2014).

Assessment of physical function

Participants completed tests of linear speed (10 m and 20 m sprint) and jumping performance (countermovement jump, broad jump and drop jump for reactive strength index) to measure physical function in variables relevant to optimal football performance. Linear speed was recorded using electronic timing gates (TC Timing Systems, Brower Timing Systems, Draper, USA). Vertical jumping performance was recorded using an optical timing system (Optojump Next, Microgate, Milan, Italy). For CMJ, participants were instructed to jump as high as possible, with hands akimbo. For drop jumps (DJ), participants were instructed to keep hands akimbo, step off a 30 cm box, and jump as quickly and as maximally as possible. To ensure the DJ protocol was assessing fast stretch-shortening cycle function, participants were required to attain ground contract times of <200 ms (Hamilton, 2012). Visual feedback

of ground contact time and jump height was provided via a computer monitor after each jump. Reactive strength index (RSI) was calculated as the ratio between jump height (cm) and ground contact time (s). For assessment of horizontal jump performance, participants stood with their toes behind a marked line and jumped maximally in a horizontal direction. Jump distance was recorded at the heel of the backmost foot (m). All participants completed three maximal attempts at each jump, with 60 s separating each repetition, and the best score was recorded for analysis.

Perceptual & blood markers

Participants completed visual analogue scales to assess their perception of muscle soreness (active and passive), fatigue, and readiness to train (post-warm-up) using visual analogue scales. All measures required participants to draw a vertical line on a 15 cm horizontal line to rate their muscle soreness, levels of fatigue and readiness to train. The scales were anchored by verbal descriptors as follows: “extremely sore” to “no soreness”, “extremely fatigued” to “not fatigued at all” and “not ready/tired/fatigued” to “ready/alert/focussed”. Fingertip samples of capillary blood were obtained at each time point and immediately assayed for creatine kinase (CK) concentration (Reflotron, Roche Diagnostics, Germany).

Data analysis

The peak-to-peak amplitudes of the evoked M-wave and MEP responses, measured as the absolute difference between the minimum and maximum points of the biphasic waveform (Fowles *et al.*, 2002) were quantified offline. Corticospinal excitability was quantified as the ratio between the average unconditioned MEP elicited during 10% MVC, and the maximum M-wave. The average of the conditioned paired-pulse MEP was expressed relative to the averaged unconditioned MEP to quantify SICI. Additionally, the root mean square EMG amplitude (EMG_{RMS}) and average force were measured across 80 ms prior to TMS to ensure a similar level of background muscle activity was present immediately pre-stimulation for unconditioned and conditioned MEPs. The interpolated twitch technique was used to quantify VA (Merton, 1954). In brief, the amplitude of the superimposed twitch force (SIT) measured during MVC was compared with the $Q_{tw,pot}$ elicited 2 s post-MVC at rest ($VA, \% = (1 - [SIT/Q_{tw,pot}] \times 100)$). For motor cortical stimulation, voluntary activation was assessed by measurement of the superimposed twitch responses to TMS at 100%, 75% and 50% MVC. As corticospinal excitability increases during voluntary contraction, it is necessary to estimate

the amplitude of the resting twitch in response to motor cortex stimulation. The amplitude of the estimated resting twitch (ERT) was calculated as the y -intercept of the linear regression between the mean amplitude of the superimposed twitches evoked by TMS at 100%, 75% and 50% MVC and voluntary force. Voluntary activation measured with TMS (VA_{TMS} , %) was subsequently calculated as $(1 - [SIT/ERT] \times 100)$.

Statistical analysis

Descriptive statistics are presented as means \pm SD. One-way repeated-measures ANOVA was employed for all response variables, with *a priori* defined post-hoc pairwise comparisons with the pre-test, or baseline, score as the control category. Using the baseline score as the control category focuses the analysis on ascertaining how long the responses measured remain significantly depressed compared to baseline, and therefore how long it took for participants to fully recover from the simulated match. The assumptions of these procedures, including data distribution, were verified as per the guidelines of Newell *et al.* (2010). Standardised effect sizes (Cohen's d) were calculated for focussed pairwise comparisons and interpreted as small (≥ 0.2), moderate (≥ 0.6) and large (≥ 1.2) as per guidelines from Hopkins (2002). Statistical analysis was conducted using GraphPad Prism (GraphPad Software Inc, v5, La Jolla, CA, USA). Statistical significance was accepted at $p < 0.05$.

Results

Responses during simulated football match

Sprint performance over 15 m (2.70 ± 0.12 s vs. 2.73 ± 0.13 s, $p = 0.17$) and 20 m (3.42 ± 0.14 s vs. 3.47 ± 0.17 s, $p = 0.052$) tended to decrease between the first and second halves of the simulated match (Figure 2, panel A). Rating of perceived exertion progressively rose during the simulated match, averaging 7 ± 1 and peaking at 8 ± 1 (Figure 2, panel B).

Creatine kinase

Creatine kinase ($\text{IU}\cdot\text{L}^{-1}$) significantly increased from pre- to post-match (215 ± 125 $\text{IU}\cdot\text{L}^{-1}$ vs. 563 ± 368 $\text{IU}\cdot\text{L}^{-1}$, $p < 0.05$), peaked at 24 h post (813 ± 391 $\text{IU}\cdot\text{L}^{-1}$) and remained significantly elevated at 48 and 72 h (Figure 3).

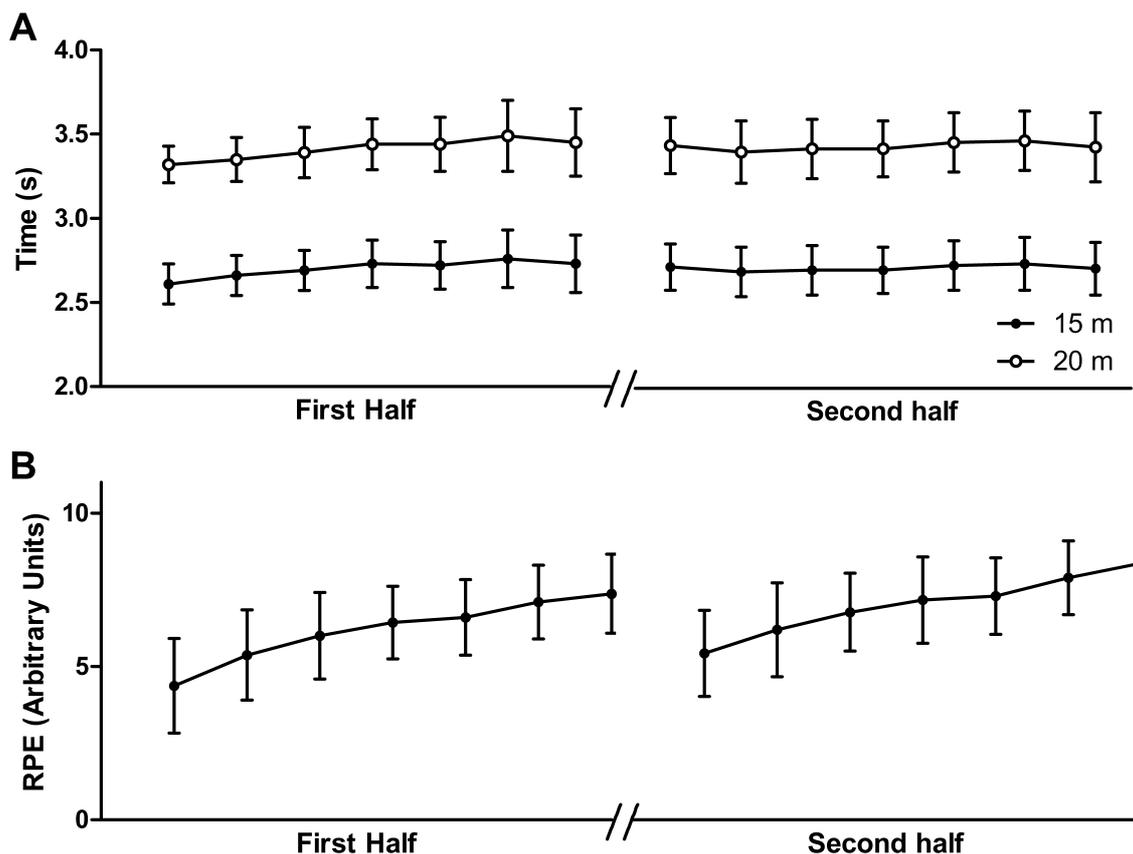


Figure 2. Sprint performance (15 m and 20 m, panel A) and rating of perceived exertion (RPE, panel B) during the simulated football match. Each data point is the mean \pm SD score for the block of activity ($n = 15$).

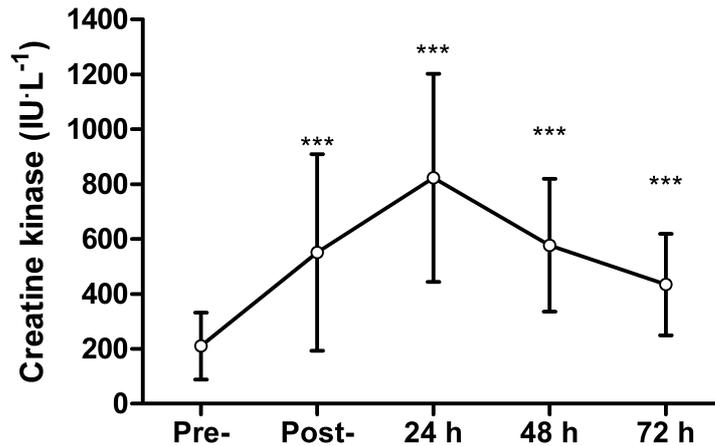


Figure 3. Creatine kinase (CK) measured pre-, immediately post- and at 24, 48 and 72 h post-simulated football match-play ($n = 15$). *** = significant difference at $p \leq 0.001$.

Neuromuscular function

Maximum voluntary force (MVC) was significantly reduced from pre- to post-match (632 ± 54 N vs. 527 ± 64 N, $p < 0.001$, $d = 1.77$), and had not fully recovered by 72 h post-match (614 ± 53 N, $p = 0.01$, $d = 0.33$, Figure 4, panel A). Voluntary activation measured with motor nerve stimulation decreased from pre- to post-match ($91.8 \pm 3.0\%$ vs. $83.3 \pm 4.0\%$, $p < 0.001$, $d = 2.41$), remained depressed at 24 h ($88.0 \pm 3.4\%$, $p < 0.001$, $d = 1.18$) and 48 h ($89.8 \pm 4.1\%$, $p = 0.03$, $d = 0.56$), but recovered by 72 h ($90.3 \pm 3.6\%$, $p = 0.09$, $d = 0.46$ Figure 4, panel B). Voluntary activation measured with motor cortical stimulation (VA_{TMS}) decreased pre- to post-match ($92.5 \pm 2.9\%$ vs. $82.2 \pm 6.3\%$, $d = 2.23$), remained depressed at 24 h ($89.4 \pm 4.2\%$, $d = 0.85$) but recovered by 48 h ($p = 0.44$, $d = 0.25$, Figure 4, panel C). Quadriceps potentiated twitch force was reduced from pre- to post-match (197 ± 22 N vs. 170 ± 26 N, $p < 0.001$, $d = 1.11$), remained similarly depressed at 24 h (171 ± 21 N, $p < 0.001$, $d = 1.19$) and continued to be different from baseline at 48 h (181 ± 23 N, $p < 0.001$, $d = 0.71$) and 72 h post-match (188 ± 30 N, $p = 0.01$, $d = 0.33$, Figure 4, panel D).

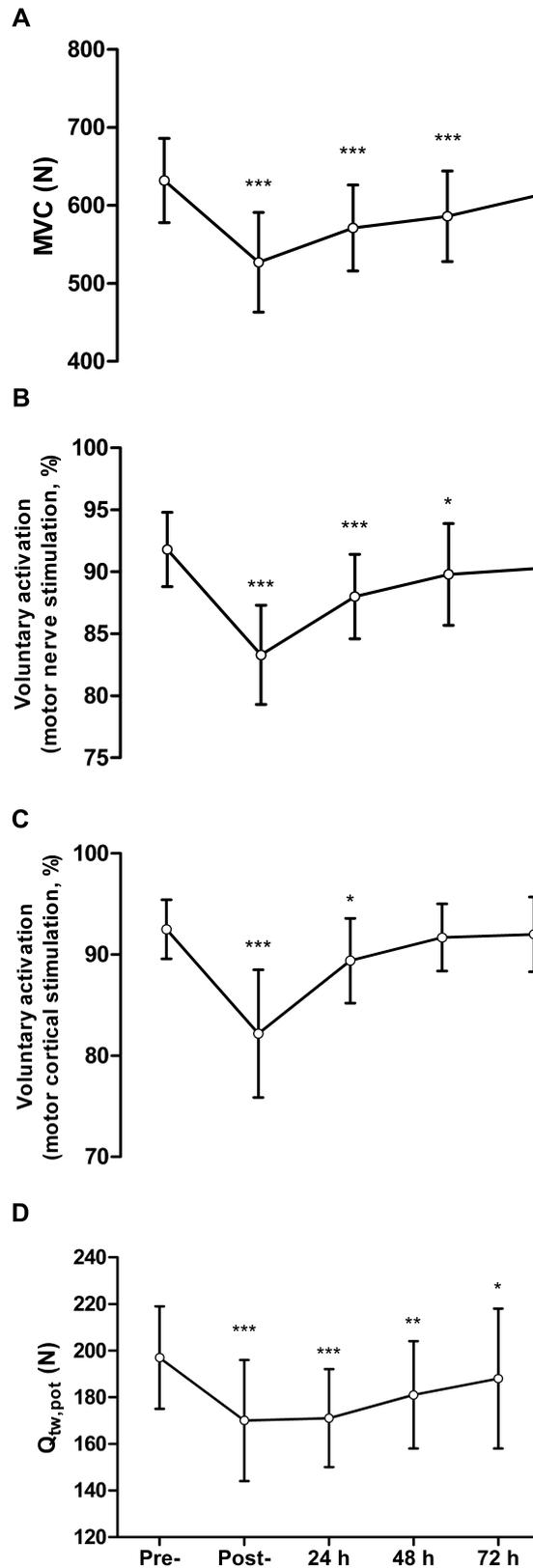


Figure 4. Maximum voluntary contraction force (MVC, A), voluntary activation measured with femoral nerve stimulation (B), voluntary activation measured using motor cortical stimulation (C) and quadriceps potentiated twitch force ($Q_{tw,pot}$, D) measured pre-, immediately post- and at 24, 48 and 72 h post- simulated football match-play (n = 15). Significant differences indicated by * = $p \leq 0.05$, ** = $p \leq 0.01$, *** $p \leq 0.001$.

Central nervous system excitability & inhibition

Corticospinal excitability (unconditioned MEP/ M_{max}) was reduced at 24 h compared to baseline ($34 \pm 8\%$) when measured during a sub-maximal contraction at both absolute ($29 \pm 11\%$, $p = 0.047$) and relative ($28 \pm 12\%$, $p = 0.04$) contraction strengths (Figure 5, panel A). The reduction in corticospinal excitability was explained by a small reduction in the amplitude of the MEP, concurrent with a small increase in M_{max} (see appendix 1, Table 1 for details). No other differences were observed at any other time point. Short intracortical-inhibition was unchanged post-football-match-play, and was not different to the baseline value at any time point (Figure 5, panel B). Full detail regarding the EMG responses to TMS and femoral nerve stimulation procedures can be viewed in appendix 1, Table 1.

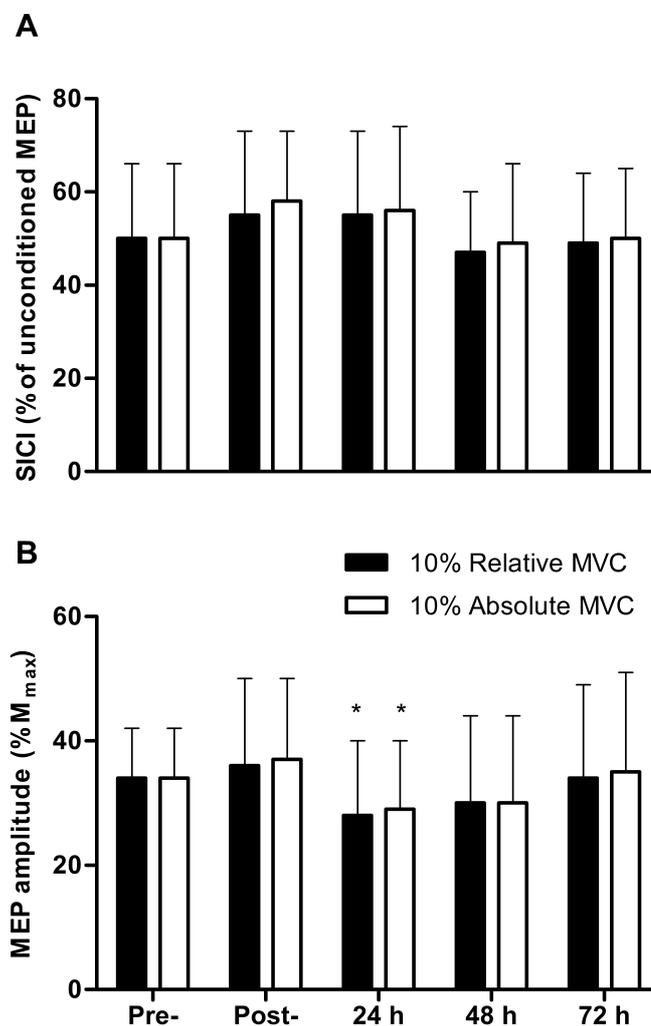


Figure 5. Short-intracortical inhibition (SICI, A) and corticospinal excitability (Unconditioned MEP/ M_{max} , B) pre-, immediately post- and at 24, 48 and 72 h post-simulated football match-play ($n = 15$). Black bars represent measurements elicited during a contraction equivalent to 10% of relative (measured daily) maximum voluntary contraction force. White bars represent measurements elicited during a contraction equivalent to 10% of the absolute, non-fatigued MVC measured on day 1. Values are mean + SD. Significant differences indicated by * = $p \leq 0.05$.

Physical function

Countermovement jump performance was reduced from pre- to post-match (38.8 ± 4.3 cm vs. 34.0 ± 5.0 cm, $p < 0.001$, $d = 1.04$), and there were moderate, significant effects thereafter at 24 h (36.8 ± 4.3 cm, $p < 0.001$, $d = 0.46$), 48 h (36.9 ± 4.2 cm, $p < 0.001$, $d = 0.44$) and 72 h post-match (37.3 ± 4.1 cm, $p = 0.009$, $d = 0.36$, Figure 6, panel A). For DJ measurements, ground contact time averaged 180 ± 16 ms at baseline, and was successfully maintained on subsequent days (range 180 to 186 ms). Reactive strength index (DJ height/ground contact time) was significantly impaired post-match (161 ± 22 cm·s⁻¹ vs. 126 ± 19 cm·s⁻¹, $p < 0.001$, $d = 1.73$), remained depressed at 24 h (144 ± 24 cm·s⁻¹, $p < 0.001$, $d = 0.74$) and 48 h (144 ± 23 cm·s⁻¹, $p < 0.001$, $d = 0.75$), and had recovered by 72 h (156 ± 26 cm·s⁻¹, $p = 0.11$, $d = 0.24$ Figure 6, panel B). Broad jump performance decreased pre- to post-match (2.38 ± 0.11 m vs. 2.23 ± 0.11 m, $p < 0.001$, $d = 1.36$), remained reduced at 24 h (2.32 ± 0.14 m, $p = 0.03$, $d = 0.47$) but had recovered from 48 h onwards (2.37 ± 0.13 m, $p = 0.24$, $d = 0.24$, Figure 6, panel C). Sprinting performance was reduced pre- to post-match for both 10 m (1.87 ± 0.08 s vs. 1.92 ± 0.07 s, $p = 0.01$, $d = 0.62$) and 20 m (3.15 ± 0.09 s vs. 3.26 ± 0.10 s, $p < 0.001$, $d = 1.18$) but was not different at any other time point (Figure 7).

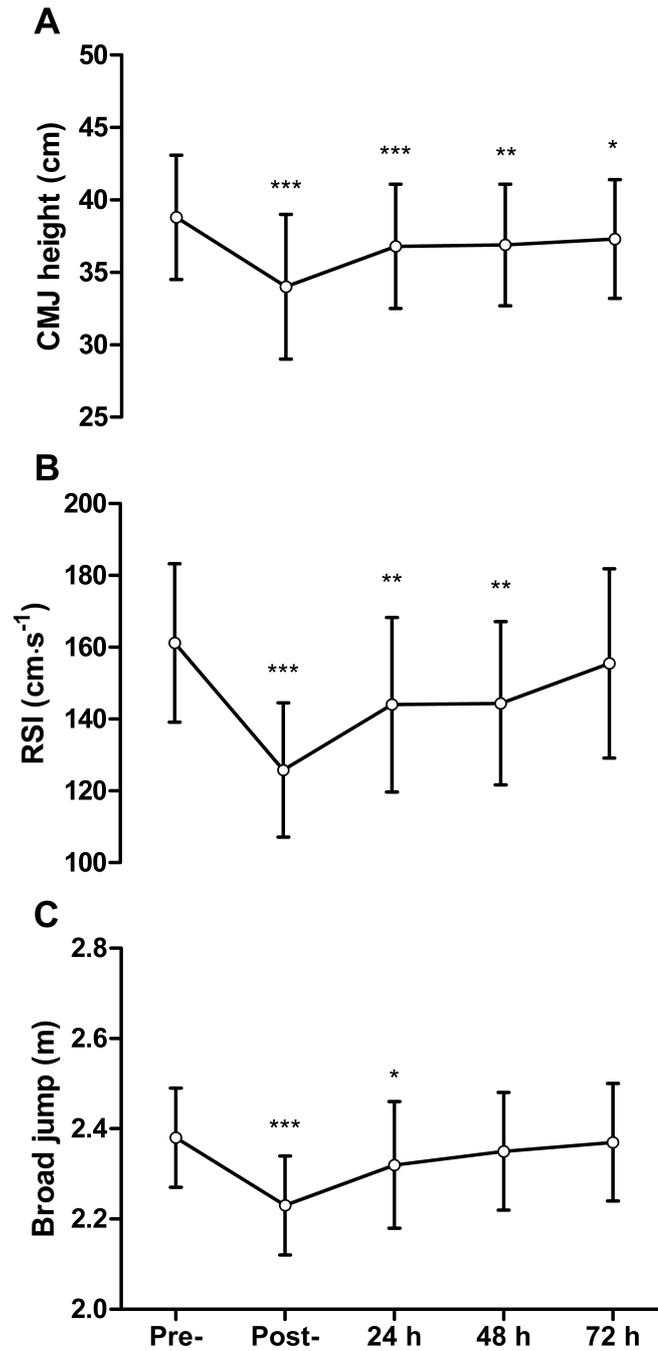


Figure 6. Countermovement jump (CMJ, A), reactive strength index (RSI, B) and broad jump (C) measured pre-, immediately post- and at 24, 48 and 72 h post- simulated football match-play (n = 15). Significant differences indicated by * = $p \leq 0.05$, ** = $p \leq 0.01$, *** $p \leq 0.001$.

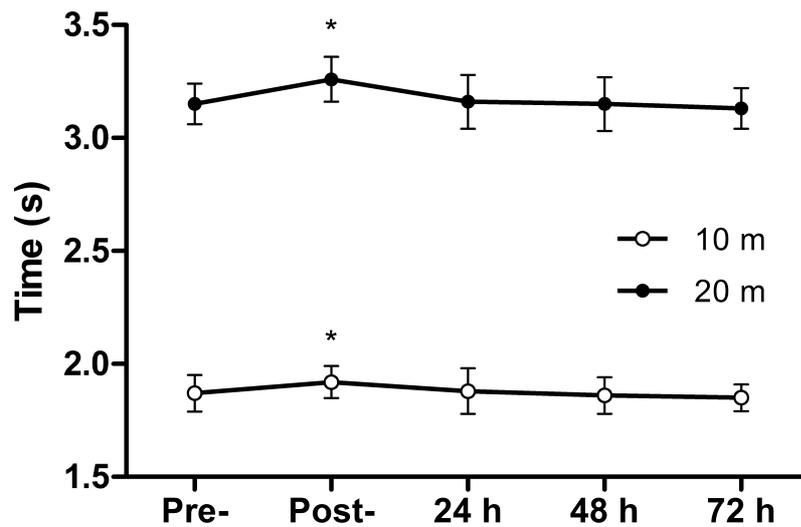


Figure 7. 10m and 20m sprint performance (s) measured pre-, immediately post- and at 24, 48 and 72 h post- simulated football match-play (n = 15). Significant differences indicated by * = $p \leq 0.05$.

Perceptual responses

Perceptions of passive and active muscle soreness, and fatigue were similarly affected by the simulated football match (Figure 8). Soreness and fatigue peaked post-match, and were significantly depressed at 24 and 48 h (all $p < 0.05$, Figure 8). All variables had recovered to baseline values by 72 h post-match (all $p > 0.05$, Figure 8). However, perceptions of readiness to train, measured pre- and at 24 h intervals post-match before assessment of physical function and after a standardised warm-up, were not affected by the simulated game ($p > 0.05$, Figure 9).

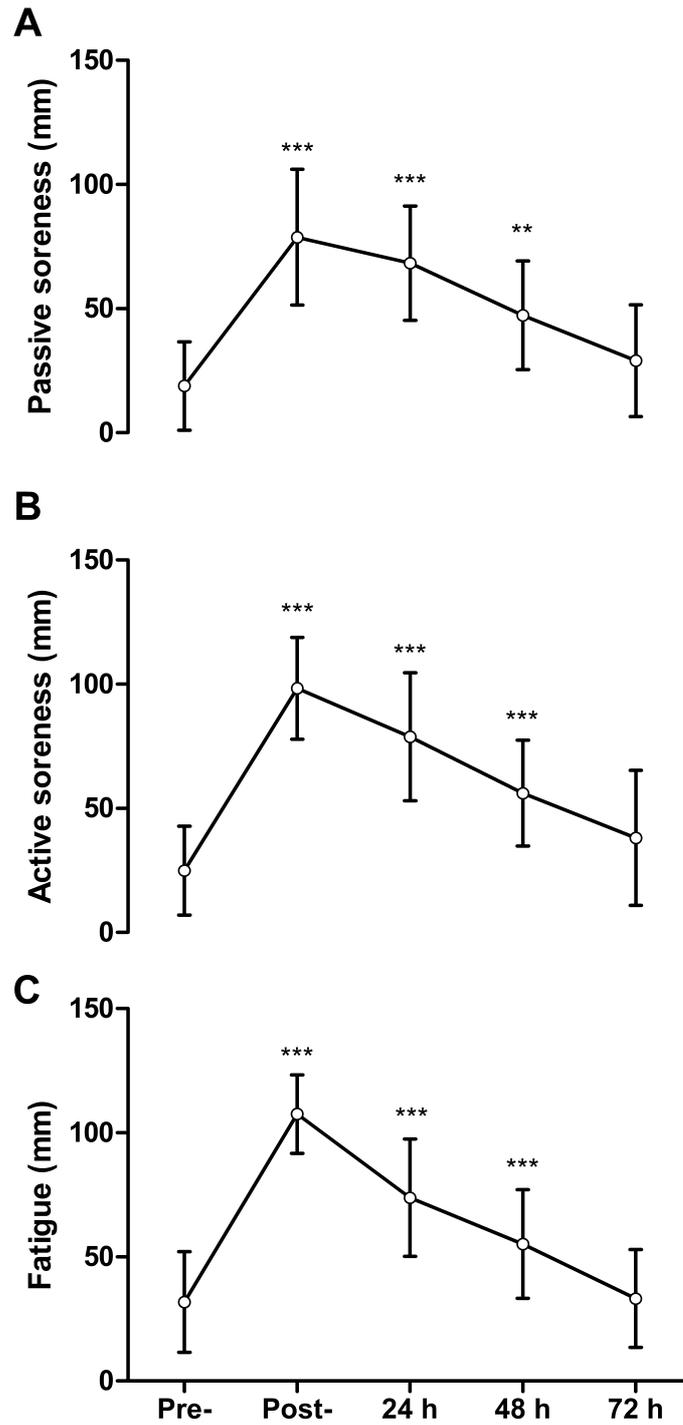


Figure 8. Perceptions of passive muscle soreness (A), active muscle soreness (B) and fatigue (C) measured using visual analogue scales pre-, immediately post- and at 24, 48 and 72 h post- simulated football match-play ($n = 15$). Significant differences indicated by $** = p \leq 0.01$, $*** p \leq 0.001$.

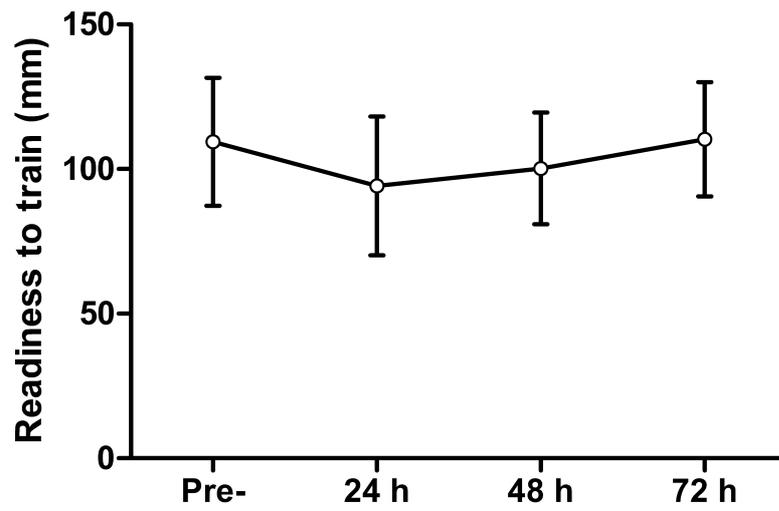


Figure 9. Readiness to train measured using a visual analogue scale, after a standardised warm-up, pre-, immediately post- and at 24, 48 and 72 h post- simulated football match-play (n = 15).

Discussion

The primary aim of the study was to ascertain the fatigue and time-course recovery of neuromuscular function following simulated football match-play. A secondary aim was to investigate the potential of simple physical and perceptual assessments to profile recovery after football match-play, in order to provide practitioners with suitable tools to monitor recovery and inform the assessment of a player's readiness to train. The data demonstrate significant central and peripheral fatigue is elicited by football match-play, which persists for 48 to 72 h post-match. Central fatigue is manifest in large reductions in voluntary activation post-exercise, which recovers markedly by 24 h but remains different to baseline values for 48 h post-match. Supraspinal fatigue, a subset of central fatigue attributable to a suboptimal output from motor cortical cells, contributes to the observed fatigue for up to 24 h post-match but is recovered thereafter. The magnitude and prolonged reduction in the quadriceps potentiated twitch force (a measure of peripheral fatigue) indicates that changes in skeletal muscle primarily explain the resolution of fatigue in the days post-football-match-play. The similar decline and subsequent time-course recovery of physical and perceptual function suggests these might be appropriate tools to indirectly assess the recovery of neuromuscular function following football match-play.

Central and peripheral fatigue post-match-play. The simulated football match elicited significant fatigue that was both central and peripheral in origin. Maximum voluntary force (a measure of global fatigue) and potentiated twitch force (a measure of peripheral fatigue) were reduced post-match and remained different from baseline at 72 h post. Voluntary activation (a measure of central fatigue) was depressed for 48 hours, but had recovered by 72 h. This U-shaped time-course recovery of neuromuscular function is similar to findings reported following prolonged intermittent sprint exercise (Pointon and Duffield, 2012; Pointon *et al.*, 2012; Minett *et al.*, 2013; Skein *et al.*, 2013; Minett and Duffield, 2014), and suggests the fatigue experienced after football match-play has both central and peripheral origins. Voluntary activation assessed with TMS, a subset of central fatigue attributable to supraspinal mechanisms, was depressed post-match and at 24 h but had recovered by 48 h post. Therefore, while VA (measured with motor nerve stimulation) remained depressed for 48 h, the earlier recovery of VA_{TMS} suggests the origin of central fatigue observed from 24 h onwards was not attributable to a suboptimal output from the motor cortex. One previous study profiling the time-course recovery of neuromuscular function post-football-match-play

reported a similar pattern of response to the present study, but with a faster return to baseline where central and peripheral markers of fatigue had recovered by 48 h post (Rampinini *et al.*, 2011). Rampinini *et al.* (2011) studied fatigue in a higher standard of footballer (professional academy players), at a different stage of the season (competition phase) and after a friendly, rather than simulated, football match. All of these factors could explain the faster recovery of neuromuscular function observed and emphasises the need for more detailed study in this area. Collectively, the available data suggest that significant central and peripheral fatigue occurs in response to football match-play, which persists for up to 72 h after the game.

Although it is not possible to accurately quantify the relative contribution of central and peripheral processes to the observed decrease in maximal voluntary force, a comparison of the magnitude of the decrement of each with previous work provides some insight. For central fatigue, the magnitude of decrease immediately post-exercise ($-9 \pm 4\%$ for VA, $-10 \pm 5\%$ for VA_{TMS}) was comparable to previous data from our lab examining fatigue after repeat sprint exercise ($-9 \pm 9\%$ for VA, $-9 \pm 7\%$ for VA_{TMS}; Goodall *et al.*, 2015), self-paced time-trial cycling exercise exceeding 30 min ($-10 \pm 10\%$ for VA, $-12 \pm 6\%$; Thomas *et al.*, 2015) and constant-load cycling exercise of 30-45 min duration ($-9 \pm 5\%$ for VA, $-9 \pm 8\%$ for VA_{TMS}; Thomas *et al.*, 2016). This suggests that central fatigue contributed significantly to the fatigue measured immediately post-exercise, and is consistent with previous work demonstrating that central fatigue is prominent after long-duration locomotor exercise (Thomas *et al.*, 2016; 2015; Decorte *et al.*, 2012). At 24 and 48 h post-exercise there was evidence of residual central fatigue, but the magnitude of this depression was relatively small in comparison to the post-exercise decrease ($-4 \pm 2\%$ for VA, $-3 \pm 4\%$ for VA_{TMS} at 24 h, $-2 \pm 3\%$ for VA at 48 h), suggesting a relatively rapid recovery of central fatigue. Although statistically significant, and representing moderate to large effects, the functional relevance of such small differences in voluntary activation is not possible to accurately quantify, and could be questioned. In contrast, the degree of peripheral fatigue (reductions in $Q_{tw,pot}$) evident immediately post-exercise ($-14 \pm 10\%$), remained similarly depressed at 24 h post- ($-13 \pm 5\%$), and was still different to baseline at 72 h post-match ($-5 \pm 6\%$). The magnitude of the reduction in potentiated twitch is largely dictated by the extent of muscle mass involved (Rossman *et al.*, 2012; 2014), and the intensity of the exercise task (Thomas *et al.*, 2016), whereby a smaller active muscle mass and a higher exercise intensity results in a greater absolute magnitude of peripheral fatigue. Consequently, the 14% reduction in $Q_{tw,pot}$

immediately post-exercise observed after simulated football match-play is relatively small compared to previous observations in high-intensity single-leg ($-44 \pm 6\%$) vs. double-leg cycling ($-33 \pm 7\%$; Rossman *et al.*, 2014), and for all-out repeat-sprint running exercise ($-23 \pm 9\%$; Goodall *et al.*, 2015) where the active muscle mass was smaller and/or the intensity of exercise was higher. However, that the magnitude of this reduction persists at 24 h post-exercise, where central fatigue has demonstrated a quicker recovery, suggests the fatigue experienced in the days post-match can be explained to a greater extent by processes occurring at the muscle relating to the inflammatory, muscle damage response, rather than processes within the central nervous system. Recent reviews have suggested that future research should focus more on the recovery of central factors of fatigue in the days post-intermittent-sprint exercise (Minnet & Duffield, 2014; Rattray *et al.*, 2015); our data would suggest this is a valuable endeavour given the significant central fatigue present in the days post-exercise, but that recovery of skeletal muscle function should remain the primary target of intervention aimed at optimising recovery from football match-play.

Central nervous system excitability and inhibition. Corticospinal excitability, inferred from changes in the unconditioned MEP to M_{\max} ratio, was different to baseline only at 24 h post-match. The lack of difference in this variable when measured 2 min post-match was not unexpected, and is consistent with a number of previous investigations of this measure post-fatiguing exercise in various exercise modes (Thomas *et al.*, 2016; 2015; Goodall *et al.*, 2015; Sidhu *et al.*, 2009). The magnitude of SICI, inferred from changes in the unconditioned MEP expressed relative to the conditioned, paired-pulse, MEP, was not different at any time point. These measures are proposed to represent the excitability of the brain-to-muscle pathway, and the status of intracortical inhibitory interneurons, and in the context of exercise have been shown to modulate with acute (Nuzzo *et al.*, 2016) and chronic (Beck *et al.*, 2007; Weier *et al.* 2012) resistance exercise, fatiguing locomotor cycling exercise (Sidhu *et al.*, 2013) and single limb maximal (Butler *et al.*, 2003) and submaximal (Williams *et al.*, 2014) fatiguing contractions. On this basis we hypothesised the status of these variables in the days post-exercise could reflect residual, central nervous system fatigue, but their lack of change did not support this posit. The reduction in excitability 24 h post-exercise was concurrent with a reduction in VA_{TMS} at the same time point, with both recovering by 48 h. There is a plausible theoretical link between changes in corticospinal excitability and the degree of voluntary activation of muscle inferred from stimulation of motor cortical cells, but the functional

relevance of changes in corticospinal excitability is also questionable (Bestmann & Krakauer, 2015), and more research is required before firm conclusions could be drawn from this finding. That these measures were not sensitive to fatigue and recovery of neuromuscular function are not altogether surprising given that the measurement of the MEP response to TMS is notoriously variable (Heroux *et al.*, 2015), the functional relevance of changes in the MEP response is questionable, and that the size of the MEP is subject to modulation by multiple mechanisms and sites; including pre-motor and motor supraspinal areas (Bestmann & Krakauer, 2015), the excitability of the spinal motoneuron pool (Taylor, 2006) and afferent inputs at both motor and spinal sites (Carroll *et al.*, 2011). A detailed physiological underpinning to the MEP evoked by TMS remains incompletely understood (Bestmann & Krakauer, 2015), but the present data suggests their use to understand any residual fatigue of the central nervous system in the days post-football-match-play is limited.

Recovery of physical function. All measures of physical function were impaired immediately post-game, but recovered at different rates. Vertical jumping performance (countermovement and drop jump for reactive strength index) followed a similar decline and recovery as measures of neuromuscular function, with countermovement jump height remaining reduced at 72 h post. This decrease and recovery of jumping performance is similar to that previously reported in the days following football match-play (Andersson *et al.*, 2008; Rampinini *et al.*, 2011; Nedelec *et al.*, 2012). Broad jump and sprint performance were less sensitive as markers of fatigue, suggesting their use to profile the recovery process after football match-play is limited. These observations are supported by previous research demonstrating jump tests to be superior in their consistency and sensitivity to fatigue in the days post-exercise compared to sprinting tests (Gathercole *et al.*, 2015a), and that the decrements in jumping performance following football match-play are relatively consistent (remaining depressed for 48-72 h post; Andersson *et al.*, 2008; Rampinini *et al.*, 2011; Nedelec *et al.*, 2014) whereas the effect on sprinting performance ranges from no effect (Oliver *et al.*, 2008), through to full recovery by 24 h (Rampinini *et al.*, 2011), 48 h (Ascensao *et al.*, 2008) and >72 h (Nedelec *et al.*, 2014).

The use of a jump test as a surrogate measure of neuromuscular fatigue is a promising avenue of investigation, given the simplicity with which this can be administered, however there are caveats to this recommendation. Firstly, measurement of countermovement jump

performance alone might mask fatigue-induced changes in jump strategy; that is, the same jump performance can be achieved by a change in the contraction time/flight time ratio indicative of a “slower” jump. Such a change in jumping strategy could serve to mask changes induced by fatigue (Gathercole *et al.*, 2014; 2015b). The CMJ is also a relatively slow stretch-shortening cycle action, and as such mechanical damage and subsequent effects on muscle stiffness might not be fully revealed by changes in this measure. The measurement of RSI using a drop jump with a very short (<200 ms) ground contact time could address this limitation and provide a better measure of “fast” stretch-shortening cycle function (Flanagan & Comyns, 2008; Hamilton, 2012), and the time-course recovery and sensitivity of this measure on a group level in the present data suggests this could be a promising tool. However, inspection of the individual data for both jumping assessments reveals some inconsistencies. For example, at the 24 h time-point the reduction in potentiated twitch was $\geq 8\%$ for all participants, but this was concurrent with decreases in jump performance $\geq 5\%$ relative to baseline in 11 of 15 participants for RSI, and 9 of 15 participants for CMJ. At 48 h post-match reductions in potentiated twitch of $\geq 8\%$ persisted for 8 out of the 15 participants; all 8 still demonstrated reductions in RSI $\geq 5\%$, but only 6 of 8 had CMJ decrements of $\geq 5\%$, and there were 2 participants who demonstrated compromised jump performance despite measures of neuromuscular fatigue recovering to near baseline (within 5%) scores. These data demonstrate that the RSI might be a more sensitive surrogate measure of neuromuscular fatigue, but that the variability inherent in voluntary performance will likely lead to both “false positives” and “false negatives” if practitioners rely on a single tool as an assessment of readiness.

Recovery of perceptual responses. Measures of perceptual function had a similar time-course recovery pattern to the physical and neuromuscular responses studied. Perceptual scales such as those utilised within this study can be used daily and are a simple, non-invasive method of assessing an athlete’s recovery status without disrupting their training schedule (Laurent *et al.*, 2011) and as a result might be a better alternative to a physical monitoring tool (Saw *et al.*, 2016). As a minimum the variability inherent in jumping performance would suggest that an assessment of the athlete’s perceived recovery would offer valuable ancillary information in determining recovery status. Interestingly, perceptions of readiness to train assessed after a standardised warm-up were not significantly impaired at any time point within the study, despite the documented declines in neuromuscular and

physical function. This suggests that a thorough warm-up might mask the deleterious effects of fatigue present in the days post-match, which has implications for the timing of perceptual assessment for practitioners.

Limitations & Future Directions. The simulated football match protocol used in the present study included the use of forced decelerations after each sprint in an attempt to account for the frequency and mechanical demand of such events observed in real football match-play (Akenhead *et al.*, 2013; Osgnach *et al.*, 2010). Although the simulated football match protocol has been validated previously relative to the physiological response observed in a real football game (Nicholas *et al.*, 2000; Maghalaes *et al.*, 2010; Russell *et al.*, 2011), the addition of forced decelerations was novel to this study. In defence of this procedure, the simulated match protocol employed in the current study elicited physiological and perceptual responses during exercise consistent with those observed previously in simulated compared to real football matches (Nicholas *et al.*, 2000; Maghalaes *et al.*, 2010; Russell *et al.*, 2011), and the responses observed in the days post-exercise, including markers of muscle damage (measures of creatine kinase and soreness) and decrements in neuromuscular and physical function, were comparable to previous work (Andersson *et al.*, 2008; Rampinini *et al.*, 2011; Nedelec *et al.*, 2014), indicating the stimulus was appropriate to study the research question in a laboratory environment. Further research is required with real football matches in order to further corroborate these findings in a more ecologically valid model.

The measurements of neuromuscular function were studied in the dominant knee extensor musculature at rest, and during submaximal and maximal isometric contractions, with evoked responses recorded from the *rectus femoris*. These procedures have been previously validated (Merton, 1954; Todd *et al.*, 2003; Sidu *et al.*, 2009; Goodall *et al.*, 2009) and allow an assessment of voluntary and involuntary force capacity, and the magnitude of central and peripheral fatigue. However the fatigue elicited by the physical demands of football, which requires complex whole-body maximal and submaximal multi-directional movements, might not be fully elucidated by studying the fatigue of a single muscle group in a single-limb isometric contraction. Additionally, there is a significant cognitive component to successful football performance that is not present in a simulated match, which could contribute to impairments in performance by increasing mental fatigue and the perception of effort required during a match (Smith *et al.*, 2014). These limitations notwithstanding, the

significant and prolonged neuromuscular fatigue observed after football match-play in the present study, which was concurrent with prolonged muscle damage and decrements in physical function, provide support for the usefulness of the methods employed in revealing new information about the fatigue induced by football match-play, and the likely time-course recovery of central and peripheral components of fatigue.

The present study provides useful information on the time-course recovery of neuromuscular function after simulated football match-play, which has a number of practical implications, but also raises a number of pertinent questions. The prolonged decrement in physical and neuromuscular function for up to 72 h post-match has implications for both practitioners and competition organisers. At 72 h post-match, eight participants had residual muscle fatigue such that their scores differed by $>5\%$ compared to baseline, with four of these individuals exhibiting muscle fatigue that was $\geq 10\%$ compared to baseline. In this sense, over 50% of the sample still exhibited marked muscle fatigue three days post-match. For practitioners this information highlights the need to appropriately monitor recovery from football match-play, and to modify training in the days post-match to account for individual responses. For competition organisers, the requirement to schedule multiple fixtures in a congested calendar poses significant challenges to afford players optimal recovery. Indeed, fixtures are often scheduled with as little as 48 h between, whereas the data presented here suggests that 72 h might not be sufficient for full recovery for some players. The effect of playing multiple fixtures separated by incomplete recovery over a prolonged period could further exacerbate this problem, and though data suggests that match-play physical performance during congested fixture periods is not negatively affected (Dellal *et al.*, 2015; Carling *et al.*, 2012; Dupont *et al.*, 2010), the increased incidence of injury observed during these periods (Carling *et al.*, 2015; Bengtsson *et al.* 2014; Dellal *et al.*, 2015; Dupont *et al.*, 2010; Ekstrand *et al.*, 2004) suggests there is likely an accumulation of fatigue as a consequence of playing multiple games with inadequate recovery. A better understanding of the consequences of football match-play is required, and further study of appropriate intervention to accelerate recovery from football match-play is also warranted. In the present study participants followed no structured training or recovery plan in between testing occasions, and a worthwhile area for future research would be to establish the potential positive effects of restorative training and recovery strategies, particularly on the recovery of neuromuscular function following football match-play.

Conclusions

Simulated football match-play induced significant fatigue that was both central and peripheral in origin, and persisted for up to 72 h post-match. The magnitude of peripheral fatigue incurred post-match remained similar at 24 h post, and was still different to baseline at 72 h. In comparison, central fatigue was prominent immediately post-match, but showed a more complete recovery by 24 h post, and had fully recovered by 72 h post-match. Collectively, these data suggest central processes contribute significantly to the fatigue experienced in the days post-match-play, but the magnitude and slower recovery of peripheral fatigue indicates that it is processes relating to muscle function that primarily explain the resolution of fatigue after games. That these processes can persist for up to 72 h post-match has significant practical implications for the training process and the scheduling of matches. The assessment of fast stretch- shortening-cycle function via measurement of the reactive strength index provides a promising surrogate measurement of neuromuscular fatigue, but it is recommended practitioners use a range of tools, including simple assessments of perceived recovery, to combat the variability inherent in voluntary performance when assessing recovery status.

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Appendix 1

Table 1. Surface electromyographic responses to transcranial magnetic stimulation and electrical stimulation of the femoral nerve at rest and during contraction (n = 15). Evoked responses were recorded from *rectus femoris*. Unconditioned motor evoked potentials are reported for weak contraction (10% of relative MVC measured daily (relative), and 10% of MVC measured at baseline (absolute)), and for strong contractions (100, 75 & 50% MVC during measurement of voluntary activation with TMS). The average pre-stimulation root mean square EMG amplitude and force for each MEP configuration was equivalent within trial. Values are mean \pm SD.

	Pre-	Post	24 h	48 h	72 h
<i>Evoked amplitudes (mV)</i>					
M_{\max}	5.84 \pm 2.08	5.74 \pm 1.99	6.18 \pm 2.00	6.15 \pm 2.14	5.99 \pm 2.33
Unconditioned MEP (absolute)	1.99 \pm 0.78	2.15 \pm 1.10	1.72 \pm 0.63	1.74 \pm 0.76	1.95 \pm 0.94
Unconditioned MEP (relative)	1.99 \pm 0.78	2.07 \pm 1.06	1.65 \pm 0.67	1.69 \pm 0.74	1.92 \pm 0.90
Conditioned (SICI) MEP (absolute)	0.97 \pm 0.44	1.29 \pm 0.84	0.91 \pm 0.33	0.84 \pm 0.36	0.95 \pm 0.45
Conditioned (SICI) MEP (relative)	0.97 \pm 0.44	1.14 \pm 0.69	0.86 \pm 0.30	0.78 \pm 0.33	0.91 \pm 0.41
<i>EMG_{RMS} (mV)</i>					
Unconditioned MEP (absolute)	0.064 \pm 0.007	0.063 \pm 0.010	0.063 \pm 0.005	0.061 \pm 0.061	0.061 \pm 0.007
Unconditioned MEP (relative)	0.064 \pm 0.007	0.062 \pm 0.008	0.063 \pm 0.005	0.061 \pm 0.006	0.061 \pm 0.007
Conditioned (SICI) MEP (absolute)	0.064 \pm 0.007	0.063 \pm 0.012	0.064 \pm 0.006	0.061 \pm 0.006	0.006 \pm 0.006
Conditioned (SICI) MEP (relative)	0.064 \pm 0.007	0.062 \pm 0.010	0.063 \pm 0.006	0.061 \pm 0.006	0.060 \pm 0.006
<i>Force (N)</i>					
Unconditioned MEP (absolute)	63.0 \pm 6.1	62.3 \pm 6.5	63.0 \pm 6.8	62.0 \pm 7.0	61.7 \pm 5.7
Unconditioned MEP (relative)	63.0 \pm 6.1	54.3 \pm 6.3	58.3 \pm 5.1	59.3 \pm 5.5	61.3 \pm 5.1
Conditioned (SICI) MEP (absolute)	63.2 \pm 6.1	62.0 \pm 5.9	63.2 \pm 6.4	61.8 \pm 6.8	61.9 \pm 5.3
Conditioned (SICI) MEP (relative)	63.2 \pm 6.1	54.4 \pm 6.3	58.5 \pm 5.2	59.2 \pm 5.7	61.3 \pm 4.6
<i>Evoked MEPs (mV)</i>					
100% MVC	2.96 \pm 1.14	3.31 \pm 1.27	2.98 \pm 1.02	3.01 \pm 1.20	2.96 \pm 1.13
75% MVC	3.17 \pm 1.20	3.35 \pm 1.19	3.29 \pm 1.06	3.39 \pm 1.21	3.44 \pm 1.37
50% MVC	3.50 \pm 1.43	3.26 \pm 1.28	3.59 \pm 1.21	3.72 \pm 1.63	3.71 \pm 1.41