



LEEDS  
BECKETT  
UNIVERSITY

---

Citation:

Thurlow, F and McLaren, SJ and Townshend, A and Morrison, M and Cowley, N and Weakley, J (2024) Repeated sprint training: The effects of session volume on acute physiological, neuromuscular, perceptual and performance outcomes in athletes. *European Journal of Sport Science*. pp. 1-13. ISSN 1746-1391 DOI: <https://doi.org/10.1002/ejsc.12217>

Link to Leeds Beckett Repository record:

<https://eprints.leedsbeckett.ac.uk/id/eprint/11583/>

Document Version:

Article (Published Version)

---

Creative Commons: Attribution 4.0

© 2024 The Author(s).

The aim of the Leeds Beckett Repository is to provide open access to our research, as required by funder policies and permitted by publishers and copyright law.

The Leeds Beckett repository holds a wide range of publications, each of which has been checked for copyright and the relevant embargo period has been applied by the Research Services team.

We operate on a standard take-down policy. If you are the author or publisher of an output and you would like it removed from the repository, please [contact us](#) and we will investigate on a case-by-case basis.

Each thesis in the repository has been cleared where necessary by the author for third party copyright. If you would like a thesis to be removed from the repository or believe there is an issue with copyright, please contact us on [openaccess@leedsbeckett.ac.uk](mailto:openaccess@leedsbeckett.ac.uk) and we will investigate on a case-by-case basis.

# Repeated sprint training: The effects of session volume on acute physiological, neuromuscular, perceptual and performance outcomes in athletes

Fraser Thurlow<sup>1,2</sup>  | Shaun J. McLaren<sup>3,4</sup>  | Andrew Townshend<sup>1,2</sup>  |  
 Matthew Morrison<sup>1,2</sup>  | Nicholas Cowley<sup>1,2</sup>  | Jonathon Weakley<sup>1,2,5</sup> 

<sup>1</sup>School of Behavioural and Health Sciences, Australian Catholic University, Brisbane, Queensland, Australia

<sup>2</sup>Sports Performance, Recovery, Injury and New Technologies (SPRINT) Research Centre, Australian Catholic University, Brisbane, Queensland, Australia

<sup>3</sup>Newcastle Falcons Rugby Club, Newcastle Upon Tyne, UK

<sup>4</sup>Department of Sport and Exercise Sciences, Manchester Metropolitan University Institute of Sport, Manchester, UK

<sup>5</sup>Carnegie Applied Rugby Research (CARR) Centre, Carnegie School of Sport, Leeds, UK

## Correspondence

Jonathon Weakley.

Email: [Jonathon.Weakley@acu.edu.au](mailto:Jonathon.Weakley@acu.edu.au)

## Abstract

We examined the effects of repeated sprint training (RST) session volume on acute physiological, neuromuscular, perceptual and performance outcomes. In a randomised, counterbalanced, and crossover design, 14 healthy and trained male and female athletes (age:  $23 \pm 3$  years) completed two sets of  $10 \times 40$  m ( $10 \times 40$ ),  $5 \times 40$  m ( $5 \times 40$ ),  $10 \times 20$  m ( $10 \times 20$ ) and  $5 \times 20$  m ( $5 \times 20$ ) sprints with 30 s rest between repetitions and 3 min rest between sets for all protocols. Average and peak heart rate, average oxygen consumption ( $\text{VO}_2$ ), time >90% of maximal oxygen consumption ( $\text{VO}_{2\text{max}}$ ), differential ratings of perceived exertion (RPE), session-RPE training load (sRPE-TL), percentage sprint decrement ( $S_{\text{dec}}$ ), acceleration load and distance >90% of maximal sprint speed were recorded during each session. Neuromuscular performance (i.e. countermovement jump, lower-limb stiffness and isometric hamstring strength) were measured post-session, 24 h, and 48 h and compared to pre-session. A univariate analysis of variance was used to compare within- and between-protocol differences. To aid data interpretation, all effects were expressed as an effect size and accompanied by probability values ( $p_{\text{MET}}$ ). The  $10 \times 40$  protocol induced the greatest training load compared to all other protocols ( $p_{\text{MET}} < 0.05$ ), including *moderate* to *very large* differences in breathlessness RPE, *large* differences in  $S_{\text{dec}}$  and time >90%  $\text{VO}_{2\text{max}}$  and *very large* differences in sRPE-TL. The  $5 \times 20$  protocol induced the lowest training load compared to all other protocols ( $p_{\text{MET}} < 0.05$ ), including *moderate* to *large* differences in sRPE-TL and leg muscle RPE. Heart rate,  $\text{VO}_2$ , sRPE-TL, leg muscle RPE and  $S_{\text{dec}}$  were similar between  $5 \times 40$  and  $10 \times 20$  ( $p_{\text{MET}} < 0.05$ ), but the acceleration load was greater for  $10 \times 20$  when compared to  $5 \times 40$  ( $p_{\text{MET}} < 0.001$ ), and this difference was *large*. Changes in neuromuscular performance across all timepoints and all protocols were

This manuscript is original and not previously published in any form including on preprint servers, nor is it being considered elsewhere until a decision is made as to its acceptability by the editorial review board.

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2024 The Author(s). European Journal of Sport Science published by Wiley-VCH GmbH on behalf of European College of Sport Science.

unclear. Larger session volumes increase the demands of RST and by manipulating volume, sprint distance and the number of repetitions, practitioners can alter the internal and external training load.

#### KEYWORDS

cardiorespiratory, fitness, periodisation, team sport, training load

#### Highlights

- The 10 × 40 protocol (i.e. 800 m volume) induced the greatest physiological and perceptual demands, which was demonstrated by a session average heart rate and  $\text{VO}_2$  of  $89\% \pm 3\%$  and  $72\% \pm 8\%$  of max, respectively, whereas differential RPE were rated hard to very hard on average.
- Performing 10 repetitions did not substantially increase the average  $\text{VO}_2$  demands when sprint distance was matched (e.g. 10 × 40 vs. 5 × 40). Rather than prescribing high repetition protocols, practitioners are encouraged to increase sprint distance if a greater aerobic stimulus is desired.
- There were no differences in the heart rate and  $\text{VO}_2$  recovery between the 2nd and 3rd minute of inter-set recovery. Therefore, to reduce session duration while providing adequate recovery of cardiorespiratory function, 2-min passive rest periods can be prescribed.

## 1 | INTRODUCTION

Repeated sprint training (RST) is an effective training method that can improve a range of physical qualities, including speed, aerobic fitness and intermittent running performance (Taylor et al., 2015; Thurlow, Huynh, et al., 2023). Sessions are typically 10–20 min in duration and involve maximal effort, short duration sprints ( $\leq 10$  s) and interspersed with brief recovery times ( $\leq 60$  s; Girard et al., 2011; Thurlow, Weakley, et al., 2023). There are several situations where RST can be applied in an athlete's training programme, such as the specific preparation stage of pre-season where an increase in intensity is often implemented (Bompa et al., 2019). Alternatively, it could be used to maintain physical qualities during the playing season or as part of late-stage rehabilitation. Recent evidence has demonstrated that RST induces substantial acute physiological demands, including considerable increases in blood lactate and mean and peak heart rate (Thurlow, Weakley, et al., 2023). However, these responses can be moderated by the manipulation of programming variables (Thurlow, Weakley, et al., 2023). For example, peak heart rate, blood lactate and sprint performance are maintained during RST when four repetitions are completed per set compared to six, but a 10-m-long repetition distance (40 vs. 30 m) can amplify these demands and increase fatigue (Thurlow, Weakley, et al., 2023). Thus, to ensure that the appropriate training load is imposed upon athletes, practitioners need to carefully consider the manipulation of programming variables.

One programming variable that has a large influence on the acute physiological demands of RST is session volume (i.e. repetition

distance ( $m$ ) × number of repetitions ( $n$ )). The volume of RST prescribed within the scientific literature typically ranges from 200 to 800 m per session and this appears to strongly influence the acute demands of RST (Taylor et al., 2015; Thurlow, Weakley, et al., 2023). For example, larger session volumes ( $\geq 800$  m) cause a peak heart rate of  $\geq 90\%$  of the maximal heart rate ( $\text{HR}_{\text{max}}$ ) (Figueira et al., 2021; Paulauskas et al., 2020), which may help to maximise aerobic adaptations with high-intensity training (Buchheit et al., 2013a). Additionally, Dupont et al. (2005) showed that players could reach maximal oxygen consumption ( $\text{VO}_{2\text{max}}$ ) when a session volume of 600 m was implemented. Despite its acknowledged importance within the scientific literature (Thurlow, Weakley, et al., 2023), evidence of the effects of different session volumes on the acute physiological demands of RST is lacking. Studies have manipulated repetition distance (Alemdaroğlu et al., 2018; Dellal et al., 2015) or the number of repetitions (Gharbi et al., 2014) but never compared both while standardising all other programming variables. This information could provide coaches with strategies to amplify the training stimulus, which would be expected to enhance subsequent physiological adaptation.

Athletes require regular exposure to sprinting within the training environment to effectively prepare them for high-speed demands of competition (Gabbett, 2016; Malone et al., 2017; Oakley et al., 2018). In team sports, such as soccer and Australian Rules Football, players can achieve mean sprint ( $>23 \text{ km}\cdot\text{h}^{-1}$ ) distances of 337 and 571 m per game, respectively (Coutts et al., 2010; Di Salvo et al., 2007). RST can provide controlled doses of near-to-maximal speed running (Edouard et al., 2019; Malone et al., 2017; Mendiguchia et al., 2020),

but coaches need to consider the optimal volume of maximal velocity exposure so that excessive or insufficient volumes of sprint training do not hinder performance (Gabbett, 2016; Malone et al., 2017). There can be a considerable neuromuscular demand during RST (Thurlow, Weakley, et al., 2023) and this may be exacerbated by the prescription of larger session volumes (Buchheit et al., 2013b). Previous studies have shown that greater RST volumes reduce countermovement jump (CMJ) performance and acute knee flexor strength (Baumert et al., 2021; Clifford et al., 2016; Timmins et al., 2014). Furthermore, these reductions may persist for up to 48 h post-exercise (Baumert et al., 2021; Woolley et al., 2014). Given the possible effects of volume on fatigue and recovery time course, it is important to understand the effects of this programming variable as well as the relationship between the two individual factors that constitute session volume (i.e. repetition distance and the number of repetitions). Therefore, the aims of our investigation were to examine the effects of manipulating session volume on acute physiological, perceptual and performance demands during RST and the recovery time course of neuromuscular performance and determine whether repetition distance or the number of repetitions has a greater effect on the acute demands and the recovery time course.

## 2 | MATERIALS AND METHODS

### 2.1 | Experimental approach to the problem

A randomised, crossover and counterbalanced design (Latin square) was used to compare the effects of four different RST protocols. Heart rate,  $\text{VO}_2$ , differential ratings of perceived exertion (dRPE), percentage sprint decrement ( $S_{\text{dec}}$ ), acceleration load and volume of sprinting >90% of maximal sprint speed (MSS) were recorded during each session. Lower-limb stiffness, CMJ performance and isometric hamstring strength were measured immediately pre- and post-session, 24 h and 48 h, whereas session ratings of perceived exertion (sRPE) were also recorded post-session. The study was conducted over 4 weeks for each participant and involved one RST session per week performed on Monday and two follow-up testing sessions 24 and 48 h afterwards. In total, the athletes attended 13 sessions (i.e. familiarisation and 12 testing sessions). The RST protocols were prescribed with different combinations of the number of repetitions and sprint distance (i.e., 5 or 10 repetitions and 20 or 40 m distance), whereas all other programming variables were fixed across all sessions (Table 1). Together, the training protocols

represent the typical range of session volumes (200–800 m) used in research and practice (Thurlow et al., 2023a, 2023b). Furthermore, it is common for coaches to progress session volume from 200 to 800 m across the course of training program.

### 2.2 | Subjects

Fourteen trained athletes, training at least three times per week with the purpose of competing at a local level or higher, were recruited from a university to take part in our study. The physical characteristics of the athletes are presented in Table 2. Before initiating the study, athletes were informed of the procedures, risks and benefits and signed an institutionally approved informed consent form. All athletes were injury-free for at least 3 months before the study and no injuries or dropouts occurred during the study. The study protocol adhered to the declaration of Helsinki and was approved by a university institutional review board (ethics number: 2021-244H).

### 2.3 | Procedures

All athletes attended a familiarisation session one week before the commencement of the study where they signed consent forms, practised all testing procedures and had their height measured (Seca Alpha stadiometer, model 213). Additionally, the athletes completed a graded exercise test on a motorised treadmill (T22.1, Vertex Fitness) with respiratory gas analysis (K5, COSMED, Rome, Italy) to determine their  $\text{VO}_{2\text{max}}$  ( $\text{mL}\cdot\text{kg}\cdot\text{min}^{-1}$ ) and  $\text{HR}_{\text{max}}$ . All testing took place at the same time of day ( $\pm 1$  h) to minimise any potential influence of diurnal or circadian variation. In the day preceding the familiarisation sessions, each RST session as well as between each session and the follow-ups, the athletes were instructed to refrain from strenuous exercise involving the leg muscles (e.g., running, resistance training, sports activity) and from consuming alcohol. The athletes were also instructed to abstain from the consumption of food and beverage other than water within 2 h of each session, and the consumption of caffeine 6 hours before each session. In addition to these restrictions, the athletes were also asked to maintain their usual nutritional habits during the intervention period. The sprints were performed on a grass sports oval, under similar environmental conditions (21°C–28°C and 54%–78% humidity).

The experimental procedures for each RST session and its follow-up recovery sessions can be seen in Figure 1. At the beginning

TABLE 1 Prescription of the repeated sprint training protocols.

Protocol	Sets $\times$ Reps	Sprint distance (m)	Inter-rep rest time (s)	Inter-set rest time (s)	Rest mode	Prescribed volume (m)
10 $\times$ 40	2 $\times$ 10	40	30	180	Passive	800
10 $\times$ 20	2 $\times$ 10	20	30	180	Passive	400
5 $\times$ 40	2 $\times$ 5	40	30	180	Passive	400
5 $\times$ 20	2 $\times$ 5	20	30	180	Passive	200

TABLE 2 Physical characteristics of the athletes.

	Age (years)	Height (cm)	Weight (kg)	VO <sub>2max</sub> (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )
Males (n = 10)	24 ± 4	182 ± 9	83 ± 10	57 ± 6
Females (n = 4)	22 ± 1	169 ± 6	62 ± 3	45 ± 2

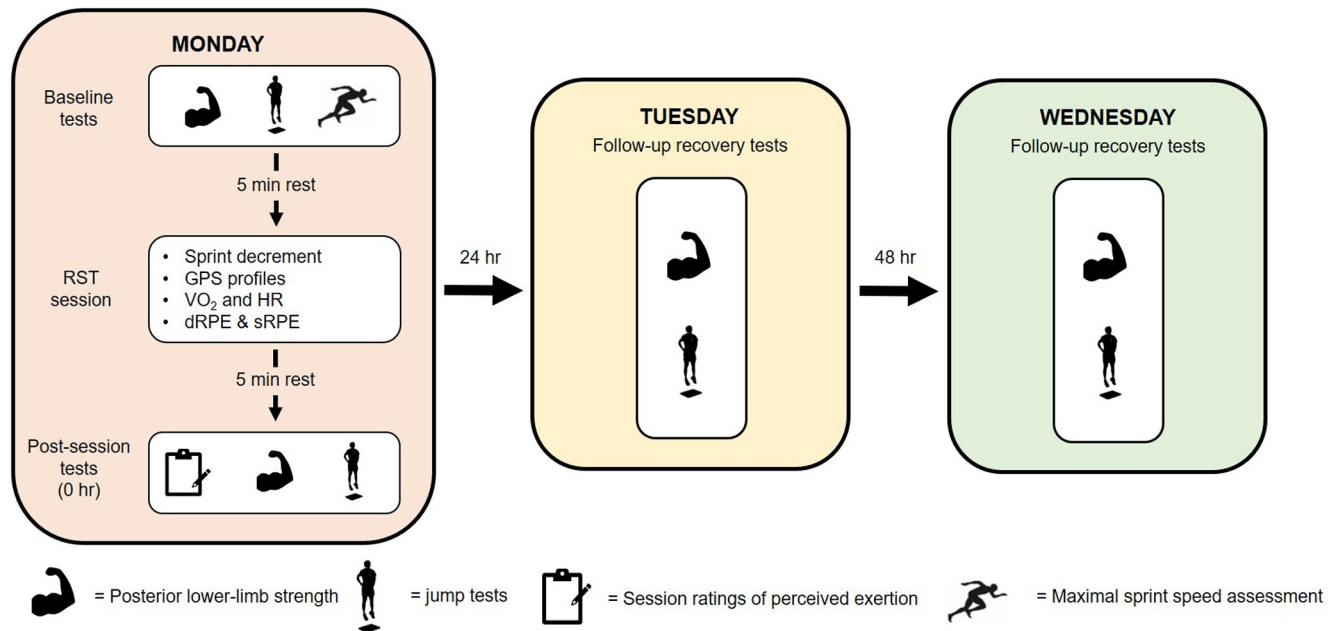


FIGURE 1 The experimental procedures for one repeated sprint training session and its follow-up sessions. This design is repeated for each of the four repeated-sprint training protocols, which are separated by 1 week. dRPE, differential ratings of perceived exertion; GPS, global positioning system; HR, heart rate; RST, repeated-sprint training and VO<sub>2</sub>, oxygen consumption.

of each RST session, the athletes performed the same standardised warm-up (warm-up A) consisting of a series of dynamic movements performed over a distance of 10 m (e.g. walking lunges, heel sweeps and A-skips). Baseline testing was then performed in the following order: (1) a unilateral isometric strength test of the hamstring muscles, (2) a CMJ test and (3) a double-leg hopping test. Following the baseline tests, the athletes performed an additional warm-up (warm-up B), which involved 4 × 40-m strides at an estimated 50%, 70%, 80% and 90% of maximal speed. Between each effort, the athletes slowly walked back to the starting point. Following the final stride, the athletes performed 1 × 40 m maximal sprint to determine their peak velocity for that day, which was identified via a 10-Hz global position system (GPS; Apex, STATSports) that was fitted within a vest on the athlete's upper thoracic region (Crang et al., 2021, 2022). The athletes were then provided a 5-min rest before beginning the RST session and during this rest period, they were fitted with the same automated, wearable, gas analysis system as used during the graded exercise test. Heart rate, VO<sub>2</sub>, repetition times and GPS data were recorded throughout the RST session. Differential ratings of perceived exertion were recorded at the end of set one and set two, whereas session ratings of perceived exertion (sRPE) were recorded 5 min following the end of the RST session, with both having been used extensively throughout the literature to quantify the perception of effort that athletes experience during exercise (Dudley

et al., 2023; Weakley et al., 2019, 2022a). Although we acknowledge that the collection of sRPE has typically taken 30 min post-session (McLaren et al., 2016, 2017), as follow-up tests were conducted 5 min post-session, sRPE was taken immediately before these. The post-session testing was conducted in the same order as baseline testing. For the 24 and 48 h follow-up sessions, the athlete's perceived muscle soreness was recorded at the beginning of the session. The same standardised dynamic warm-up was performed (warm-up A) before commencing testing. Athletes wore the same footwear and were fitted with the same GPS unit across each session (Crang et al., 2021).

### 2.3.1 | Repeated-sprint training

The RST protocols are shown in Table 1. A 3-min rest period was provided between sets, from the end of set one (i.e. the moment the athlete crossed the finish line after the final sprint) to the start of the first sprint in set two. During the inter-set recovery period, athletes decelerated and walked back to the starting point, where they sat on a chair until the beginning of set two. Athletes started each sprint in a standing start position with their foot 0.3 m behind the first timing gate (Weakley, McCosker, et al., 2022). A 10-s warning and a 3-s countdown was provided for each repetition. Athletes were instructed to give

maximal effort and sprint through the finish line. Loud verbal encouragement was given to all athletes during each repetition. During the recovery period between sprints, athletes decelerated and walked back to the starting point. Two sets of single-beam timing gates (TCi, Brower Timing Systems) were used that worked in both directions, which allowed the athletes to start each sprint at the end they finished the previous sprint. The timing gates were used to determine the sprint times of each repetition, whereas GPS was used to determine the acceleration load (i.e. dynamic stress load during acceleration: the sum of the magnitude of the tri-axial accelerometer data above 2G, raised to a body load factor and scaled to manageable values) and the volume of sprinting >90% of each individuals MSS during each session (Murray et al., 2018). The fastest peak velocity derived from the GPS achieved during baseline testing (1 × 40 m maximal sprint) for each athlete on each training day was used as the reference MSS. This approach allowed daily individual fluctuations in sprint performance to be accounted for. To calculate the decline in sprint speed across each set,  $S_{dec}$  was used (Fitzsimons et al., 1993). While  $S_{dec}$  has been shown to be less reliable than best and average times for detecting changes in performance (Impellizzeri et al., 2008), it is the most ecologically valid index to quantify fatigue during RST (Glaister et al., 2008). It was calculated as follows:

$$S_{dec} = (100 \times (\text{total sprint time} / \text{ideal sprint time})) - 100$$

where total sprint time represents the sum of sprint times from all sprints and ideal sprint time represents the number of sprints multiplied by the fastest sprint time. The average of both sets for  $S_{dec}$  was used for analysis.

### 2.3.2 | Hamstring strength

Maximal sprinting induces a high degree of stress and strain on the hamstring muscles (Schache et al., 2012; Thelen et al., 2005; Timmins et al., 2014), with previous evidence demonstrating that declines in hamstring strength may persist for several days following repeated-sprints (Baumert et al., 2021; Timmins et al., 2014). To monitor changes in hamstring strength, an isometric assessment was performed on a portable force plate (ForceDecks, VALD Performance). Isometric tests result in little or no structural muscle damage (Faulkner et al., 1993; Lieber et al., 1991; McCall et al., 2015; Nosaka et al., 2002); thus they are useful to assess muscle function between recovery timepoints. The test was performed on the athletes' dominant limb at knee angles of 90° and 30°. These angles were chosen because the biceps femoris has been shown to be maximally activated between 15° and 30° of knee flexion (from full knee extension), whereas the semimembranosus and semitendinosus were maximally activated between 90° and 105° of knee flexion (Onishi et al., 2002). The tests have previously demonstrated good–high levels of reliability (intraclass correlation coefficient = 0.86–0.95 and typical error as a coefficient of variation = 4.3%–6.3%; McCall et al., 2015). To complete this test, athletes laid on their back on a mat, with the non-working leg resting flat on the floor and the heel of the working leg

positioned on the force plate, which was placed on a firm box. The knee angle of the athletes' working leg was set using a goniometer (EZ Read Jamar, Patterson Medical). The athlete was instructed to push the heel of their working leg into the force platform as hard as possible as though they were trying to perform a hamstring curl, without lifting their hips, hands or head off the mat. The contraction was performed for 3 s and repeated three times at each angle with 30 s rest between trials. The highest peak force (N) from the three trials was recorded for analysis. Investigators ensured strict adherence to the technique by pressing the athletes' hips to the floor during each repetition and giving loud verbal encouragement throughout to ensure maximal effort.

### 2.3.3 | Jump testing

The CMJ test is a suitable athlete monitoring method for the detection of neuromuscular fatigue (Gathercole et al., 2015). It has been recommended that a battery of CMJ variables be used rather than jump height alone (Gathercole et al., 2015). Therefore, metrics were chosen which have acceptable intra-day and inter-day reliability (<10% coefficient of variation) are sensitive to changes in neuromuscular function and provide a more detailed analysis that reflects changes in CMJ output and strategy (Cormack et al., 2008; Gathercole et al., 2015; Weakley, Black, et al., 2022). Jump testing was performed on the same portable force plates as the hamstring strength assessment. For the CMJ, athletes began in a standing position and were instructed to jump as high as possible while keeping their hands on their hips. The depth of the countermovement was self-selected by the athlete (Cormack et al., 2008). Three maximal trials were performed with a 30-s rest between each effort. Jump height was analysed using the impulse–momentum method as it gives the most accurate result (Linthorne, 2001) (Linthorne, 2001), with jump initiation detected as a change of 20 N from the start of the movement. The trial with the greatest jump height was used for analysis.

The double-leg hopping test has been previously used with athletic populations to provide a measure of leg stiffness and consisted of sub-maximal rebounding at 2.5 Hz (150 bpm) (Dalleau et al., 2004; Leduc et al., 2020; Oliver et al., 2015). This frequency possesses the highest reliability and allows participants to maintain a consistent hopping pace while acting in a true spring-mass manner (Lloyd et al., 2009). Athletes completed one trial of 20 consecutive hops with hopping frequency controlled by a digital metronome (Tempo-Perfect, version 4.07, HCH Software). The first and last five hops were discarded, with an average of the hops 6–15 used for analysis. Leg stiffness was calculated through Dalleau's equation (50):

$$\text{Leg stiffness} = \frac{M \times \pi (Ft + Ct)}{Ct^2 \left( \left( Ft + \frac{Ct}{\pi} \right) - \left( \frac{Ct}{4} \right) \right)}$$

where M is the mass (kg), Ft is the flight time (s) and Ct is the contact time (s).

### 2.3.4 | Perceptual measures

Differential ratings of perceived exertion can enhance the accuracy of the internal load measurement by better discriminating between central (e.g. uptake and transport of oxygen and central nervous system) and peripheral exertions (e.g. neuromuscular, musculoskeletal and metabolite characteristics; McLaren et al., 2016). Immediately following the completion of each RST set, athletes provided dRPE for breathlessness (RPE-B) and leg exertion (RPE-L) by considering verbal anchors on a Borg CR100 Scale<sup>®</sup> (Borg, 2010). Athletes were instructed that their ratings should reflect the perceptions of effort experienced for the preceding set only (McLaren et al., 2020) and they were informed about the definition of perceived exertion and its scaling, including the importance of separating rating of perceived exertion from other exercise-related sensations such as pain, discomfort and fatigue (McLaren et al., 2020). Instructions were also given to athletes on how to appraise dRPE, such that RPE-B depends mainly on the breathing rate and/or heart effort and RPE-L depends mainly on the strain and exertion in the leg muscles (McLaren et al., 2020). The average of both sets for dRPE was used for analysis. Five minutes after the RST session, athletes also provided a global sRPE by considering verbal anchors on a modified version (Foster et al., 2001) of the Borg CR100 Scale<sup>®</sup> (Borg, 2010), which was multiplied with the session duration to determine sRPE-training load (sRPE-TL; Foster et al., 2001).

### 2.3.5 | Oxygen consumption and heart rate

During the familiarisation session, athletes completed a graded exercise test on a motorised treadmill (T22.1, Vertex Fitness) with respiratory gas exchange data collected via a portable metabolic system and heart rate measured using a chest strap monitor (HRM-Dual, Garmin Australasia Pty Ltd), which was integrated with the metabolic system. To become familiarised with the portable metabolic system and Hans Rudolph face mask, participants wore these apparatuses during the warm-up, which consisted of 3–5 min of running at a self-selected pace and any other preparatory exercise of their choosing. Depending on the athlete's fitness level, the test then began at a speed between 6 and 10 km·h<sup>-1</sup>. Each stage lasted for 2 min and increased by 2 km·h<sup>-1</sup> for the first three stages, after which the speed was maintained while the gradient increased by 2%, every 2 min until the participant reached volitional exhaustion, which was achieved within 10–14 min for all participants (Beltz et al., 2016). Analysis of the graded exercise test was performed by removing erroneous fluctuations in raw data and then averaging VO<sub>2</sub> into 15 s time bins, with the highest value used to determine the athlete's VO<sub>2max</sub>.

For the RST sessions, the heart rate and respiratory gas exchange were continuously recorded from the start of the first

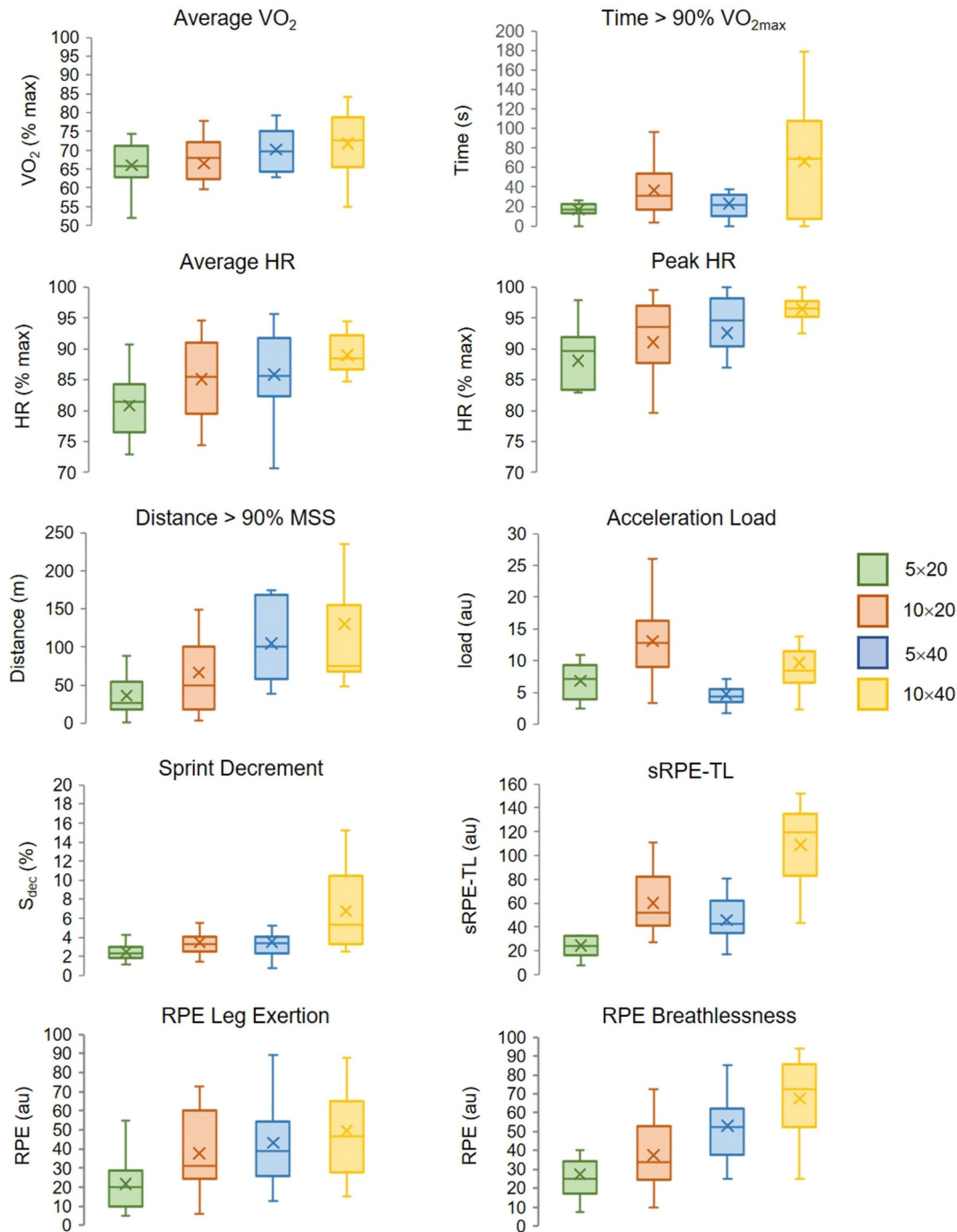
repetition to 30 s following the final repetition, using the same equipment as the graded exercise test. Erroneous fluctuations in raw data were removed if they were considered to be higher or lower than physiologically possible. Heart rate and VO<sub>2</sub> data were averaged for each repetition, set and the overall RST session (excluding the inter-rest recovery period). Peak heart rate was identified from the highest value during each set and the overall RST session. Heart rate and VO<sub>2</sub> data from the inter-set rest period were also analysed, which included the value at the end of set one (from the moment the athlete passed the timing gate after the last sprint), and the decline after 1, 2 and 3 min. For the analysis of VO<sub>2</sub> during the inter-set rest period, a 15-s average was used, so that the VO<sub>2</sub> decline at 1, 2 and 3 min were recorded from 45 to 60 s, 105 to 120 s and 165 to 180 s, respectively.

### 2.4 | Statistical analyses

The mean ± standard deviation (SD) was calculated for all outcomes. The Shapiro-Wilk test confirmed all variables were normally distributed. A univariate analysis of variance (ANOVA) was used to compare between protocol differences in physiological, perceptual and sprint performance outcomes and within protocol differences (pre–post, pre-24 h and pre-48 h) in recovery outcomes. To aid with data interpretation, all effects were expressed as an effect size (ES) by dividing the estimate and its confidence limit (CL) by the pooled between-subject SD of each protocol (subsequently adjusted for small sample bias; Hedges G) and day-to-day variability (Bernards et al., 2017). Values of 0.2, 0.6, 1.2 and 2.0 represent thresholds for small, moderate, large and very large differences for the standardised difference in means (Hopkins, 2002). A difference was declared when the upper and lower confidence interval fell entirely or predominantly outside the non-substantial region (i.e. outside –0.2 to 0.2). When this was visually apparent, a minimum effects test (MET) was used to provide a probabilistic description of the CL's disposition relative to the threshold for a non-substantial effect. Given that this study was not powered for definitive conclusions, we elected to present probability values for the one-sided tests ( $p_{MET}$ ) as continuous estimates only, rather than declaring a fixed alpha level representing 'practical significance'. Data analysis was conducted using the SPSS 29 program for Windows (SPSS, Inc.).

## 3 | RESULTS

Descriptive data on the acute physiological, perceptual and performance demands of each RST protocol are presented in Figure 2 and Supplementary Digital Contents 1 and 2. Additionally, Figure 3 displays the change in heart rate and VO<sub>2</sub> across the inter-set recovery period for each RST protocol.



**FIGURE 2** The acute demands of each RST protocol. Green = 5 × 20, orange = 10 × 20, blue = 5 × 40, yellow = 10 × 40 and × = mean. au, arbitrary units; HR, heart rate; RPE, rating of perceived exertion;  $S_{dec}$ , percentage sprint decrement; sRPE-TL, session RPE-training load;  $VO_2$ , oxygen consumption and  $VO_{2max}$ , maximal oxygen consumption.

### 3.1 | Training load

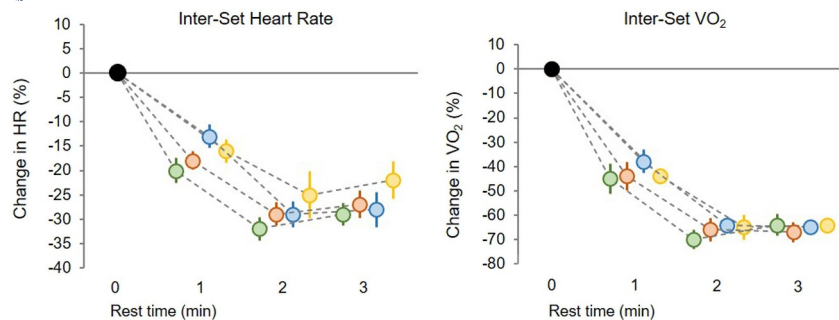
#### 3.1.1 | Physiological and perceptual measures (internal training load)

Session average heart rate was higher for 10 × 40 and 5 × 40 when compared to 5 × 20 ( $p_{MET} = 0.002$  and  $0.059$ , respectively), and these differences were *large* and *moderate* (ES:  $1.38 \pm 0.65$  and  $0.80 \pm 0.64$ ,

respectively). Additionally, the session peak heart rate was higher for 10 × 40 when compared to 5 × 20, and this difference was *moderate* (ES:  $1.10 \pm 0.83$  and  $p_{MET} = 0.011$ ). Time >90%  $VO_{2max}$  was greater for 10 × 40 when compared to 5 × 40 ( $p_{MET} = 0.002$ ) and 5 × 20 ( $p_{MET} < 0.001$ ), and these differences were *large* (ES:  $1.29 \pm 0.62$  and  $1.47 \pm 0.63$ , respectively).

Differential RPE-L was greater for 10 × 40 ( $p_{MET} = 0.001$ ), 5 × 40 ( $p_{MET} = 0.013$ ) and 10 × 20 ( $p_{MET} = 0.063$ ) when compared to





**FIGURE 3** Changes (mean  $\pm$  90% confidence limit) in the heart rate and oxygen consumption across the inter-set recovery period between set one and set two for each repeated-sprint training protocol. green =  $5 \times 20$ , orange =  $10 \times 20$ , blue =  $5 \times 40$  and yellow =  $10 \times 40$ . The inter-set recovery period is the time between the end of the last sprint repetition in set one (0 min) and the start of the first sprint repetition in set two (3 min).

$5 \times 20$ , and these differences were *large*, *moderate* and *moderate* (ES:  $1.37 \pm 0.63$ ,  $1.06 \pm 0.63$  and  $0.78 \pm 0.63$ , respectively). RPE-B was greater for  $10 \times 40$  when compared to  $5 \times 40$  ( $p_{MET} = 0.064$ ),  $10 \times 20$  ( $p_{MET} < 0.001$ ) and  $5 \times 20$  ( $p_{MET} < 0.001$ ), and these differences were *moderate*, *large* and *very large* (ES:  $0.79 \pm 0.64$ ,  $1.64 \pm 0.64$  and  $2.19 \pm 0.64$ ). Furthermore, RPE-B was greater for  $5 \times 40$  when compared to  $10 \times 20$  ( $p_{MET} = 0.046$ ) and  $5 \times 20$  ( $p_{MET} = 0.001$ ), and these differences were *moderate* and *large* (ES:  $0.85 \pm 0.64$  and  $1.41 \pm 0.64$ , respectively).

Session RPE-TL was greater for  $10 \times 40$  when compared to  $5 \times 40$  ( $p_{MET} < 0.001$ ),  $10 \times 20$  ( $p_{MET} < 0.001$ ) and  $5 \times 20$  ( $p_{MET} < 0.001$ ), and these differences were *very large* (ES:  $2.59 \pm 0.63$ ,  $2.00 \pm 0.63$  and ES:  $3.47 \pm 0.63$ , respectively). Session RPE-TL was also greater for  $5 \times 40$  ( $p_{MET} = 0.039$ ) and  $10 \times 20$  ( $p_{MET} < 0.001$ ) when compared to  $5 \times 20$ , and these differences were *moderate* and *large* (ES:  $0.88 \pm 0.63$  and  $1.47 \pm 0.63$ , respectively). All other comparisons of the internal training load were not definitive and can be found in Supplementary Digital Content 3 and 4.

### 3.1.2 | Performance measures (external training load)

Sprint decrement was greater for  $10 \times 40$  when compared to  $5 \times 40$  ( $p_{MET} = 0.002$ ),  $10 \times 20$  ( $p_{MET} = 0.001$ ) and  $5 \times 20$  ( $p_{MET} < 0.001$ ), and these differences were *large* (ES:  $1.37 \pm 0.64$ ,  $1.39 \pm 0.64$  and  $1.79 \pm 0.64$ , respectively). Session distance  $>90\%$  MSS was greater for  $10 \times 40$  when compared to  $10 \times 20$  ( $p_{MET} = 0.029$ ) and  $5 \times 20$  ( $p_{MET} = 0.001$ ), and these differences were *moderate* and *large* (ES:  $0.94 \pm 0.64$  and  $1.38 \pm 0.63$ , respectively). Additionally, session distance  $>90\%$  MSS was greater for  $5 \times 40$  when compared to  $5 \times 20$  ( $p_{MET} = 0.018$ ), and this difference was *moderate* (ES:  $1.05 \pm 0.66$ ). Session acceleration load was greater for  $10 \times 40$  when compared to  $5 \times 40$  ( $p_{MET} = 0.013$ ), and this difference was *moderate* (ES:  $1.07 \pm 0.64$ ). Furthermore, the session acceleration load was greater for  $10 \times 20$  when compared to  $5 \times 40$  ( $p_{MET} < 0.001$ ), and this difference was *large* (ES:  $1.83 \pm 0.63$ ). All other comparisons of

the external training load were not definitive and can be found in Supplementary Digital Content 5.

## 3.2 | Recovery measures

The effects of RST on the recovery time course of neuromuscular performance are presented in Figure 4 and Supplementary Digital Content 6. Changes in neuromuscular performance across all time-points and all protocols were unclear.

## 4 | DISCUSSION

Our study aimed to examine the effects of manipulating session volume on acute physiological, perceptual and performance demands during RST and the recovery time course of neuromuscular performance and determine whether repetition distance or the number of repetitions has a greater effect on the acute demands and the recovery timecourse. The  $10 \times 40$  protocol induced the greatest physiological and perceptual demands, which was demonstrated by a session average heart rate and  $VO_2$  of  $89 \pm 3\%$  and  $72 \pm 8\%$  of max, respectively, whereas dRPE were rated hard to very hard on average. Additionally, the  $10 \times 40$  protocol also had the greatest  $S_{dec}$  and incurred a sRPE-TL that was higher than all other protocols by a *very large* magnitude. Conversely, the acute demands of the  $5 \times 20$  protocol were considerably less than all other protocols. When session volume was matched at 400 m, the internal training load was similar, but the acceleration load was greater for the  $10 \times 20$  protocol, whereas sprint volume ( $>90\%$  MSS) was higher for the  $5 \times 40$  protocol. Across all protocols, there was substantial inter-individual variation in neuromuscular function, and subsequently, the return to baseline of neuromuscular performance was unclear. The findings from our investigation demonstrate that larger session volumes increase the acute demands of RST and by manipulating volume, sprint distance and the number of repetitions, practitioners can alter the internal and external training load.

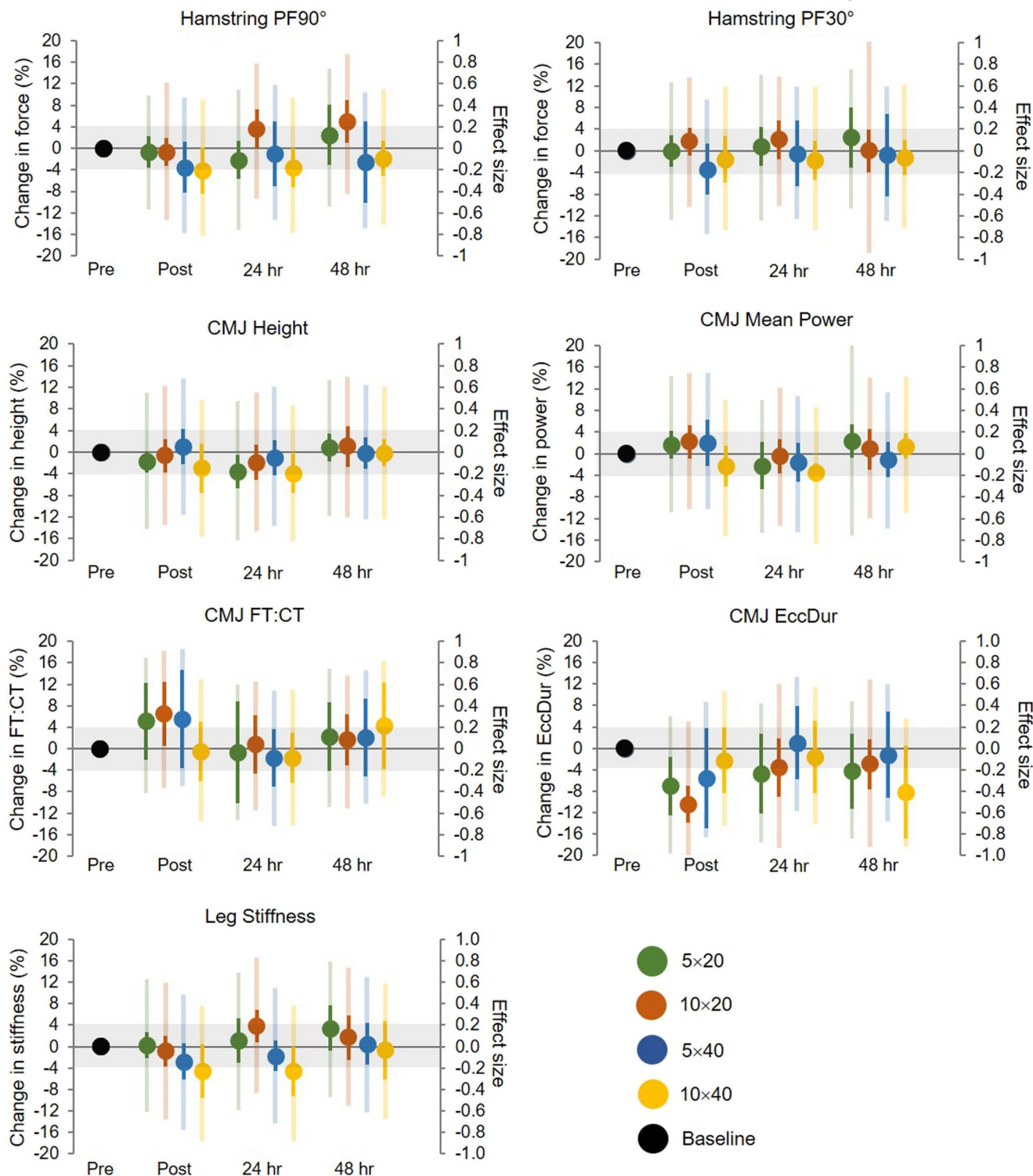


FIGURE 4 The recovery time course of neuromuscular performance within each repeated sprint training protocol. Green = 5 × 20, orange = 10 × 20, blue = 5 × 40 and yellow = 10 × 40. Dark error bar represents the 90% confidence limit for the percent change in performance; shaded colour represents the 90% confidence limit for the standardised difference and grey shaded zone represents a trivial effect. CMJ, countermovement jump; EccDur, eccentric duration; FT:CT, flight-time to contraction-time ratio; PF90°, peak force at 90° of knee flexion and PF30°, peak force at 30° of knee flexion.

This is the first investigation to directly examine time above 90% of  $VO_{2max}$  during RST, which has been suggested to be an important stimulus to elicit maximal cardiovascular and peripheral adaptations

during high-intensity interval training (Billat, 2001; Laursen et al., 2002; Midgley et al., 2006). We found that  $66 \pm 56$  s was spent above 90% of  $VO_{2max}$  during the 10 × 40 protocol, which was greater

than the other protocols by a *large* magnitude. In agreement with evidence by Gaitanos et al. (1993), performing more repetitions in succession increases aerobic metabolism. This occurs due to extended session durations and increased within session fatigue as demonstrated by a greater  $S_{dec}$  for the  $10 \times 40$  protocol. However, in comparison to other high-intensity conditioning methods, such as short- and long-intervals, which may elicit  $>10$  min above 90% of  $VO_{2max}$  (Buchheit et al., 2013b), time above 90% of  $VO_{2max}$  was low for all four RST protocols. Therefore, the strategy of implementing high repetition protocols to increase time above 90% of  $VO_{2max}$  during RST is likely futile because increases will be relatively minimal. Furthermore, compared to sets prescribed with five repetitions, performing 10 repetitions did not substantially increase the average  $VO_2$  demands when sprint distance was matched (e.g.  $10 \times 40$  vs.  $5 \times 40$ ). Rather than prescribing high repetition protocols, practitioners are encouraged to increase sprint distance or manipulate other RST variables, such as rest time (Thurlow, Weakley, et al., 2023), to enhance the aerobic stimulus. Future research should investigate the acute and chronic effects of manipulating sets and repetitions within volume-matched protocols (i.e. two sets of 10 repetitions vs. four sets of five repetitions) as this could also be an effective strategy to augment physiological responses.

The moderating effects of programming variables on RST have previously suggested that sprint distance has a substantial influence on physiological demands (Thurlow, Weakley, et al., 2023). Our present investigation lends further support to this premise, showing that 40 m sprints caused greater  $VO_2$  and heart rate compared to 20 m sprints, although this was only definitive for an average heart rate. Additionally, a greater volume of sprinting above 90% of MSS was achieved with 40 m sprints. The  $10 \times 40$  and  $5 \times 40$  protocols elicited over 100 m of maximal sprinting per session compared to  $67 \pm 64$  m and  $36 \pm 27$  m for the  $10 \times 20$  and  $5 \times 20$  protocols, respectively. Sprint training above 90% of MSS has been proposed as a key component of hamstring injury risk management (Edouard et al., 2023), and our findings suggest that the prescription of RST with a repetition distance of 40 m can provide a concurrent sprint and physiological stimulus that is substantial. Alternatively, the acceleration load was increased during the 20-m sprint protocols, which would be attributed to the athlete's accelerating faster with greater horizontal propulsive force over the short distance and more gradually over the 40-m distance. Considering the importance of acceleration ability in intermittent sports (Johnston et al., 2014, 2018; Little et al., 2005), RST protocols that emphasise acceleration may be a worthwhile component of a training program. Differential RPE were also lower in the 20-m RST protocols compared to the 40-m protocols by *moderate to large* magnitudes. Therefore, shorter sprint protocols may reduce the perceptual demand on athletes during RST and target the development of acceleration performance.

The  $10 \times 40$  protocol tended to cause greater decrements in neuromuscular performance following the RST sessions, particularly for leg stiffness, CMJ height and CMJ mean power (Figure 3). However, given the width of the effect size confidence limits, these and all

other recovery outcomes were unclear. The certainty in these results was affected by considerable inter-individual variation, with athletes demonstrating a decrement, no change or potentiation of neuromuscular performance following RST. Furthermore, the training volumes may have been insufficient to induce consistent change in neuromuscular performance across the athletes, but these were considered to be the lower (200 m) and upper (800 m) limits of volume that are prescribed within applied training environments (Thurlow, Weakley, et al., 2023). While practitioners are encouraged to consider the individual fatigue responses to RST, future research may benefit from using more sensitive measures to detect neuromuscular fatigue and a larger sample size to form more definitive conclusions.

There are several practical applications from our findings that coaches can use to improve the prescription of RST. Session volumes of 200 m, prescribed as two sets of  $5 \times 20$  m sprints, could be applied at the beginning of a RST program to introduce athletes to maximal acceleration, while limiting training load, before progressing to larger volumes such as 400 m. If 400 m of volume is implemented, prescribing this session as two sets of  $5 \times 40$  m sprints will provide athletes with exposure to maximal sprinting ( $\sim 100$  m  $> 90\%$  of MSS), whereas the prescription of two sets of  $10 \times 20$  m sprints will emphasise the acceleration load. To maximise the acute physiological and neuromuscular demands of RST, which may result in a greater stimulus for adaptation, larger session volumes (i.e. 800 m) are recommended and these are best achieved by implementing longer sprint distances (i.e. 40 m). Lastly, we administered 3 min inter-set rest periods and found that there were no differences in the heart rate and  $VO_2$  recovery between the 2nd and 3rd minute mark (Figure 3). Therefore, during congested training sessions, to reduce session duration while providing adequate recovery of cardiorespiratory function, 2 min passive rest periods can be prescribed.

Our study provides evidence of the acute effects of RST volume, but it has some limitations. First, given the altered sprint distances across our protocols, we acknowledge that the work-to-rest ratios were subsequently different, and this would influence the recovery between sprints and subsequent physiological demands. However, the application of work-to-rest ratios in a sporting environment is logistically difficult because the time taken to perform each sprint varies between repetitions and athletes. Accordingly, standardised rest times were selected because these are more common within the scientific literature (Thurlow, Weakley, et al., 2023) and practical within real-world training environments. Second, we used measures of neuromuscular recovery that are frequently implemented within sports settings, but recognise that there is no single ideal model to study fatigue (Cairns et al., 2005), and other disruptions to homeostasis may have occurred. Additionally, we did not assess changes in eccentric hamstring strength or muscle activity. Considering the eccentric demands of sprint activity on the hamstring muscles (Mendiguchia et al., 2020), this may provide different results to our isometric hamstring strength assessment, which reduced the potential influence of testing fatigue on our recovery outcomes and is highly practical within sporting environments (McCall et al., 2015;

O'Keefe, 2020). Lastly, because of the small sample size, this study provides an exploratory analysis rather than definitive findings.

## 5 | CONCLUSION

The findings from our study demonstrate that larger session volumes increase the acute demands of RST. A session volume of 800 m induces the greatest aerobic stimulus but also causes substantially greater within-session fatigue (i.e.  $S_{dec}$ ), sRPE-TL and dRPE. When session volume is matched at 400 m, the physiological and perceptual demands are similar but the external training loads (i.e. acceleration load and volume > 90% MSS) are dependent on the sprint distance. A session volume of 200 m elicits a low physiological stimulus but could be useful to introduce or maintain exposure to maximal sprinting. Practitioners can use our findings to alter the acute training stimulus based on the aims of the training program.

## ACKNOWLEDGEMENTS

All authors contributed to the writing of this manuscript. No funding was received by any of the authors for the writing of this manuscript.

## CONFLICT OF INTEREST STATEMENT

All authors declare that they have no conflicts of interest.

## ORCID

Fraser Thurlow  <https://orcid.org/0000-0002-0234-9615>

Shaun J. McLaren  <https://orcid.org/0000-0003-0480-3209>

Andrew Townshend  <https://orcid.org/0000-0002-6714-8304>

Matthew Morrison  <https://orcid.org/0000-0002-3535-6707>

Jonathon Weakley  <https://orcid.org/0000-0001-7892-4885>

## REFERENCES

- Alemдарođlu, U., Y. Köklü, F. Bektaş, G. Çelik, F. Ünver, and R. Duffield. 2018. "Comparison of Repeated Sprint Tests in Young Soccer Players: Straight versus Shuttle." *Kinesiology Slovenica* 24(2): 5–16.
- Baumert, Philipp, S. Temple, J. M. Stanley, M. Cocks, J. A. Strauss, S. O. Shepherd, B. Drust, M. J. Lake, C. E. Stewart, and R. M. Erskine. 2021. "Neuromuscular Fatigue and Recovery after Strenuous Exercise Depends on Skeletal Muscle Size and Stem Cell Characteristics." *Scientific Reports* 11(1): 1–14. <https://doi.org/10.1038/s41598-021-87195-x>.
- Beltz, Nicholas M., Ann L. Gibson, Jeffrey M. Janot, Len Kravitz, Christine M. Mermier, and Lance C. Dalleck. 2016. "Graded Exercise Testing Protocols for the Determination of VO<sub>2</sub>max: Historical Perspectives, Progress, and Future Considerations." *The Journal of Sports Medicine* 2016: 1–12. <https://doi.org/10.1155/2016/3968393>.
- Bernards, Jake, Kimitake Sato, G. Haff, and Caleb Bazzyler. 2017. "Current Research and Statistical Practices in Sport Science and a Need for Change." *Sports* 5(4): 87. <https://doi.org/10.3390/sports5040087>.
- Billat, L. V. 2001. "Interval Training for Performance: a Scientific and Empirical Practice: Special Recommendations for Middle-And Long-Distance Running. Part I: Aerobic Interval Training." *Sports Medicine* 31(1): 13–31. <https://doi.org/10.2165/00007256-200131010-00002>.
- Bompa, T. O., and C. Buzzichelli. 2019. *Periodization: Theory and Methodology of Training*. Human Kinetics.
- Borg, G. 2010. *The Borg CR Scales Folder. Methods for Measuring Intensity of Experience*. Hasselby, Sweden: Stockholm University.
- Buchheit, Martin, and Paul B. Laursen. 2013a. "High-intensity Interval Training, Solutions to the Programming Puzzle." *Sports Medicine* 43(5): 313–38. <https://doi.org/10.1007/s40279-013-0066-5>.
- Buchheit, Martin, and Paul B. Laursen. 2013b. "High-intensity Interval Training, Solutions to the Programming Puzzle. Part 2: Anaerobic Energy, Neuromuscular Load and Practical Applications." *Sports Medicine* 43(10): 927–54. <https://doi.org/10.1007/s40279-013-0066-5>.
- Cairns, S. P., A. J. Knicker, M. W. Thompson, and G. Sjøgaard. 2005. "Evaluation of Models Used to Study Neuromuscular Fatigue." *Exercise and Sport Sciences Reviews* 33(1): 9–16.
- Clifford, Tom, Bram Berntzen, Gareth Davison, Daniel West, Glyn Howatson, and Emma Stevenson. 2016. "Effects of Beetroot Juice on Recovery of Muscle Function and Performance between Bouts of Repeated Sprint Exercise." *Nutrients* 8(8): 506. <https://doi.org/10.3390/nu8080506>.
- Cormack, Stuart J., Robert U. Newton, Michael R. McGuigan, and Tim L. A. Doyle. 2008. "Reliability of Measures Obtained during Single and Repeated Countermovement Jumps." *International Journal of Sports Physiology and Performance* 3(2): 131–44. <https://doi.org/10.1123/ijspp.3.2.131>.
- Coutts, Aaron J., John Quinn, Joel Hocking, Carlo Castagna, and Ermanno Rampinini. 2010. "Match Running Performance in Elite Australian Rules Football." *Journal of Science and Medicine in Sport* 13(5): 543–8. <https://doi.org/10.1016/j.jsams.2009.09.004>.
- Crang, Zachary L., Grant Duthie, Michael H. Cole, Jonathon Weakley, Adam Hewitt, and Rich D. Johnston. 2021. "The Validity and Reliability of Wearable Microtechnology for Intermittent Team Sports: A Systematic Review." *Sports Medicine* 51(3): 549–65. <https://doi.org/10.1007/s40279-020-01399-1>.
- Crang, Zachary L., Grant Duthie, Michael H. Cole, Jonathon Weakley, Adam Hewitt, and Rich D. Johnston. 2022. "The Inter-device Reliability of Global Navigation Satellite Systems during Team Sport Movement across Multiple Days." *Journal of Science and Medicine in Sport* 25(4): 340–4. <https://doi.org/10.1016/j.jsams.2021.11.044>.
- Dalleau, G., A. Belli, F. Viale, J.-R. Lacour, and M. Bourdin. 2004. "A Simple Method for Field Measurements of Leg Stiffness in Hopping." *International Journal of Sports Medicine* 25(03): 170–6.
- Dellal, Alexandre, David Casamichana, Julien Castellano, Monoem Haddad, Wassim Moalla, and Karim Chamari. 2015. "Cardiac Parasympathetic Reactivation in Elite Soccer Players during Different Types of Traditional High-Intensity Training Exercise Modes and Specific Tests: Interests and Limits." *Asian Journal of Sports Medicine* 6(4). <https://doi.org/10.5812/asjsm.25723>.
- Di Salvo, V., R. Baron, H. Tschan, F. Calderon Montero, N. Bachl, and F. Pigozzi. 2007. "Performance Characteristics According to Playing Position in Elite Soccer." *International Journal of Sports Medicine* 28(03): 222–7. <https://doi.org/10.1055/s-2006-924294>.
- Dudley, Charles, Rich Johnston, Ben Jones, Kevin Till, Harrison Westbrook, and Jonathon Weakley. 2023. "Methods of Monitoring Internal and External Loads and Their Relationships with Physical Qualities, Injury, or Illness in Adolescent Athletes: A Systematic Review and Best-Evidence Synthesis." *Sports Medicine* 53(8): 1–35. <https://doi.org/10.1007/s40279-023-01844-x>.
- Dupont, Grégory, Grégoire P. Millet, Comlavi Guinhouya, and Serge Berthoin. 2005. "Relationship between Oxygen Uptake Kinetics and Performance in Repeated Running Sprints." *European Journal of Applied Physiology* 95(1): 27–34. <https://doi.org/10.1007/s00421-005-1382-8>.
- Eduard, Pascal, Jurdan Mendiguchia, Kenny Guex, Johan Lahti, Caroline Prince, Pierre Samozino, and J.-Benoît Morin. 2023. "Sprinting: a Key Piece of the Hamstring Injury Risk Management Puzzle." *British*

- Journal of Sports Medicine* 23(1): 4–6. <https://doi.org/10.1136/bjsports-2022-105532>.
- Edouard, P., J. Mendiguchia, K. Guex, J. Lahti, P. Samozino, and J.-B. Morin. 2019. "Sprinting: a Potential Vaccine for Hamstring Injury?" *Sport Perform Science Reports* 1: 1–2.
- Faulkner, John A., Susan V. Brooks, and Julie A. Opitck. 1993. "Injury to Skeletal Muscle Fibers during Contractions: Conditions of Occurrence and Prevention." *Physical Therapy* 73(12): 911–21. <https://doi.org/10.1093/ptj/73.12.911>.
- Figueira, Bruno, Bruno Gonçalves, Eduardo Abade, Rūtenis Paulauskas, Nerijus Masiulis, Paulius Kamarauskas, and Jaime Sampaio. 2021. "Repeated Sprint Ability in Elite Basketball Players: the Effects of 10× 30 M vs. 20× 15 M Exercise Protocols on Physiological Variables and Sprint Performance." *Journal of Human Kinetics* 77(1): 181–9. <https://doi.org/10.2478/hukin-2020-0048>.
- Fitzsimons, M., B. Dawson, D. Ward, and A. Wilkinson. 1993. "Cycling and Running Tests of Repeated Sprint Ability." *Australian Journal of Science and Medicine in Sport* 25: 82.
- Foster, Carl, Jessica A. Florhaug, Jodi Franklin, Lori Gottschall, Lauri A. Hrovatin, Suzanne Parker, Pamela Doleshal, and Christopher Dodge. 2001. "A New Approach to Monitoring Exercise Training." *The Journal of Strength & Conditioning Research* 15(1): 109–15. [https://doi.org/10.1519/1533-4287\(2001\)015<0109:anatme>2.0.co;2](https://doi.org/10.1519/1533-4287(2001)015<0109:anatme>2.0.co;2).
- Gabbett, Tim J. 2016. "The Training–Injury Prevention Paradox: Should Athletes Be Training Smarter and Harder?" *British Journal of Sports Medicine* 50(5): 273–80. <https://doi.org/10.1136/bjsports-2015-095788>.
- Gaitanos, G. C., C. Williams, L. H. Boobis, and S. Brooks. 1993. "Human Muscle Metabolism during Intermittent Maximal Exercise." *Journal of Applied Physiology* 75(2): 712–9. <https://doi.org/10.1152/jappl.1993.75.2.712>.
- Gathercole, Rob, Ben Sporer, Trent Stellingwerff, and Gord Sleivert. 2015. "Alternative Countermovement-Jump Analysis to Quantify Acute Neuromuscular Fatigue." *International Journal of Sports Physiology and Performance* 10(1): 84–92. <https://doi.org/10.1123/ijssp.2013-0413>.
- Gharbi, Zied, Wajdi Dardouri, Radhouane Haj-Sassi, Carlo Castagna, Karim Chamari, and Nizar Souissi. 2014. "Effect of the Number of Sprint Repetitions on the Variation of Blood Lactate Concentration in Repeated Sprint Sessions." *Biology of Sport* 31(2): 151–6. <https://doi.org/10.5604/20831862.1099046>.
- Girard, Olivier, Alberto Mendez-Villanueva, and David Bishop. 2011. "Repeated-sprint Ability – Part I." *Sports Medicine* 41(8): 673–94. <https://doi.org/10.2165/11590550-000000000-00000>.
- Glaister, Mark, Glyn Howatson, John R. Pattison, and Gill McInnes. 2008. "The Reliability and Validity of Fatigue Measures during Multiple-Sprint Work: an Issue Revisited." *The Journal of Strength & Conditioning Research* 22(5): 1597–601. <https://doi.org/10.1519/jsc.0b013e318181ab80>.
- Hopkins, W. G. 2002. "A Scale of Magnitudes for Effect Statistics." *A New View of Statistics* 502(411): 321.
- Impellizzeri, F., E. Rampinini, C. Castagna, D. Bishop, D. Ferrari Bravo, A. Tibaudi, and U. Wisloff. 2008. "Validity of a Repeated-Sprint Test for Football." *International Journal of Sports Medicine* 29(11): 899–905. <https://doi.org/10.1055/s-2008-1038491>.
- Johnston, Rich D., Georgia M. Black, Peter W. Harrison, Nick B. Murray, and Damien J. Austin. 2018. "Applied Sport Science of Australian Football: A Systematic Review." *Sports Medicine* 48(7): 1673–94. <https://doi.org/10.1007/s40279-018-0919-z>.
- Johnston, Rich D., Tim J. Gabbett, and David G. Jenkins. 2014. "Applied Sport Science of Rugby League." *Sports Medicine* 44(8): 1087–100. <https://doi.org/10.1007/s40279-014-0190-x>.
- Laursen, Paul B., and David G. Jenkins. 2002. "The Scientific Basis for High-Intensity Interval Training." *Sports Medicine* 32(1): 53–73. <https://doi.org/10.2165/00007256-200232010-00003>.
- Leduc, Cédric, Jason Tee, Mathieu Lacombe, Jonathon Weakley, Jeremy Cheradame, Carlos Ramirez, and Ben Jones. 2020. "Convergent Validity, Reliability, and Sensitivity of a Running Test to Monitor Neuromuscular Fatigue." *International Journal of Sports Physiology and Performance* 15(8): 1067–73. <https://doi.org/10.1123/ijssp.2019-0319>.
- Lieber, R. L., T. M. Woodburn, and J. Friden. 1991. "Muscle Damage Induced by Eccentric Contractions of 25% Strain." *Journal of Applied Physiology* 70(6): 2498–507. <https://doi.org/10.1152/jappl.1991.70.6.2498>.
- Linthorne, Nicholas P. 2001. "Analysis of Standing Vertical Jumps Using a Force Platform." *American Journal of Physics* 69(11): 1198–204. <https://doi.org/10.1119/1.1397460>.
- Little, Thomas, and Alun G. Williams. 2005. "Specificity of Acceleration, Maximum Speed, and Agility in Professional Soccer Players." *The Journal of Strength & Conditioning Research* 19(1): 76–8. <https://doi.org/10.1519/00124278-200502000-00013>.
- Lloyd, Rhodri S., Jon L. Oliver, Michael G. Hughes, and Craig A. Williams. 2009. "Reliability and Validity of Field-Based Measures of Leg Stiffness and Reactive Strength Index in Youths." *Journal of Sports Sciences* 27(14): 1565–73. <https://doi.org/10.1080/02640410903311572>.
- Malone, Shane, Mark Roe, Dominic A. Doran, Tim J. Gabbett, and Kieran Collins. 2017. "High Chronic Training Loads and Exposure to Bouts of Maximal Velocity Running Reduce Injury Risk in Elite Gaelic Football." *Journal of Science and Medicine in Sport* 20(3): 250–4. <https://doi.org/10.1016/j.jsams.2016.08.005>.
- McCall, Alan, Mathieu Nedelec, Christopher Carling, Franck Le Gall, Serge Berthoin, and Gregory Dupont. 2015. "Reliability and Sensitivity of a Simple Isometric Posterior Lower Limb Muscle Test in Professional Football Players." *Journal of Sports Sciences* 33(12): 1298–304. <https://doi.org/10.1080/02640414.2015.1022579>.
- McLaren, Shaun J., Michael Graham, Iain R. Spears, and Matthew Weston. 2016. "The Sensitivity of Differential Ratings of Perceived Exertion as Measures of Internal Load." *International Journal of Sports Physiology and Performance* 11(3): 404–6. <https://doi.org/10.1123/ijssp.2015-0223>.
- McLaren, Shaun J., Andrew Smith, Iain R. Spears, and Matthew Weston. 2017. "A Detailed Quantification of Differential Ratings of Perceived Exertion during Team-Sport Training." *Journal of Science and Medicine in Sport* 20(3): 290–5. <https://doi.org/10.1016/j.jsams.2016.06.011>.
- McLaren, Shaun J., Jonathan M. Taylor, Tom W. Macpherson, Iain R. Spears, and Matthew Weston. 2020. "Systematic Reductions in Differential Ratings of Perceived Exertion across a 2-week Repeated-Sprint-Training Intervention that Improved Soccer Players' High-Speed-Running Abilities." *International Journal of Sports Physiology and Performance* 1(aop): 1–8. <https://doi.org/10.1123/ijssp.2019-0568>.
- Mendiguchia, Jurdan, Filipe Conceição, Pascal Edouard, Marco Fonseca, Rogerio Pereira, Hernani Lopes, J.-Benoît Morin, and Pedro Jiménez-Reyes. 2020. "Sprint versus Isolated Eccentric Training: Comparative Effects on Hamstring Architecture and Performance in Soccer Players." *PLoS One* 15(2): e0228283. <https://doi.org/10.1371/journal.pone.0228283>.
- Midgley, Adrian W., Lars R. McNaughton, and Michael Wilkinson. 2006. "Is There an Optimal Training Intensity for Enhancing the Maximal Oxygen Uptake of Distance Runners? Empirical Research Findings, Current Opinions, Physiological Rationale and Practical Recommendations." *Sports Medicine* 36(2): 117–32. <https://doi.org/10.2165/00007256-200636020-00003>.
- Murray, Nick B., Tim J. Gabbett, and Andrew D. Townshend. 2018. "The Use of Relative Speed Zones in Australian Football: Are We Really Measuring what We Think We Are?" *International Journal of Sports*

- Physiology and Performance* 13(4): 442–51. <https://doi.org/10.1123/ijssp.2017-0148>.
- Nosaka, K., M. Newton, and P. Sacco. 2002. "Responses of Human Elbow Flexor Muscles to Electrically Stimulated Forced Lengthening Exercise." *Acta Physiologica Scandinavica* 174(2): 137–45. <https://doi.org/10.1046/j.1365-201x.2002.00936.x>.
- Oakley, Aiden J., Jacob Jennings, and Chris J. Bishop. 2018. "Holistic Hamstring Health: Not Just the Nordic Hamstring Exercise." *British Journal of Sports Medicine* 52(13): 816–7. <https://doi.org/10.1136/bjsports-2016-097137>.
- O'Keefe, J. M. 2020. *Force Platforms for Isometric Hamstring Testing: Reliability, Validity and Practical Applications in Professional Soccer* [Masters Thesis]. Liverpool (UK): Liverpool John Moores University.
- Oliver, Jonathan L., Rhodri S. Lloyd, and Adam Whitney. 2015. "Monitoring of In-Season Neuromuscular and Perceptual Fatigue in Youth Rugby Players." *European Journal of Sport Science* 15(6): 514–22. <https://doi.org/10.1080/17461391.2015.1063700>.
- Onishi, Hideaki, Ryo Yagi, Mineo Oyama, Kiyokazu Akasaka, Kouji Ihashi, and Yasunobu Handa. 2002. "EMG-Angle Relationship of the Hamstring Muscles during Maximum Knee Flexion." *Journal of Electromyography and Kinesiology* 12(5): 399–406. [https://doi.org/10.1016/s1050-6411\(02\)00033-0](https://doi.org/10.1016/s1050-6411(02)00033-0).
- Paulauskas, Rūtenis, Paulius Kamarauskas, Ričardas Nekriošius, and Nicholas Malcolm Bigwood. 2020. "Physical and Physiological Response to Different Modes of Repeated Sprint Exercises in Basketball Players." *Journal of Human Kinetics* 72(1): 91–9. <https://doi.org/10.2478/hukin-2019-0100>.
- Schache, Anthony G., Tim W. Dorn, Peter D. Blanch, Nicholas A. T. Brown, and Marcus G. Pandy. 2012. "Mechanics of the Human Hamstring Muscles during Sprinting." *Medicine & Science in Sports & Exercise* 44(4): 647–58. <https://doi.org/10.1249/mss.0b013e318236a3d2>.
- Taylor, Jonathan, Tom Macpherson, Iain Spears, and Matthew Weston. 2015. "The Effects of Repeated-Sprint Training on Field-Based Fitness Measures: a Meta-Analysis of Controlled and Non-controlled Trials." *Sports Medicine* 45(6): 881–91. <https://doi.org/10.1007/s40279-015-0324-9>.
- Thelen, Darryl G., Elizabeth S. Chumanov, Dina M. Hoerth, Thomas M. Best, Stephen C. Swanson, Li Li, Michael Young, and Bryan C. Heiderscheit. 2005. "Hamstring Muscle Kinematics during Treadmill Sprinting." *Medicine & Science in Sports & Exercise* 37(1): 108–14. <https://doi.org/10.1249/01.mss.0000150078.79120.c8>.
- Thurlow, Fraser, Minh Huynh, Andrew Townshend, Shaun J. McLaren, Lachlan P. James, Jonathon M. Taylor, Matthew Weston, and Jonathon Weakley. 2023. "The Effects of Repeated-Sprint Training on Physical Fitness and Physiological Adaptation in Athletes: a Systematic Review and Meta-Analysis." *Sports Medicine* 54(4): 1–22. <https://doi.org/10.1007/s40279-023-01959-1>.
- Thurlow, Fraser, Jonathon Weakley, Andrew D. Townshend, Ryan G. Timmins, Matthew Morrison, and Shaun J. McLaren. 2023. "The Acute Demands of Repeated-Sprint Training on Physiological, Neuromuscular, Perceptual and Performance Outcomes in Team Sport Athletes: a Systematic Review and Meta-Analysis." *Sports Medicine* 53(8): 1–32. <https://doi.org/10.1007/s40279-023-01853-w>.
- Timmins, R. G., D. A. Opar, M. D. Williams, A. G. Schache, N. M. Dear, and A. J. Shield. 2014. "Reduced Biceps Femoris Myoelectrical Activity Influences Eccentric Knee Flexor Weakness after Repeat Sprint Running." *Scandinavian Journal of Medicine & Science in Sports* 24(4): e299–305. <https://doi.org/10.1111/sms.12171>.
- Weakley, J., G. Black, S. McLaren, S. Scantlebury, T. J. Suchomel, E. McMahon, et al. 2022. "Testing and Profiling Athletes: Recommendations for Test Selection, Implementation, and Maximizing Information." *Strength and Conditioning Journal* 10: 1519.
- Weakley, J., A. P. Castilla, A. G. Ramos, H. Banyard, F. Thurlow, T. Edwards, et al. 2022. "Effect of Traditional, Rest Redistribution, and Velocity-Based Prescription on Repeated Sprint Training Performance and Responses in Semiprofessional Athletes." *The Journal of Strength & Conditioning Research* 10: 1519.
- Weakley, Jonathon, Chris McCosker, Daniel Chalkley, Rich Johnston, Gabriella Munteanu, and Matthew Morrison. 2022. "Comparison of Sprint Timing Methods on Performance, and Displacement and Velocity at Timing Initiation." *The Journal of Strength & Conditioning Research* 37(1): 234–8. <https://doi.org/10.1519/jsc.00000000000004223>.
- Weakley, Jonathon, Shaun McLaren, Carlos Ramirez-Lopez, Amador García-Ramos, Nick Dalton-Barron, Harry Banyard, Bryan Mann, Dan Weaving, and Ben Jones. 2019. "Application of Velocity Loss Thresholds during Free-Weight Resistance Training: Responses and Reproducibility of Perceptual, Metabolic, and Neuromuscular Outcomes." *Journal of Sports Sciences* 38(5): 1–9. <https://doi.org/10.1080/02640414.2019.1706831>.
- Woolley, B., J. Jakeman, and J. Faulkner. 2014. "Multiple Sprint Exercise with a Short Deceleration Induces Muscle Damage and Performance Impairment in Young, Physically Active Males." *J Athl Enhance* 3: 2.

## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.