

Acute Effects of Repeated Sprints on Performance Measures During the Countermovement Rebound Jump

1 **ABSTRACT**

2 The countermovement rebound jump (CMRJ) test is an alternative to traditional jump assessments,
3 providing unique insights into slow and fast stretch-shortening cycle mechanics. This study investigated the
4 effects of repeated sprint-induced fatigue (4 sets of 6 × 40-m sprints with 20-s inter-repetition rest) on CMRJ
5 performance metrics, including jump heights, time to take-off, ground contact time, reactive strength index
6 modified (RSImod), reactive strength index (RSI), countermovement depth, and leg stiffness, measured at
7 baseline, during sprints, and over a 24-hour recovery period. Twenty-four elite male team-sport athletes
8 completed CMRJ tests before and after each sprint set, with additional assessments at 0.5-hour, 1-hour,
9 and 24-hour post-sprints. Results showed significant reductions in CMRJ heights, RSImod, and RSI
10 immediately following sprints (effect size = 0.27 to 1.78, $p \leq 0.040$), indicating acute decrements in jump
11 performance. Strategy-based metrics, such as leg stiffness and contact times, remained stable (effect size =
12 0.09 to 0.57, $p \geq 0.079$), suggesting limited sensitivity to fatigue. These findings support the use of CMRJ
13 outcome metrics to evaluate neuromuscular fatigue effectively in an athlete population with a non-invasive
14 solution suitable for field settings.

15
16 **Key Words:** jump performance, neuromuscular fatigue, stretch-shortening cycle

INTRODUCTION

Jump testing is widely used in experimental settings with athletes for numerous reasons, such as: evaluating performance fatigability and lower limb neuromuscular status, assessing adaptations to training, and determining readiness to return to sport after injury (12, 18, 41). Two of the most commonly used jump tests are the countermovement jump (CMJ) and drop jump (DJ). Although relatively under-investigated, the countermovement rebound jump (CMRJ) test has recently been introduced as a valid and reliable alternative to the CMJ and DJ tests, offering comparable information in assessing neuromuscular performance (48, 49). The CMRJ consists of two consecutive jumps, requiring athletes to perform a maximal-effort CMJ (CMRJ1) with an immediate rebound jump (CMRJ2) upon landing from the first jump, which requires athletes to concurrently focus on maximizing jump height and minimizing ground contact time. Consequently, this provides an examination of both slow and fast stretch-shortening cycle (SSC) mechanics in CMRJ1 and CMRJ2, respectively, as defined by the commonly referenced 250-millisecond threshold (28). Practitioners commonly monitor both jump height and strategy-based metrics to assess CMRJ test performance (6, 49). In the CMJ and CMRJ1, key metrics include: countermovement depth, time to take-off, and reactive strength index modified (RSImod). For the DJ and CMRJ2, focus is often on leg stiffness, ground contact time, and reactive strength index (RSI) (6, 49). Recent CMRJ investigations have shown acceptable reliability of these outcome and strategy-based metrics for assessing CMRJ performance (48, 49). Therefore, measuring these metrics provides practitioners with understandings of jump performance and jump strategy, enabling them to make informed decisions relating to the efficacy of training interventions (18, 41).

Neuromuscular fatigue is defined as an exercise-induced reduction in the maximal voluntary force or rapid force production that a muscle or muscle group can produce (16)(45). Evidence suggests that neuromuscular fatigue negatively impacts outcome measures in jump tests, with reductions in jump height commonly evident as an indicator of fatigue (5, 12, 33). Given the critical role of sprint ability in many sports, repeat sprint protocols are often used to simulate acute fatigue states that closely resemble those encountered during competition (15, 17, 24). For example, Armada-Cortés et al. (2) measured CMJ performance before and after one set of 6 × 40-meter (m, 30 seconds [s] rest) sprints and found a significant

decrease in CMJ height (effect size [ES] = 0.40, $p < 0.001$). Furthermore, Hughes et al. (22) reported a statistically significant reduction in CMJ height (0.28 ± 0.03 m vs. 0.30 ± 0.03 m, ES = 0.12, $p < 0.05$) among 17 semi-professional soccer players following 6×16 -minute varied-intensity exercise sessions, including walking, jogging, running, and sprinting with changes of direction. Recently, another study examined the effect of 4 sets of 6×40 -m sprints on CMJ height at different time points (13). Significant reductions from baseline jump height (0.37 ± 0.05 m) were observed at 2-hours (0.32 ± 0.05 m, ES = 0.92, $p < 0.05$), 24-hours (0.35 ± 0.06 m, ES = 0.32, $p < 0.05$) and 48-hours (0.36 ± 0.05 m, ES = 0.27, $p < 0.05$). Although these results supported the notion that CMJ height is a useful marker for detecting sprinting-induced fatigue (5, 33, 44), it is important to acknowledge that athletes may be able to manipulate their jump strategy while still achieving comparable jump heights (7). Specifically, and by way of an example, a fatigued athlete may utilize a deeper countermovement or prolonged contraction times prior to take-off, so that force can be applied over extended time frames. This strategy can result in maintaining similar jump heights compared to non-fatigued conditions, even though the underlying jump strategy and performance mechanics may be significantly altered (18, 39). Thus, relying solely on monitoring jump height in jump testing may be missing important information relating to the fatigue-induced adaptations in jump strategies. Consequently, the simultaneous evaluation of jump height with other strategy-based metrics in jump testing is suggested (6-8).

Oliver et al. (33) investigated the effects of 42 minutes of treadmill-based, soccer-specific intermittent exercise (consisting of walking, jogging and sprinting) on CMJ and DJ performance. They reported a significant reduction in jump height during both CMJ (0.31 ± 0.04 m vs. 0.28 ± 0.05 m, ES = 0.72, $p < 0.05$) and DJ (0.27 ± 0.05 m vs. 0.25 ± 0.05 m, ES = 0.44, $p < 0.01$). Similarly, Gathercole et al. (17) examined the impacts of a fatiguing Yo-Yo running session on CMJ and DJ performance in 11 male team-sport athletes, with the jump tests conducted before and after (at 0-, 24-, and 72-hours) the fatiguing session. Results demonstrated similar fatigue time courses for CMJ and DJ tests, indicating their sensitivity to detect neuromuscular fatigue, particularly during the later stages of the recovery phase (i.e., ~72-hours). In a separate study, Stone et al. (42) compared the performance of the CMJ and five consecutive rebound jumps on two playing surfaces before and after a fatigue simulation using the same aforementioned protocol as

Hughes et al. (22). However, this protocol did not elicit a significant effect on CMJ height measured across the four different time points (pre: 0.20-0.33 m; 0-hour: 0.27-0.29 m; 24-hour: 0.29-0.30 m; 48-hour: 0.31-0.32 m, $p > 0.05$). In contrast, RSI as measured during a 5-rebound jump assessment was significantly reduced at 0-hours post-simulation (1.22 on both surfaces) compared to the pre-simulation results (1.32 and 1.33 on both surfaces, $p < 0.05$), although this effect did not extend to RSI at either 24-hours (1.37-1.40) or 48-hours (1.36-1.49, $p > 0.05$) post-testing. These results suggest that practitioner may consider using both CMJ and rebound jump tests to capture fatigue and recovery dynamics (17, 42). Furthermore, authors in the aforementioned studies only reported significant changes in jump height and RSI values in the post-training measurements compared to baseline testing, raising questions regarding whether neuromuscular fatigue would also affect other strategy-based metrics, such as time to take-off, ground contact time or leg stiffness, measured in both CMJ and DJ tests.

In contrast, there is a paucity of research examining the effects of fatigue on performance outcomes measured during the CMRJ test. Considering the potential changes in jump performance were associated with altered jump strategies, investigating the effects of neuromuscular fatigue on jump performance is warranted. Therefore, this study aimed to examine the impact of a series of controlled repeated sprints on CMRJ performance measures, with repeated testing of these variables both after each sprint set (e.g., inter-set 1 to inter-set 3) and at specific intervals post-sprints (e.g., 0-hours [immediately after set 4], 0.5-hours, 1-hour, and 24-hours) to assess the time course of recovery within the 24-hour period. Retesting the CMRJ at different time points as post-training evaluations could offer valuable insights into acute changes in CMRJ metrics and the temporal evaluation of CMRJ performance (13). It was hypothesized that the sprinting-induced impacts would lead to an immediate decline in CMRJ performance at the post-intervention measurement, followed by a return towards the baseline values at the 24-hours measurement (2, 5, 13, 33, 44).

METHODS

Experimental Approach to the Problem

Subjects were required to attend two testing sessions. The first session included familiarization with the CMRJ test, allowing subjects to practice the protocol as much as they deemed necessary to ensure accurate and consistent performance. Data collection began 4-minutes after familiarization, which included baseline measurements of CMRJ metrics (jump height and strategy-based metrics) and repeated sprint ability. These CMRJ metrics were recorded before, during, and after the repeated sprint testing to assess acute fatigue effects. A second session was conducted 24-hours later to retest the CMRJ metrics, enabling an assessment of recovery from sprint induced acute fatigue. When the standardized warm-up was completed, subjects performed three repetitions of CMRJ (baseline measurements), followed by four rounds of 6 × 40-m sprints on an indoor running track, that was interspersed with two repetitions of CMRJ, and another eight repetitions of CMRJ (post-test measurements at 0-hours, 0.5-hours and 1-hour). The second testing session solely involved the standardized warm-up and three repetitions of CMRJ. Limiting follow-up testing to 24 hours aligns with findings from previous research, where jump metrics frequently return to baseline at 24-hours (42). Additionally, re-testing at 24-hours reflects common scheduling practices in team sports, where athletes return to training after a minimum of 24 hours (26). Subjects were told to avoid exercise for 24-hours before testing and heavy meals an hour before testing. This protocol examined the time course of CMRJ performance response to the acute and accumulated fatigue resulting from repeated sprint training.

Subjects

A power analysis was conducted using G Power software (version 3.1.9.6, Mac OS X), suggesting a sample of 24 was required to have an 80% chance ($G\text{ power} = 0.8$) to find a statistically significant difference with a moderate ES (Hedges' $g = 0.5$, $p < 0.05$) (23). Twenty-four elite team-sports male (age: 23.9 ± 3.3 years; height: 1.8 ± 0.3 m; mass: 83.3 ± 10.5 kg) athletes (participating in soccer, football or rugby) volunteered to participate in this study. At the time of data collection, all players were competing at both national and regional levels. To be eligible, all subjects were required to be free of any musculoskeletal injury within six months and have at least three years' experience of sprint, plyometric and their sports specific training. All subjects were required to sign a written informed consent form, and this study was approved by the ***

*delete for peer-review**** research and ethics committee at *** *delete for peer-review**** (Application No: 26109).

Procedure

Before the data collection, subjects performed a standardized warm-up, including 5-minutes light-intensity aerobic jogging, followed by lower body dynamic stretches (consisting of forward lunges, hip stretches, and forward and lateral hip swings) to help optimize the subsequent jumping and sprinting performance (5). A demonstration of the CMRJ tests and repeated sprint protocol was provided to subjects, and then they performed the CMRJ with 50%, 75%, and 100% of their perceived maximal effort, and 40-m sprints with 50% and 100% of their perceived maximal speed. Once the warm-up and familiarization practices were done, three repetitions of CMRJ with subjects' maximal effort were recorded as the baseline test, and 30 s rest was given between each trial. Then, subjects performed four sets of 6 × 40-m sprints, with 20 s inter-repetition passive rest. This interval was selected to replicate typical rest durations between sprints commonly observed during team sports competitions (5, 44). Subjects were given 120 s of rest after the completion of the sixth sprints (44). Following this, they performed two maximal CMRJ tests with 30 s of rest between each jump trial. After a further 120 s of rest, subjects performed the sprint protocol in full again. Figure 1 shows the schematic of the study design. This protocol was modified (with shorter inter-repetition rest durations) from previous studies that have used CMJ metrics to evaluate neuromuscular fatigue after repeated sprint training (2, 13). The sprint distance and rest durations were designed to ensure that subjects sprinted with maximal effort, aiming to induce an acute fatigue response that reflects the physical demands of repeated sprint activities in sport (44). Finally, subjects were required to complete three repetitions of CMRJ as post-test measurements immediately and after 24 hours of completing the last 40-m sprint, respectively.

**** Insert Figure 1 about here ****

Countermovement Rebound Jump. For collecting CMRJ metrics, all jumps were performed on twin force platforms (Hawkin Dynamics, Westbrook, ME, USA). Subjects were instructed to stand still for at least 1 s keeping their hands on hips, remaining stationary, until the flash of the screen from the Hawkin Dynamics tablet. This flash signaled that an accurate estimation of body mass was obtained and the jump could be subsequently performed. A verbal cue “jump as high as you can in both jumps whilst spending as little amount of time on the ground for both jumps” was given to subjects, aiming to concurrently maximize the RSI_{mod} and RSI values (50). The calculation of CMRJ metrics was done in MATLAB (R2022a; The MathWorks, Inc., Natick, MA), with the mean values exported to a customized Microsoft Excel spreadsheet for further statistical analysis. The movement initiation of CMRJ1 was identified as the instant of 30 milliseconds before the vertical ground reaction force exceeded a threshold of $\pm$ five times the subject’s body mass (34). The take-off and landing instants for both jump actions were defined as the vertical ground reaction force being lower and larger than $\pm$ five times the vertical force extracted from only the middle part of the flight phase where subjects were no longer in contact with the force platforms, respectively (11). The jump heights (both CMRJ1 and CMRJ2 height) were calculated via the impulse-momentum theory (49), whereby the net propulsive impulse was used to determine the velocity of the center of mass at take-off, which was then used to calculate jump height. RSI_{mod} and RSI were then calculated by dividing each jump height by its respective time to take-off and ground contact time. Countermovement depth was measured as the vertical displacement of the center of mass from the start of the jump to the lowest squat position during the braking phase (48-50). This metric provides insight into the factors influencing time to take-off and braking strategies, which are critical for understanding neuromuscular performance and fatigue-related adaptations (6). Leg stiffness from CMRJ2 is a ratio computed by dividing the peak CMRJ1 landing force by the center of mass displacement of leg compression upon ground contact (48-50), which represents the ability of the lower limbs to resist deformation under eccentric load (6).

6 × 40-M Repeated Sprint Test. Electronic timing gates (Brower Timing Systems, Draper, UT) were positioned at 0 m, with each timing gate adjusted based on the individual subject’s iliac crest height. Subjects stood with a two-point started position with their preferred foot placed 0.3-m behind the timing gate. Upon

receiving a “go” command, subjects sprinted to the 20-m turning points, performed a 180-degree turn and sprinted back another 20 m to the starting line, totalling 40 m per repetition. They were verbally encouraged to sprint at their maximum speed. The timing gate recorded the time taken to complete each sprint, while a stopwatch (Gymboss, St. Clair, MI) was used to record the rest duration between each sprint. To minimize delays and maintain consistency, subjects were notified to be ready for the next repetition after 15 s of rest, and they were provided with a 5-s countdown to signal the start of each sprint (5). The sprint times were recorded into Microsoft Excel for the data summary and calculation of percentage decrement scores. For effectively monitoring subject’s level of fatigue, the percentage decrement score described by Glaister et al. (20) was calculated via the equation: $(100 \times (\text{total sprint time} \div \text{ideal sprint time})) \times 100$, where the total sprint time was the sum of sprint times from all repetitions and ideal sprint time was the number of sprints multiplied by the fastest sprint time.

Statistical Analyses

All CMRJ metrics were calculated from MATLAB and sprint times were inputted into Microsoft Excel to compute descriptive statistics (mean values and standard deviation [SD]). Subsequent statistical analyses were conducted via SPSS (version 27; SPSS Inc., Chicago, IL, USA). Normality of the data was assessed by the Shapiro–Wilk statistic, and homogeneity of variance was verified with the Levene’s test. Within-session reliability of the baseline metrics measured from CMRJ was computed using a 2-way ICC random effects model intraclass correlation coefficient (ICC) with absolute agreement and 95% confidence intervals (CI), coefficient of variation (CV) with 95% CI and the standard error of the measurement (SEM). The magnitude of ICC was evaluated in line with suggestions by Koo and Li (29) where the lower bound of the 95% CI was deemed: > 0.90 = excellent, $0.75\text{--}0.90$ = good, $0.50\text{--}0.74$ = moderate, and < 0.50 = poor (29). The CV was calculated as $(\text{CV}\% = \text{SD}/\text{mean} \times 100)$, with CV and 95% CI upper bound considered good if $< 5\%$, moderate if between $5\text{--}10\%$, and poor if $> 10\%$ (4). The 95% CI for CV was calculated as $((\text{CV}/\sqrt{2n}) \times 1.96)$, where n was the total number of subjects. The SEM was calculated as $(\text{SD} \times \sqrt{1 - \text{ICC}})$, where the SD was calculated by using the mean value of each metric from the individual subject (43). A 1-way repeated-measures analysis of variance (ANOVA) with a Bonferroni confidence interval adjustment was used to examine within-

and between-set differences in sprint times, and between-set differences in fatigue index, to guarantee that subjects are fatigued from the first to the sixth sprints within individual sets, and from the first sprint in set one to the last sprint in set four. A 1-way repeated-measures ANOVA was also used to determine the changes in mean CMRJ metrics over times, with statistical significance set at $p \leq 0.05$. Finally, Hedges' g ES with 95% CI were used to quantify the magnitude of difference in Microsoft Excel. These ES were interpreted as $g < 0.35$ = trivial; $0.35 - 0.80$ = small; $0.81 - 1.50$ = moderate; and > 1.5 = large (38).

RESULTS

All measured data were normally distributed ($p > 0.05$). The reliability was excellent with good to moderate variability for all metrics at baseline measures, including time to take-off (ICC = 0.95 [0.90-0.98], CV = 4.69% [3.37-6.02%], SEM = 0.15 s), CMRJ1 height (ICC = 0.99 [0.99-1.00], CV = 2.31% [1.66-2.97%], SEM = 0.03 m), RSI_{mod} (ICC = 0.97 [0.93-0.98], CV = 5.19% [3.72-6.66%], SEM = 0.11), countermovement depth (ICC = 0.96 [0.93-0.98], CV = 7.55% [5.41-9.69], SEM = 0.05 m), ground contact time (ICC = 0.96 [0.91-0.98], CV = 3.85% [2.76-4.94]%, SEM = 0.06 s), CMRJ2 height (ICC = 0.97 [0.95-0.99], CV = 4.38% [3.14-5.62%], SEM = 0.05 m) and RSI (ICC = 0.97 [0.95-0.99], CV = 6.22% [4.46-7.98], SEM = 0.28). Leg stiffness was the only metric that showed good ICC (0.90 [0.81-0.95]), but poor CV (12.20% [8.76-15.68], SEM = 10.58 KN/m). Table 1 shows the mean CMRJ metrics measured across different time points and mean sprint times for each set, with the comparisons relative to baseline data. Significant decreases in two jump heights ($g = 0.27$ to 1.78 , $p \leq 0.003$), RSI_{mod} ($g = 0.68$ to 1.39 , $p < 0.001$) and RSI ($g = 0.66$ to 1.69 , $p < 0.001$) at all time points were noted relative to baseline measures. In contrast, non-significant increase (or decrease) in time to take-off ($g = 0.10$ to 0.57 , $p \geq 0.220$), ground contact time ($g = 0.23$ to 0.57 , $p \geq 0.123$), countermovement depth ($g = 0.17$ to 0.32 , $p \geq 0.079$), and leg stiffness ($g = 0.09$ to 0.26 , $p \geq 0.721$) were revealed at any time points compared to the baseline. Sprint times significantly increased compared to baseline levels over all sets ($g = 0.75$ to 1.84 , $p \leq 0.020$).

**** Insert Table 1 about here ****

229

230 Figure 2 shows the differences in CMRJ metrics measured within and after the repeated sprint intervention
231 (note: no comparisons are being made relative to baseline in Figure 2). Significant trivial to moderate
232 decreases in two jump heights ($g = 0.15$ to 1.28 , $p \leq 0.040$), RSI_{mod} ($g = 0.27$ to 0.73 , $p \leq 0.033$), RSI ($g =$
233 0.26 to 0.99 , $p \leq 0.048$) and increases in countermovement depth ($g = 0.42$ to 0.53 , $p \leq 0.020$) were noted
234 from the inter-set 1 to 24-hour retest. The time-based metrics ($g = 0.01$ to 0.48 , $p \geq 0.865$) and leg stiffness
235 ($g = 0.01$ to 0.15 , $p = 1.000$) remained unchanged from the commencement of fatigue (i.e., testing
236 immediately after the four sprint sets) to the 24-hour following test. Figure 3 displays the sprint speed for
237 the first and last sprints in individual sets, with significant small to moderate differences ($g = -0.57$ to -1.30 ,
238 $p < 0.001$) seen between the first and sixth repetitions. Lastly, the mean fatigue index values in Figure 4
239 demonstrates a significant accumulation of fatigue as the intervention progress over times with small to
240 moderate magnitude ($g = -0.54$ to -1.74 , $p \leq 0.041$).

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242 ***** Insert Figures 2-4 about here *****

243

244 **DISCUSSION**

245 The aim of the present investigation was to examine the impact of a series of controlled repeated sprints
246 on CMRJ performance. The results demonstrated significant slowing of sprint time and an increased index
247 of neuromuscular fatigue throughout the intervention, indicating that the present repeated sprints protocol
248 induced substantial performance fatigability. In turn, this fatigue had a notable impact on some jump
249 performance metrics, that caused declines in both two CMRJ heights, RSI_{mod} and RSI. Additionally, while
250 countermovement depth showed a significant decrease at the onset of fatigue followed by a significant
251 increase at 24-hours, other strategy-based metrics did not differ significantly from baseline across time
252 points. These findings suggest that repeated sprinting induces acute changes in CMRJ performance, with
253 different metrics displaying varying degrees of reduction or recovery towards baseline, partially supporting
254 our initial hypothesis.

In line with existing literature (2, 5, 13, 17, 22, 24, 33, 44), the CMRJ heights showed immediate declines following the first set of sprints, with the magnitude of reduction increasing progressively throughout the intervention (Table 1). Neuromuscular fatigue is widely understood to be a continuous process on athletic performance rather than a failure-point phenomenon, and it typically manifests as a reduction in the force-generating capability of the muscles involved or negative impacts of the timing element of force production (16, 45). The progressively slower sprint speeds, as evidenced by increasing sprint times compared to baseline (Table 1), further reinforces this notion. The decline in force output during jumping and sprinting, often referred to as “SSC fatigue” (32), can be attributed to structural changes (impaired excitation–contraction coupling and muscle damage) (10), neural changes (activation of group III/IV muscle afferents induced altered stretch reflex responses and muscle-tendon stiffness reduction) (3), and metabolic disturbances (muscle glycogen depletion, elevated blood lactate and increased ammonia concentrations) (17, 24, 32). Furthermore, the most substantial reductions in two jump heights were observed at 0-hours as indicated by the largest ES (CMRJ1: $g = 1.10$, $p < 0.001$; CMRJ2: $g = 1.78$, $p < 0.001$). However, contrasting findings were observed in the study by Gathercole et al. (19), where they observed a small increase in jump height (0.45 ± 0.09 vs. 0.47 ± 0.08 m, typical error = 0.27) post fatigue testing, although statistical significance was not achieved. Notably, Gathercole et al. (19) calculated jump heights from a linear position transducer positioned above the participant and sampled at 200Hz, which could inevitably produce errors and result in inaccurate jump heights compared to using force platforms (47). Finally, and in agreement with our initial hypothesis, the smallest ES values (CMRJ1: $g = 0.27$, $p = 0.003$; CMRJ2: $g = 0.68$, $p < 0.001$) were observed for CMRJ heights at 24-hours (Table 1), potentially reflecting a recovery towards baseline levels (17, 18).

Given that the RSI_{mod} and RSI are ratio metrics composed by jump height and time series metrics, it is not surprising that these metrics followed similar fatigue time courses as CMRJ heights throughout intervention and recovery phases (Table 1). Surprisingly, both time to take-off and ground contact time remained relatively unchanged across all time points ($g = 0.10$ to 0.57 , $p \geq 0.220$), indicating that the significant decrements in the ratio metrics are primarily due to the reductions in magnitude element of the force-time curve. When subjects were cued to maximize the RSI_{mod} and RSI during the CMRJ, they maintained a

similar ground contact strategy resulting in non-significant changes to time-based data. However, subjects were unable to maintain comparable levels of force (i.e., propulsive impulse) compared to baseline, leading to a significant reduction in the CMRJ heights (15). Although, the present study did not directly measure the duration of unloading, braking, and propulsive phases, it is plausible that the distribution of these individual phase durations within the total contact times may have shifted under fatigue. For example, Gathercole et al. (18) reported a significant increase in eccentric phase duration (unloading and braking; ES = 0.29, $p < 0.05$) without any increase in propulsive phase duration (ES = 0.14, $p > 0.05$) or total contact time (ES = 0.24, $p > 0.05$), following a Yo-Yo fatiguing protocol. Hasegawa et al. (21) observed a significant decrease in eccentric phase duration ($\eta^2 = 0.32$, $p = 0.005$), but also with an increase in propulsive phase duration ($\eta^2 = 0.49$, $p = 0.018$), 10-minutes after a 400 m sprint protocol. These shifts in the distribution of individual phases are likely due to compromised reactivity efficiency in transitioning from the braking to the propulsive phase under fatigue (17, 18). However, while some subjects may have maintained similar levels of force output, they may have been unable to apply this force over the same duration of the braking or propulsive phases. This negative impact on the timing element of force production may have further contributed to the observed reductions in RSI_{mod} and RSI (30, 37).

Furthermore, non-significant differences in countermovement depth ($g = 0.17$ to 0.32 , $p \geq 0.079$) and leg stiffness ($g = 0.09$ to 0.26 , $p \geq 0.721$) were noted compared to baseline. These results align with previous investigations, which reported non-significant changes in normalized leg stiffness (247.88 ± 23.48 vs. 237.22 ± 21.70 KN/m, $p > 0.05$) over an exhaustive single-leg hopping trial (31), as well as in leg stiffness (males: 37.53 ± 20.51 vs. 40.58 ± 16.31 KN/m; females: 31.73 ± 12.12 vs. 33.82 ± 10.48 KN/m, $p = 0.131$) after a repeated squatting intervention at a frequency of 50 squats/min (35). However, given the poor reliability of this metric at baseline, these findings should be interpreted with caution. In current study, leg stiffness is considered as a metric to reflect the efficiency of force transmission or to assess an athlete's capacity to resist lower limb deformation during fast SSC movements (9). While the reliability of neither peak CMRJ1 landing force nor leg compression displacement was examined, changes in these components likely occurred throughout the testing. That being said, as CMRJ1 height decreased over the course of the intervention, the eccentric load placed on the lower extremities would have diminished, likely resulting in

ever decreasing peak landing forces compared to baseline. If subjects maintained the same joint angular displacement (i.e., a reliable and consistent leg compression strategy), leg stiffness should theoretically decrease in proportion to the reduction in landing force (1). However, the observed unchanged leg stiffness values alongside the relatively large SD for this metric (ranging from 7.59 to 9.99), suggests substantial variability in leg compression displacement, potentially reflecting a compensatory strategy to offset the effects of fatigue (31, 32, 35). By altering body geometry at touchdown, such as reducing joint angular displacement and increasing reliance on ankle joint contribution to the total movement (31, 50), subjects may have mitigated the impact of acute fatigue. Given that leg stiffness failed to demonstrate excellent reliability as a measure of jump strategy, it is difficult to argue that the unchanged values observed relative to baseline reflect prioritization of mechanical efficiency under fatigue (28, 32, 35). Collectively, these findings suggest that practitioners should avoid using leg stiffness as a primary marker for assessing how athletes adjust their movement strategies during the CMRJ task (irrespective of whether athletes are fresh or fatigued).

Figure 2 provides additional insights into the changes of each CMRJ metric from immediate post-fatigue period to the early and late recovery. Adjusting training loads based on these comparisons ensures athletes undertake demanding sessions only when sufficiently recovered (10, 35, 37). Compared to the acute fatigue at 0-hours, the CMRJ heights were significantly restored after passively resting for 1-hour ($g = 0.35$ to 0.68 , $p \leq 0.040$). This short-term recovery of force production capacity maybe associated with the restoration of substrate and metabolic factors, such as muscle glycogen replenishment and phosphocreatine re-synthesis (10, 14, 17, 18). While there were still residual fatigue effects on both jump heights at 24-hour testing, CMRJ1 height showed improvement surpassing its value at inter-set 1 ($g = 0.27$, $p = 0.013$) and starting to approach baseline levels. In contrast, CMRJ2 height remained lower but did not differ significantly from inter-set 1 ($g = 0.10$, $p > 0.05$). Nevertheless, this does not imply that subjects recover their slow SSC function quicker than their fast SSC function (46). This is especially evident when comparing the RSI_{mod} ($g = 0.44$, $p = 0.020$) and RSI ($g = 0.57$, $p < 0.001$) scores at 24-hours, both of which demonstrated recovery surpassing inter-set 3 levels. A previous investigation has observed a 20% decrease in countermovement depth (0.49 ± 0.13 vs. 0.39 ± 0.14 m, $p < 0.05$) under acute fatigue, due to reduced knee joint flexion to

accommodate the eccentric load that could damage the fatigued muscles (39). In the present study, subjects did not significantly modify their countermovement depth when fatigued, especially compared to baseline, likely due to the cueing that was provided to maximize RSI_{mod} (50). However, a significantly deeper depth at 24-hours was noted compared to the acute fatigue states (from inter-set 1 to 0-hour; $g = 0.42$ to 0.53 , $p \leq 0.02$). This suggests that the observed “superior” recovery in CMRJ1 height at 24-hours may be attributed to a shift in jump strategy, where athletes utilized a deeper countermovement depth (i.e., providing a longer distance for subjects to generate net propulsive impulse) to compensate for fatigue residuals that may impair the magnitude of force produced (27, 48), and thereby bring jump height closer to baseline levels. It could be speculated that under acute fatigue, subjects may avoid significantly increasing their countermovement depth due to reduced ability to control eccentric loads (39). However, as fatigue residuals diminish gradually during recovery, allowing for improved control of eccentric loads, a deeper countermovement depth strategy may be adopted to maximize CMRJ performance (28, 32, 35). Moreover, the time series metrics ($g = 0.01$ to 0.48 , $p \geq 0.865$) and leg stiffness ($g = 0.01$ to 0.15 , $p = 1.000$) showed little variation from acute fatigue to the end of recovery, highlighting that these metrics could be affected by several factors, such as ground contact strategy or stiffness control, and may not be as sensitive as jump height to detect acute fatigue or fatigue residuals (15, 31, 32, 35). Collectively then, comparing the changes in CMRJ performance between acute fatigue and both early and late recovery is as critical as comparing the fresh state to acute fatigue. Such information helps coaches and sports scientists identify whether athletes are adapting effectively or compensating in ways that could increase injury risk over time.

Figure 3 shows significant increases in mean sprint time between the first and last sprints in each set ($g = -0.57$ to -1.30 , $p < 0.001$), suggesting that the four sets of 6 x 40 m repeated sprints can be considered as an appropriate protocol to induce neuromuscular fatigue in current study’s population. The progressive increase in fatigue index (Figure 4) with each successive set further supports the efficacy of this protocol in eliciting fatigue ($g = -0.54$ to -1.74 , $p \leq 0.041$). The observed fatigue index values align closely with previous studies, which reported an index of 5.13% following the first set of 6 x 30 m sprints (20) and 5.74% following the first set of 6 x 40 m sprints (5). A key feature of the present study is the inclusion of a 180° change-of-direction between two 20-m sprints within the full 40-m repeated sprint distance. These deceleration and

reacceleration phases are known to induce greater levels of fatigue compared to linear sprint due to the increased eccentric and concentric muscle actions required to brake and change direction (25). This is evident in the longer sprint time (7.59 to 8.63 s) recorded in the present study compared to studies using 40-m linear sprints (5.76 to 6.60 s) (2, 5). Overall, these findings show the CMRJ task to be a sensitive tool for detecting neuromuscular fatigue induced by repeated sprints across various time points. Significant reductions in CMRJ heights, RSI_{mod} and RSI during acute fatigue, early recovery, and later recovery stages suggest that fatigue negatively impacts the capability to produce a large magnitude of force rapidly (as shown in Table 1 and Figure 2). Therefore, before deciding whether an athlete is ready to progress to higher-intensity training or requires additional recovery, practitioners are advised to carefully assess these CMRJ metrics to determine an athlete's readiness to train and compete.

While the current study offers novel insights into CMRJ performance under fatigue, certain methodological limitations warrant consideration. First, the absence of female subjects in our study restricts the applicability of our findings to male athletes, as it remains unclear if females would respond to fatigue in a similar fashion. Second, our subjects were recruited from different training backgrounds and sports, which in turn, may have introduced variability in fatigue responses and jump strategies. This heterogeneity could affect the generalizability of our findings, as athletes from the same sport or with similar training backgrounds may exhibit more, or less, consistent adaptations. Therefore, future research should consider recruiting elite athletes across both sexes and selecting samples with similar training backgrounds, where possible. Furthermore, the controlled repeated sprint protocol used in the present investigation cannot fully replicate the neuromechanical load induced from competition. In competitive scenarios, athletes often perform unpredictable accelerations and decelerations, and engage in sport-specific tasks such as jumping, kicking, and multidirectional changes (36, 40). Consequently, future studies could consider employing sport-specific fatigue protocols, such as conditioning drills or actual gameplay, to provide more ecologically valid insights into how fatigue affects CMRJ performance metrics in real-world contexts (40).

PRACTICAL APPLICATIONS

389 The CMRJ task provides practitioners with a sensitive tool for detecting neuromuscular fatigue through
390 outcome metrics like CMRJ heights, RSI_{mod} and RSI. These measures showed sensitive changes across
391 fatigue and recovery stages, emphasizing their utility in identifying fatigue-induced slow and fast SSC
392 performance decrements. Primarily focusing on these outcome metrics rather than more complex strategy-
393 based measures simplifies the application of fatigue monitoring, making it more usable for practitioners in
394 a variety of settings. In addition, practitioners should understand that based upon the results of this
395 investigation, leg stiffness is not suitable for measuring acute neuromuscular fatigue. Having said this,
396 variability in leg stiffness may result from off-setting changes in peak CMRJ1 landing force or lower limb
397 joint angular displacement, making it challenging to determine whether increases, decreases, or a lack of
398 change in this metric reflect true neuromuscular adaptations. Collectively though, for streamlined and
399 practical monitoring, outcome metrics such as jump height and RSI remain the most accessible and
400 actionable measures for direct application in the field when aiming to determine acute alterations in jump
401 performance.

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TABLE

Table 1. Mean countermovement rebound jump metrics and sprint time $\pm$ SD[†].

Metric	Baseline	Inter-set 1	Inter-set 2	Inter-set 3	0-hour	0.5-hour	1-hour	24-hour
TTTO	0.66 $\pm$ 0.09	0.67 $\pm$ 0.10	0.68 $\pm$ 0.19	0.69 $\pm$ 0.11	0.70 $\pm$ 0.12	0.70 $\pm$ 0.10	0.69 $\pm$ 0.12	0.71 $\pm$ 0.09
Hedge's <i>g</i> ES	-----	-0.19 (-0.28, -0.10)	-0.10 (-0.17, -0.03)	-0.30 (-0.41, -0.19)	-0.40 (-0.54, -0.26)	-0.39 (-0.53, -0.26)	-0.34 (-0.46, -0.21)	-0.57 (-0.76, -0.39)
jump height-1	0.38 $\pm$ 0.07	0.34 $\pm$ 0.08[‡]	0.33 $\pm$ 0.08[‡]	0.32 $\pm$ 0.08[‡]	0.30 $\pm$ 0.07[‡]	0.32 $\pm$ 0.08[‡]	0.33 $\pm$ 0.08[‡]	0.36 $\pm$ 0.08[‡]
Hedge's <i>g</i> ES	-----	0.52 (0.35, 0.70)	0.69 (0.47, 0.91)	0.83 (0.57, 1.10)	1.10 (0.76, 1.44)	0.77 (0.53, 1.02)	0.69 (0.47, 0.91)	0.27 (0.17, 0.38)
RSImod	0.59 $\pm$ 0.11 [‡]	0.51 $\pm$ 0.11[‡]	0.49 $\pm$ 0.10[‡]	0.47 $\pm$ 0.10[‡]	0.43 $\pm$ 0.11[‡]	0.46 $\pm$ 0.12[‡]	0.48 $\pm$ 0.11[‡]	0.51 $\pm$ 0.11[‡]
Hedge's <i>g</i> ES	-----	0.69 (0.47, 0.92)	0.84 (0.58, 1.11)	1.14 (0.79, 1.50)	1.39 (0.96, 1.82)	1.04 (0.71, 1.50)	0.98 (0.67, 1.28)	0.68 (0.46, 0.90)
CM Depth	0.28 $\pm$ 0.07	0.26 $\pm$ 0.07	0.26 $\pm$ 0.07	0.26 $\pm$ 0.07	0.26 $\pm$ 0.07	0.26 $\pm$ 0.08	0.27 $\pm$ 0.08	0.29 $\pm$ 0.07
Hedge's <i>g</i> ES	-----	0.21 (0.12, 0.30)	0.26 (0.16, 0.36)	0.30 (0.18, 0.41)	0.32 (0.20, 0.44)	0.23 (0.13, 0.32)	0.17 (0.08, 0.25)	-0.20 (-0.28, -0.22)
GCT	0.20 $\pm$ 0.02	0.21 $\pm$ 0.02	0.20 $\pm$ 0.02	0.21 $\pm$ 0.02	0.22 $\pm$ 0.02	0.21 $\pm$ 0.02	0.21 $\pm$ 0.03	0.21 $\pm$ 0.02
Hedge's <i>g</i> ES	-----	-0.35 (-0.47, -0.22)	-0.23 (-0.33, -0.14)	-0.34 (-0.46, -0.22)	-0.57 (-0.76, -0.38)	-0.46 (-0.61, -0.30)	-0.55 (-0.73, -0.37)	-0.40 (-0.54, -0.26)
jump height-2	0.33 $\pm$ 0.06	0.29 $\pm$ 0.06[‡]	0.26 $\pm$ 0.06[‡]	0.25 $\pm$ 0.06[‡]	0.22 $\pm$ 0.06[‡]	0.24 $\pm$ 0.07[‡]	0.26 $\pm$ 0.07[‡]	0.29 $\pm$ 0.05[‡]
Hedge's <i>g</i> ES	-----	0.72 (0.49, 0.95)	1.08 (0.74, 1.41)	1.34 (0.93, 1.76)	1.78 (1.24, 2.33)	1.27 (0.88, 1.66)	0.98 (0.68, 1.29)	0.68 (0.46, 0.89)
RSI	1.68 $\pm$ 0.39	1.41 $\pm$ 0.36[‡]	1.32 $\pm$ 0.36[‡]	1.22 $\pm$ 0.37[‡]	1.07 $\pm$ 0.31[‡]	1.17 $\pm$ 0.39[‡]	1.25 $\pm$ 0.41[‡]	1.43 $\pm$ 0.33[‡]
Hedge's <i>g</i> ES	-----	0.70 (0.48, 0.92)	0.91 (0.63, 1.20)	1.15 (0.80, 1.51)	1.69 (1.17, 2.20)	1.24 (0.88, 1.63)	0.97 (0.67, 1.27)	0.66 (0.45, 0.87)
Leg Stiffness	33.8 $\pm$ 9.05	31.5 $\pm$ 8.28	32.9 $\pm$ 9.99	32.2 $\pm$ 8.65	31.9 $\pm$ 9.07	32.1 $\pm$ 8.14	31.5 $\pm$ 9.16	31.6 $\pm$ 7.59
Hedge's <i>g</i> ES	-----	0.26 (0.15, 0.36)	0.09 (0.02, 0.16)	0.18 (0.09, 0.26)	0.20 (0.11, 0.29)	0.19 (0.10, 0.28)	0.24 (0.14, 0.34)	0.26 (0.16, 0.36)
Sprint Time	7.59 $\pm$ 0.44	7.92 $\pm$ 0.41[‡]	8.27 $\pm$ 0.50[‡]	8.49 $\pm$ 0.57[‡]	8.63 $\pm$ 0.66[‡]	-----	-----	-----
Hedge's <i>g</i> ES	-----	-0.75 (-0.99, -0.51)	-1.14 (-1.84, -0.97)	-1.72 (-2.25, -1.19)	-1.84 (-2.40, -1.27)	-----	-----	-----

Unit of measure for countermovement depth and jump height: meter; Unit of measure for TTTO, GCT and sprint time: second; Unit of measure for leg stiffness: kilo newton per meter.

jump height-1 = first jump height of the countermovement rebound jump; jump height-2 = second jump height of the countermovement rebound jump; CM Depth = countermovement depth; TTTO = time to take-off; RSImod = reactive strength index modified; GCT = ground contact time; RSI = reactive strength index; ES = effect size.

[†]Hedge's *g* effect sizes with 95% confident interval are reported relative to baseline.

[‡]Significantly different is reported relative to baseline ($p < 0.05$).

FIGURES

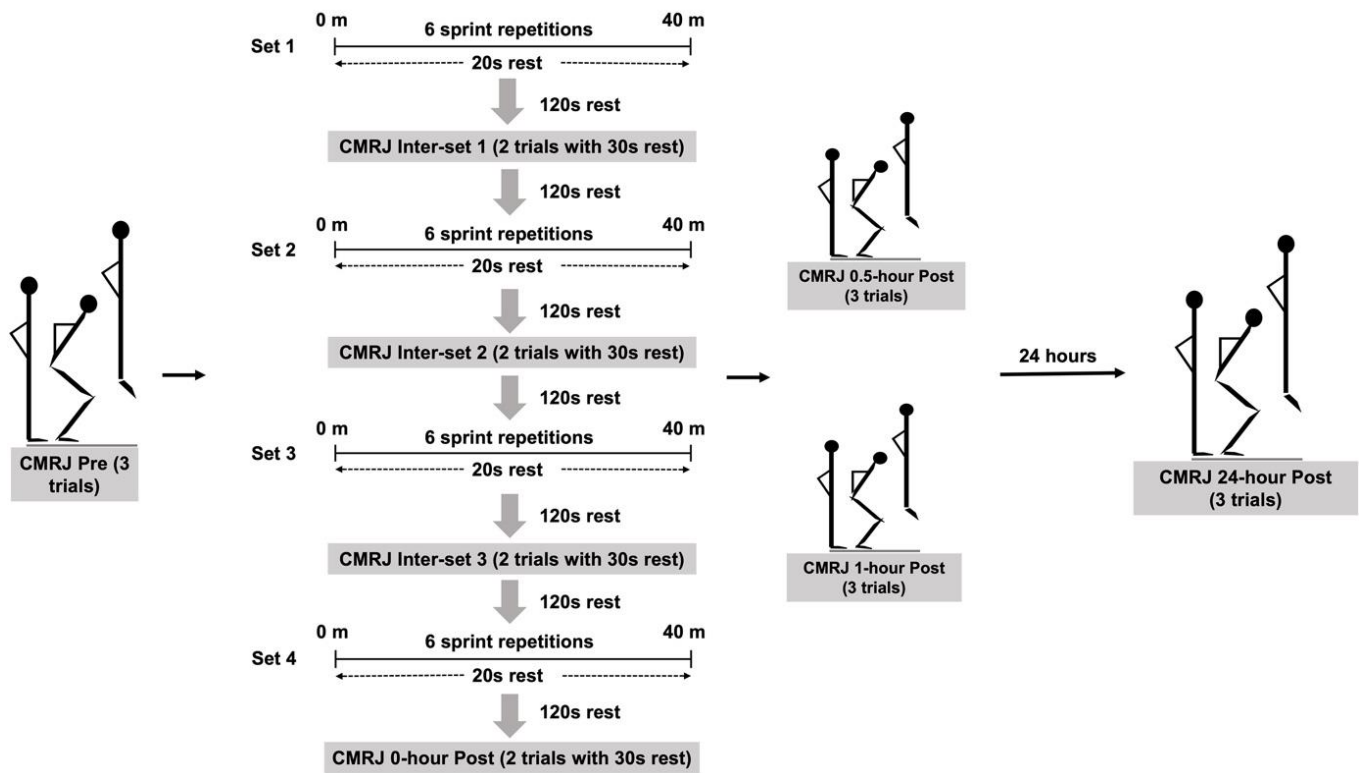


Figure 1. Schematic of study design. *Note:* CMRJ = countermovement rebound jump.

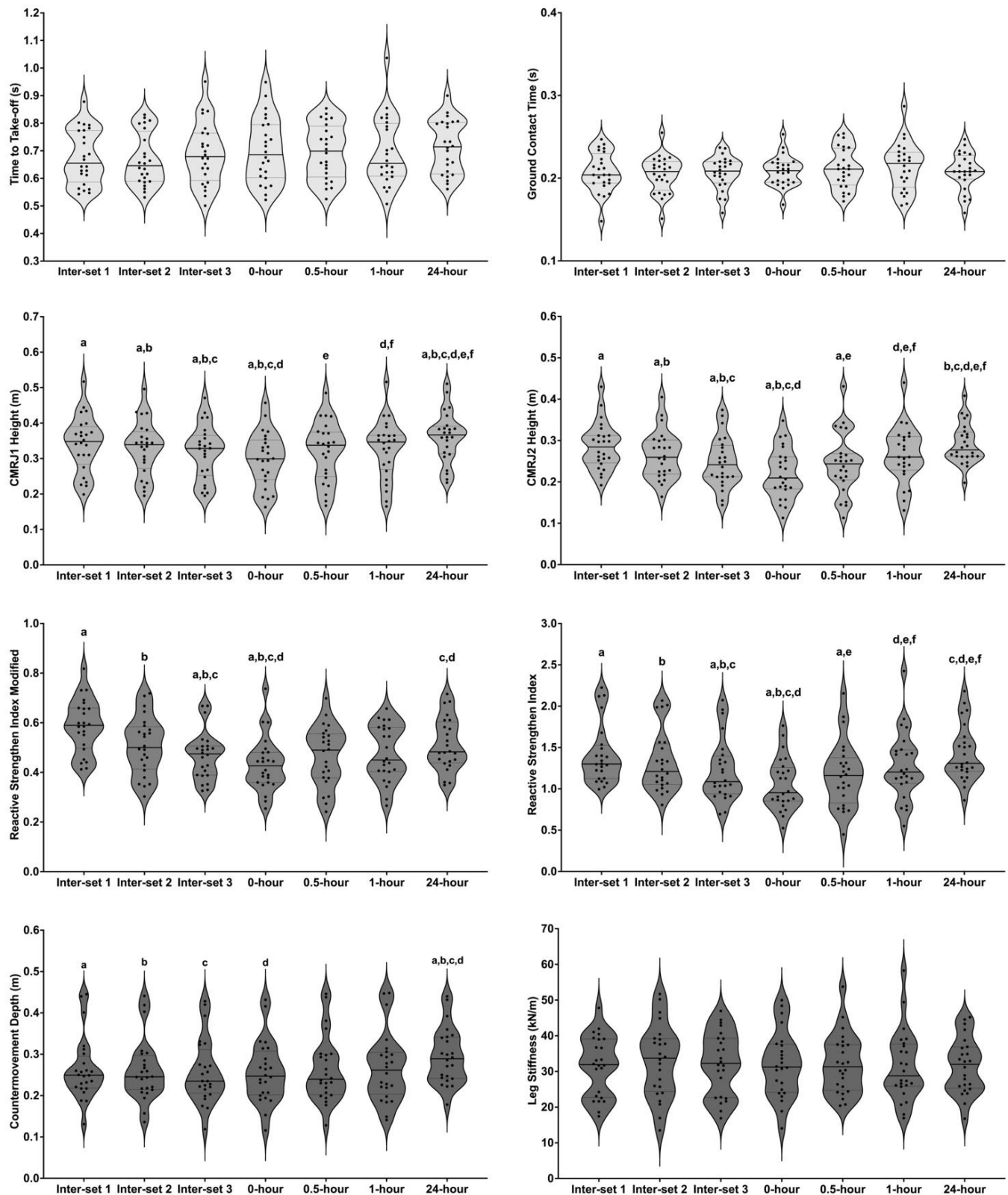


Figure 2. Mean countermovement rebound jump (CMRJ) metrics measured and compared across seven time points. Statistical significance for all comparisons were set at $p < 0.05$. *Note:* (a) indicates a significant difference to inter-set 1; (b) indicates a significant difference to inter-set 2; (c) indicates a significant difference to inter-set 3; (d) indicates a significant difference to 0-hours; (e) indicates a significant difference to 0.5-hours post intervention; (f) indicates a significant difference to 1-hour post intervention.

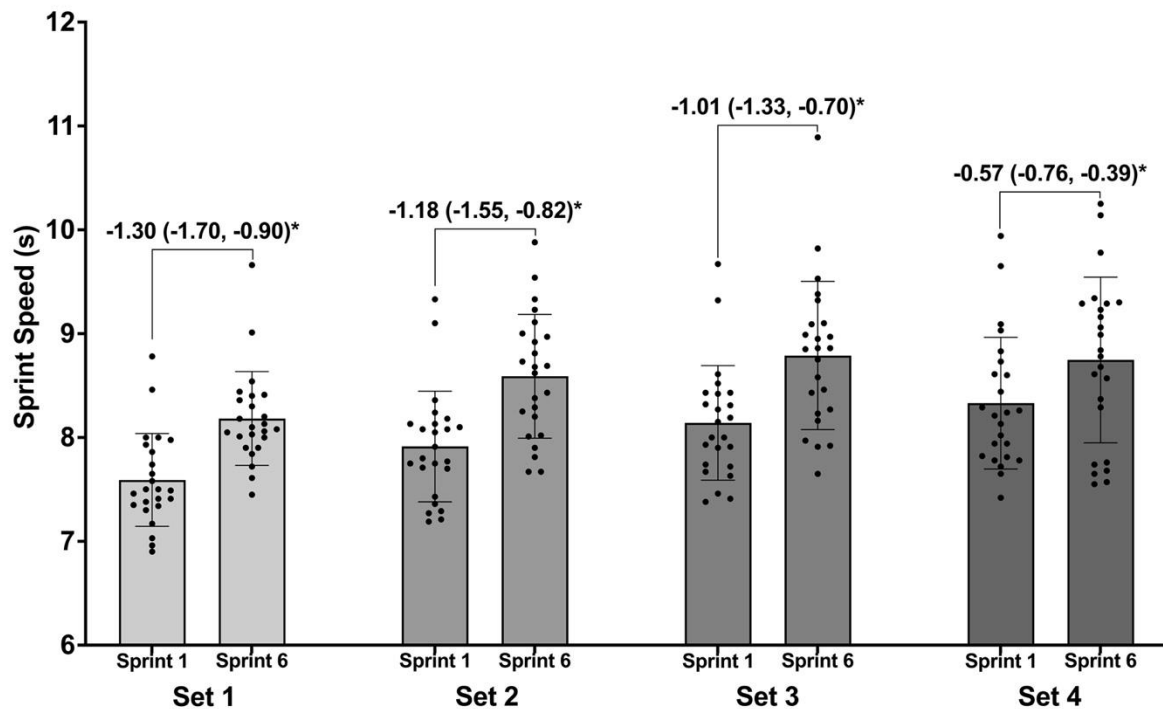


Figure 3. Sprint times (mean $\pm$ SDs [error bars]) for sprint repetition 1 and repetition 6 in all four sets of repeated sprints. *Note:* * Indicates a significant difference being evident between sprint 1 and all subsequent sprints in every set ($p < 0.05$), with Hedges' g ES data with 95% confidence intervals also shown.

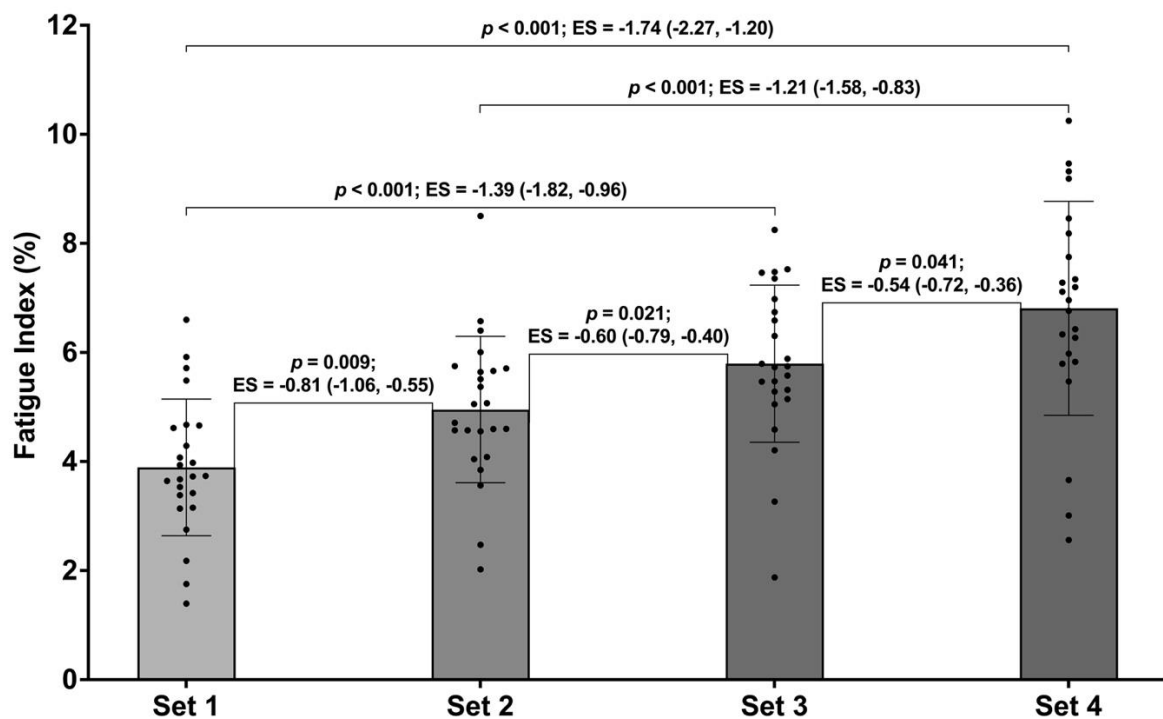


Figure 4. Fatigue index (%) and SDs (error bars) after each set of repeated sprints. Statistical significance was set at $p < 0.05$. *Note:* ES = effect size.