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ORIGINAL ARTICLE

Countermovement jump performance after metabolically, but not mechanically demanding exercise: limited sensitivity to prolonged low-frequency force depression

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Abstract

Rationale Previous studies indicate that countermovement jump (CMJ) parameters may reflect neuromuscular fatigue following exhaustive exercise. However, changes in CMJ performance in response to non-muscle damaging exercise, and its relation to prolonged low-frequency force depression (PLFFD) is yet unknown.

Purpose This study aimed to evaluate the relationship between PLFFD and CMJ test parameters following exhaustive cycling exercise to task failure.

Methods A sample of 11 recreationally active adults completed an incremental cycling protocol to task failure. CMJ performance, low-frequency (10 Hz) force, and maximal voluntary contraction (MVC) force output were assessed at baseline (pre-exercise), immediately after task failure (0 min), and at 8 min, 15 min, 60 min, 24 h, and 48 h post-task failure. PLFFD was assessed as the ratio of 10 Hz to MVC force.

Results Compared to baseline, PLFFD was larger from 0 min (7.4%) to 60-min (6.7%, $p < 0.002$). In contrast, no substantial changes in CMJ parameters were observed, except for a reduced concentric impulse (ConImp) lasting 8 min post-exercise.

Conclusion The results show that CMJ parameters remain unchanged following non-eccentrically loaded exhaustive exercise, while PLFFD is significantly higher for up to 60 min post-exercise. This raises questions about the utility of CMJ as a fatigue assessment tool in athletic populations. This suggests that CMJ testing may not effectively detect the presence of PLFFD following non-muscle damaging exercise and future research should explore alternative measures for monitoring neuromuscular fatigue in training contexts.

Keywords Countermovement jump · Low-frequency force depression · Neuromuscular fatigue · Exercise Training · Post-exercise recovery · Biomechanics · Skeletal muscle

Abbreviations

ANOVA	Analysis of variance
CMJ	Countermovement jump
ConDur	Concentric duration
ConImp	Concentric impulse
EC	Excitation–contraction
EccDur	Eccentric duration
EccImp	Eccentric impulse
ICC	Intraclass correlation coefficient
JH	Jump height
MRFD	Maximum rate of force development
NMF	Neuromuscular fatigue
PAR-Q+	Physical activity readiness questionnaire
PF	Peak force
PLFFD	Prolonged low-frequency force depression
PP	Peak power

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Introduction

The countermovement jump (CMJ) is a widely used tool for assessing neuromuscular fatigue in athletes due to its simplicity, ability to simulate athletic movement, and low physiologic strain (Petersen et al. 2007; Cormie et al. 2009; Gathercole et al. 2015b; Wiewelhove et al. 2015; Sole et al. 2018;

Lombard et al. 2021). CMJ performance is typically evaluated by computing output variables such as jump height, peak force, and peak power from force–time data during the CMJ Reductions in one or more of these metrics are assumed to suggest fatigue-related performance impairments (Gathercole et al. 2015a; Chavda et al. 2018). Consequently, monitoring changes to these computer variables has led to the broad adoption of regular CMJ testing across numerous sport contexts (Skurvydas and Zachovajevas 2000; Hori et al. 2009; Kamandulis et al. 2016; Souza et al. 2020; Alba-Jiménez et al. 2022). Additional variables, such as the duration of the eccentric and concentric phases, respectively, can be computed to provide insight into potential compensatory strategies when an athlete is apparently fatigued, but traditional metrics such as jump height or mechanical power output are unaltered (Cormie et al. 2009; Gathercole et al. 2015a; Kennedy and Drake 2017; Chavda et al. 2018).

However, most research linking CMJ performance to neuromuscular fatigue has focused on fatigue induced by stretch–shortening cycle exercises, which often involve eccentric loading and muscle damage during activities such as drop jumps and sprint intervals (Gathercole et al. 2015b; Knihs et al. 2021). This raises the question of whether CMJ can accurately assess neuromuscular fatigue in situations where muscle damage is minimal, such as after non-eccentric exercise or at time points when delayed onset muscle soreness, or serum creatine kinase (a potent marker of muscle damage) has not yet peaked.

Prolonged low-frequency force depression (PLFFD) is a form of neuromuscular fatigue characterized by long-lasting reductions in force production that can persist for hours or even days, and whose underlying mechanisms are not well understood. PLFFD has been hypothesized to result from either muscle fiber damage, excitation–contraction (EC) coupling failure, including reduced myofibrillar Ca^{2+} sensitivity or a combination of both, depending on the nature of the exertion (Jones 1996; Keeton and Binder-Macleod 2006). Richards et al. (2024) showed that the mechanisms of PLFFD are task dependent and differ between metabolically and mechanically demanding exercises. Investigating CMJ responses after metabolically, but not mechanically-demanding exercises could offer new insights into the relationship between prolonged fatigue and performance, potentially clarifying the appropriate use of CMJ performance as a potential monitoring tool to assess neuromuscular fatigue under various circumstances.

To date, no studies have examined whether commonly measured CMJ parameters are indicative of long-lasting fatigue caused by metabolically demanding, as opposed to mechanically demanding exercise. Therefore, the purpose of this study was to evaluate changes in CMJ performance in relation to PLFFD during recovery from metabolically demanding exercise. It was hypothesized that CMJ performance variables would not change appreciably whereas PLFFD would remain present well into the recovery period. That is, PLFFD would be significant minutes or hours into recovery whereas CMJ performance would not.

Methods

Participants

A cohort of nine recreationally active men (24.2 ± 2.5 yrs; 86.1 ± 12.2 kg) and two women (38.5 ± 20.5 yrs; 57.8 ± 8.1 kg) were recruited using convenience sampling ($n = 11$). The required sample size for our study was calculated using G*Power software version 3.1.9.6 (Faul et al. 2007) to conduct a within-factors repeated measures ANOVA. With a significance level (α) set at 0.05 and power ($1–\beta$) set at 0.8, we determined that a sample size of 7 participants would be necessary to detect a large effect size ($f = 0.4$) for changes in the dependent variables (PLFFD and CMJ metrics). However, Recruitment of a total of 11 participants was deemed appropriate based on previous research on this topic (Cormie et al. 2009; Gathercole et al. 2015a). Participants with a lower-limb injury restricting their ability to jump, an external pacemaker, or a history of cardiac arrhythmia were excluded from participation. Participants were required to complete a physical activity readiness questionnaire (PAR-Q+) prior to participation to ensure they were fit to exercise maximally (Warburton et al. 2011). Experimental protocols were explained to all participants and informed and written consent were obtained. The experimental protocol was approved by the Human Research Ethics Board at Mount Royal University (HREB ID#102499).

Procedure

Participants completed assessments of PLFFD and CMJ prior to and following an incremental cycling test to task failure. A total of eight paired assessments were completed over the course of three sessions (Fig. 1). On the first visit, assessments of both PLFFD and CMJ were completed at baseline and 0, 8, 15, 30, 60 min post-exercise. The time elapsed between task failure at the end of the incremental exercise and the first assessment of CMJ and PLFFD (i.e., time-point "0") was less than 30 s to mitigate any influence of potential rapid recovery on the measured parameters. Participants rested in a seated position between time points. Participants returned to the laboratory 24 and 48 h later to complete follow-up assessments of CMJ parameters and PLFFD. Follow-up assessments were completed within ± 2 h of the scheduled testing time. To mitigate the influence of any neuromuscular fatigue resulting from maximal jumping on PLFFD and maximal voluntary contractions, and vice

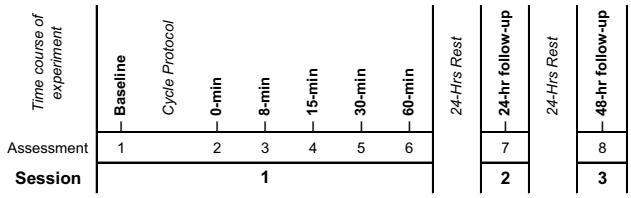

Fig. 1 Experimental timeline. Participants underwent baseline testing of prolonged low-frequency force depression (PLFFD) and countermovement jump performance prior to (herein referred to as 'baseline') a maximal, exhaustive cycling test, and again immediately following ('0-min') and at various times throughout the recovery period (8, 15, 30, 60 min, 24 and 48 h post-exercise). Data are presented as mean ± SD

versa, the order of assessments was randomized at each time point. Each assessment was performed immediately after the other (Fig. 2).

Prolonged low-frequency force depression (PLFFD)

PLFFD was measured from the force response evoked during low-frequency stimulation compared to the MVC force. Participants were seated comfortably on a bed with their legs hanging freely at a 90-degree angle (shank perpendicular to the thigh, and the shank perpendicular to the ground). Participants placed their hands across the shoulders and were encouraged to "sit up tall". The right quadriceps muscle was stimulated via two large surface electrode pads (9.25 × 4.5 cm) placed along the femoral nerve at the inguinal crease and patellar plateau. All measurements were performed on the right leg.

Single 500 µs nerve pulses were delivered from a constant voltage stimulator (GRASS-S88, Astro-Med, Mass, USA) to a stimulus isolation unit (SIU8T Auto-Med, RI, USA). Stimulus intensity was gradually increased from 0.5 mA until a maximal twitch response was achieved for each individual. This maximal twitch intensity was used to elicit low-frequency force responses. Evoked responses were recorded by a force transducer (Revere Transducers, Cal, USA) fixed to the participants ankle (Fig. 2).

During assessment of PLFFD, the quadriceps muscles were involuntarily activated at a low frequency by delivering a 500 ms train of square-wave pulses (10 Hz, 500 µs pulse width, similar to single pulse stimulation that determined maximal twitch intensity). Immediately following the 10 Hz stimulation, participants performed a MVC of the right quadriceps muscles (Fig. 3). Strong verbal encouragement was given to ensure maximal voluntary force production. The ratio of 10 Hz force to MVC force was calculated and a decrease in the ratio from baseline was interpreted as PLFFD. The MVC was used in favor of a higher frequency of stimulation (80–100 Hz) to minimize participant discomfort.

PLFFD was quantified as the ratio of maximal force output at 10 Hz muscle stimulation to that of MVC (F10:MVC), expressed as a percentage.

$$F10 : MVC = \left(\frac{F10(N)}{MVC(N)} \right) \times 100$$

Countermovement jump test

Prior to the baseline assessment, participants were allowed three submaximal (< 50% intensity) CMJ s to become familiarized with the movement. Participants were instructed to position their feet in-line with their shoulders and to place

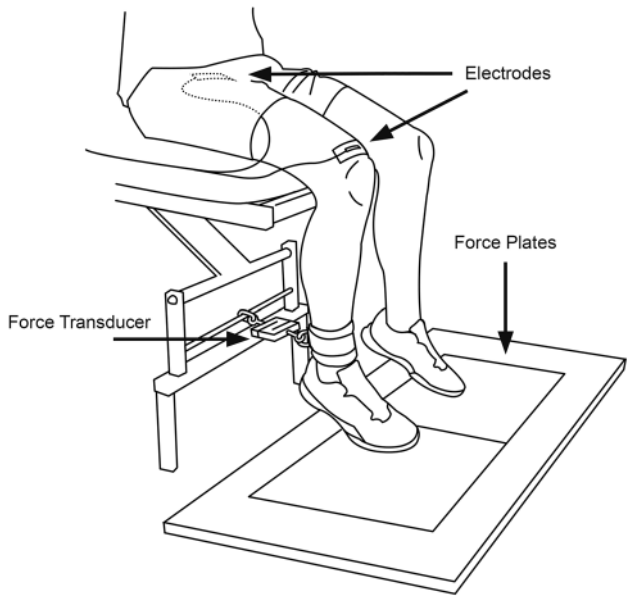

Fig. 2 Experimental setup. Jump testing was completed in the same space as LFFD to ensure rest periods were minimized while transitioning between assessments

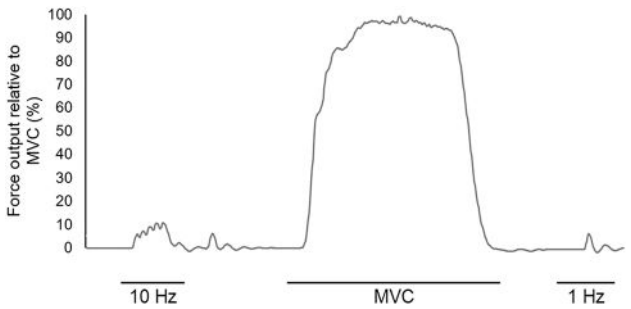

Fig. 3 Exemplar force tracing of low-frequency force production (10 Hz), during a maximal voluntary contraction (MVC) and in response to a twitch (1 Hz for 500 ms)

their hands on their hips. Following the verbal cue "3, 2, 1, jump", participants were instructed to jump as high and as fast as possible while landing on the force platform, with freedom to control the depth of their countermovement. Two maximal CMJs were performed during a single assessment, separated by a 30 s rest period. A 30 s rest period was selected to maximize recovery between CMJs, while minimizing the effect this period would have on the timing of subsequent assessments. Vertical ground reaction forces (F_z) were sampled at 1 kHz and obtained from a PS-2142 bilateral 2-axis force platform (PASCO, Cal, USA).

Jump parameters

Raw CMJ data were extracted from PASCO Capstone™ processing software and exported to Microsoft Excel® for further analysis. Force–time characteristics were obtained through custom processing as described elsewhere by Chavda et al. (2018). Body mass was recorded during quiet-standing for 3 s prior to each jump and removed from the total force–time curve during post-processing such that the measured F_z was expressed relative to body mass. A jump-start threshold was set according to a reduction in weight that exceeded 5 standard deviations from the force recorded during quiet standing. An exemplar force–time curve is shown in Fig. 4. Eight commonly reported CMJ parameters were selected for inclusion in our analysis: Jump height (JH), peak force (PF), peak power (PP), eccentric impulse (EccImp), concentric impulse (ConImp), eccentric contraction duration (EccDur), concentric contraction duration (ConDur), and maximum rate of force development (MRFD). All CMJ parameters included in our analysis are reported as a mean value taken between two CMJs at each timepoint to improve reliability (Claudino et al. 2017).

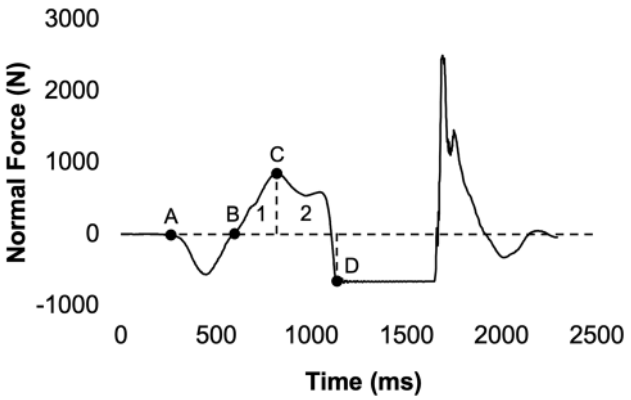

Fig. 4 Force–time curve of the countermovement jump. Points **A** to **B**: unweighted phase, points **B** to **C**: braking phase, points **C** to **D**: propulsion phase. Point C: Peak force. Area 1: eccentric impulse, area 2: concentric impulse. Horizontal dashed line shows normal force tared to the participant's body weight

Fatiguing protocol

An incremental cycle protocol to task failure was selected to maximally fatigue participants without the interference of muscle damage. Cycling was performed on an electronically braked cycle ergometer (Corival, Lode B.V., Groningen, NL). Seat height was adjusted according to participant leg length such that a slight knee flexion was present at the bottom of each pedal stroke. The incremental test began at 50 W at a self-selected cadence and increased 25 W every 2 min until volitional exhaustion. If a subject was unable to complete the final 2-min bout, 0.208 W (i.e., 25 W/120 s) was subtracted for every second remaining in the 2 min bout to calculate their maximum power output. To confirm all participants achieved near maximal exertion, strong verbal encouragement was given throughout the test and participant's heartrate was recorded at 1 Hz using a chest strap and watch (M400, Polar Electro, Kempele Finland) and expressed as a percentage of each participant's age-predicted maximum HR ($HR_{max,}$ 220-age) at the end of exercise. A mean HRmax of 96.5 ± 4.4% was achieved during cycling, with an average cycling duration of 13.5 ± 5.7 min across participants.

Statistical analysis

The power for the present study was calculated to be 98% to identify minimally ($\alpha = 0.05$, $\eta_p^2 = 0.14$, $n = 11$) significant within-participant differences to PLFFD and jump performance between time points. All statistical analyses were conducted using *JASP* (Version 0.16.2.0). Acceptable limits of missing data were set to 10% of the sample (Bennett 2001). There were five instances where data from one of two CMJs at a single timepoint were found to be erroneous. A mean of two jumps could not be taken in these instances. Instead, data from the only CMJ recorded were used for analysis. These erroneous data represented 2.8% of the total data.

To assess differences in PLFFD and CMJ variables over time, a one-way repeated measures analysis of variance (ANOVA) was performed. Our assumption of sphericity was evaluated using Mauchley's test. A Greenhouse–Geisser correction was applied to variables when sphericity was violated. Bonferroni post-hoc comparisons were used to assess significant differences between time points. The a priori level of statistical significance was set at $p < 0.05$ and effect sizes are presented as partial eta-squared (n_p^2) where appropriate. Data are presented as mean ± standard deviation (SD).

Results

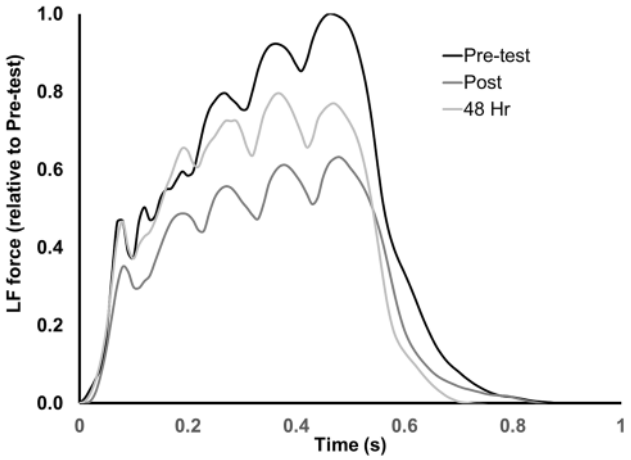

Fig. 5 Exemplar force response to 10-Hz stimulation prior to and following exhaustive exercise

An exemplar force response to 10-Hz stimulation prior to, and following exhaustive exercise is shown in Fig. 5. Compared to baseline, PLFFD was significantly greater (i.e., lower 10 Hz force production relative to MVC) at multiple timepoints: 0-min (mean difference (MD) compared to baseline = 7.4%, 95% CI 2.3–12.5, $p < 0.001$), 8 min (MD = 6.4%, 95% CI 1.4–11.5, $p = 0.003$), 15-min (MD = 8.8%, 95% CI 3.7–13.9, $p < 0.001$), 30 min (MD = 7.9%, 95% CI 2.8–13.0, $p < 0.001$), and 60-min (MD = 6.7%, 95% CI 1.6–11.8, $p = 0.002$), (Fig. 6).

ConImp also showed a s significant reduction over time following exercise ($F(7,70) = 5.171$, $p < 0.001$, $\eta^2 p = 0.341$ for main time effect). Bonferroni Post Hoc comparisons demonstrated a significant reduction in ConImp at 0-min (MD = 21.7 Ns, 95% CI 4.4–39.0, $p = 0.003$) and 8 min (MD = 18.3 Ns, 95% CI 1.0–35.6, $p = 0.028$) compared to baseline. No other CMJ parameters with significantly altered during the recovery period ($F < 5.816$, $p \geq 0.061$).

All CMJ output measures demonstrated acceptable intraday test–retest reliability between paired jumps at baseline

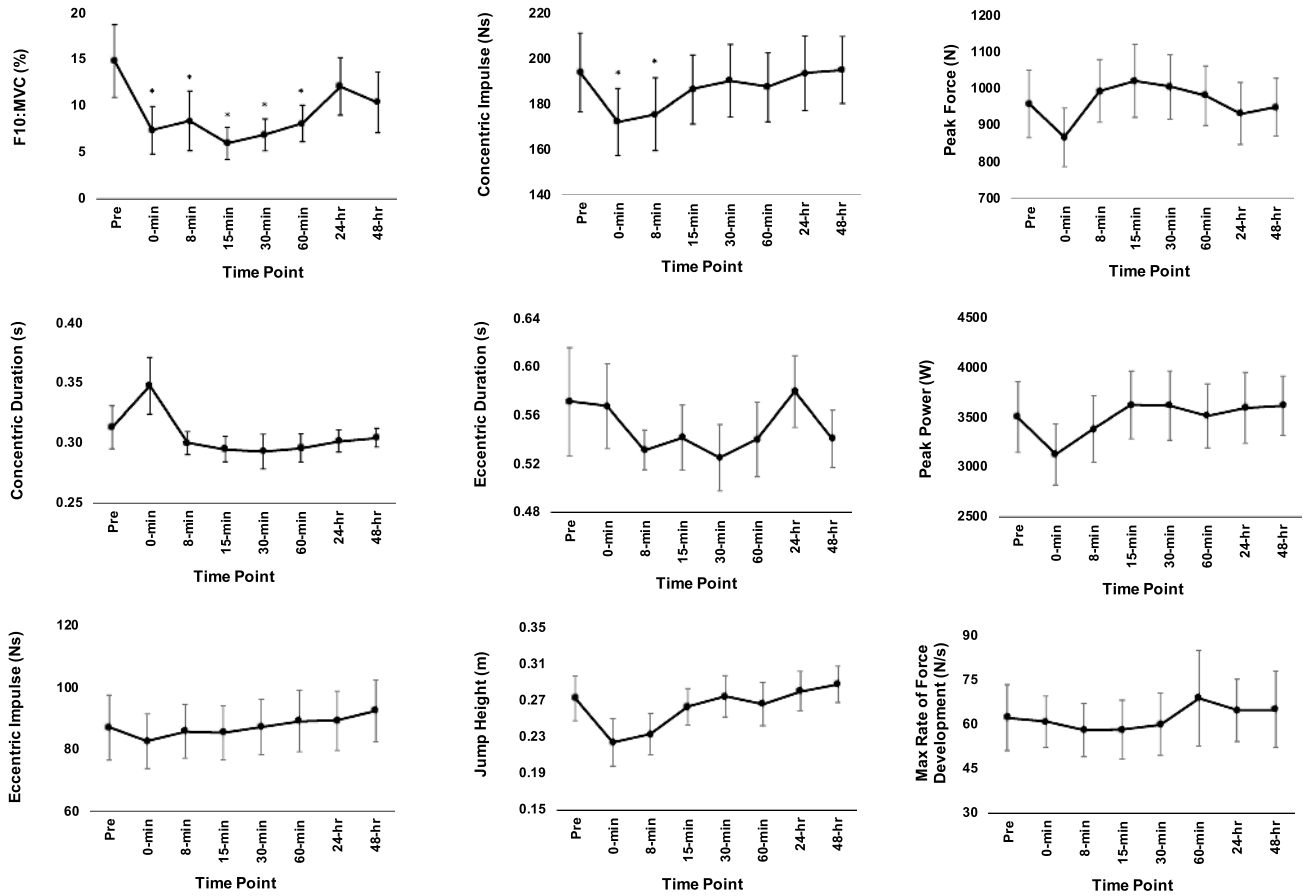

Fig. 6 Repeated measures analysis of variance for assessments of neuromuscular fatigue from prolonged low-frequency force production and countermovement jump assessmentF10:MVC was significantly reduced from baseline at 0-min, 8-min, 15-min, 30-min, and 60-min post exercise, whereas no CMJ parameters differed significantly from baseline. Data are presented as mean ± SD. *Significantly different from baseline (Pre)

(Table 1), with intraclass correlation coefficients (ICCs) ranging from excellent for EccImp, ConImp, PF, and PP (95% CI 0.935–0.997); good to excellent for JH and ConDur (95% CI 0.844–0.982); and moderate to excellent for EccDur and MRFD (95% CI 0.687–0.966). Interday test–retest reliability was excellent for EccImp, ConImp, PF, and PP (95% CI 0.951–0.995); good to excellent for JH and MRFD (95% CI 0.760–0.974); moderate to excellent for ConDur (95% CI 0.678–0.951); and poor to excellent for EccDur (0.355–0.901) for measures taken at baseline, and 24 and 48 h following exercise, confirming the consistency of these measures across trials. The force generated in response to twitch stimulation and the relative magnitude to MVC is presented in Table 2.

Discussion

The present study aimed to evaluate the utility of commonly used CMJ parameters following predominantly metabolically demanding but not mechanically demanding exercise. Our findings indicate that CMJ performance is insensitive to changes following exhaustive cycling exercise. In contrast, PLFFD was present for up to 60 min following this metabolically demanding exercise. With regards to CMJ performance, only concentric impulse showed significant reductions in the first 8 min of recovery but returned to baseline levels by 15 min. This suggests that if CMJ performance is to be used as a surrogate measurement to evaluate neuromuscular fatigue in athletes following metabolically demanding exercise, it may only be sensitive to detect performance changes for < 15 min following the exercise. Evaluating CMJ performance at points beyond this would expectedly yield erroneous interpretations of long-lasting, peripheral muscle fatigue in athletes. Our results further support the uncertainty around the utility of post-exercise fatigue monitoring and its usefulness in informing readiness to perform (Carling et al. 2018).

Our findings differ from previous reports showing significant CMJ performance impairments lasting from 30 min to 72 h following exercise modalities involving muscle-damaging eccentric contractions (Gathercole et al. 2015a, b; Wiewelhove et al. 2015; Kennedy and Drake 2017). Notably, prior studies observed CMJ impairments even before the expected presence of delayed-onset muscle soreness or peak creatine kinase levels (< 24 h). In contrast, our study found minimal CMJ changes following a non-muscle-damaging fatiguing task. These results suggest that CMJ performance may be more sensitive to injurious exercise, potentially driven by mechanisms unrelated to PLFFD, such as early inflammatory responses (Cerqueira et al. 2020; Stožer et al. 2020).

Table 1 Intraclass correlation coefficient (ICC) estimates and their 95% confidence intervals were calculated mean-ratings ($k = 2$)

	Intraday			Interday		
	ICC (3,k)	Lower CI	Upper CI	ICC (3,k)	Lower CI	Upper CI
EccImp	0.978	0.935	0.993	0.981	0.955	0.993
ConImp	0.990	0.971	0.997	0.986	0.967	0.995
JH	0.933	0.801	0.978	0.898	0.760	0.963
PF	0.984	0.952	0.995	0.979	0.951	0.992
PP	0.969	0.907	0.989	0.979	0.951	0.992
MRFD	0.900	0.702	0.966	0.929	0.833	0.974
EccDur	0.895	0.687	0.965	0.725	0.355	0.901
ConDur	0.948	0.844	0.982	0.863	0.678	0.951

Absolute agreement, 2-way mixed effects model was used to assess intraday test–retest reliability of the CMJ across two pre-exercise jumps and interday reliability of the CMJ across three visits (pre-exercise baseline, 24 h follow up, and 48 h follow-up)

Table 2 Changes in measured force parameters from baseline following metabolically, but not mechanically demanding exercise

Timepoint	MVC Force (N)	Mean Twitch Force (N)	Mean Twitch to MVC (%)	10 Hz Force (N)	PLFFD (10 Hz:MVC)
Baseline	399±160	28.4±20.7	9.0±9.0	47.2±22.0	14.8±12.5
0 min	371±159	14.1±13.0	5.0±5.7	20.3±15.8	7.4±8.2
8 min	377±121	15.5±15.6	5.3±7.1	24.1±22.2	8.3±10.4
15 min	376±110	12.6±11.9	4.0±5.1	19.3±12.3	5.9±5.5
30 min	402±128	14.5±12.2	4.4±4.7	23.4±13.6	6.8±5.5
60 min	392±129	16.4±16.0	5.2±6.5	27.3±14.4	8.1±6.3
24 hr	413±157	23.7±16.7	6.8±6.1	39.9±22.6	12.0±9.9
48 hr	403±143	26.2±24.0	7.9±9.1	33.7±23.3	10.3±10.5

It has been suggested that PLFFD is influenced by the type of fatiguing exercise and could be attributed to mechanisms such as muscle fiber damage, excitation–contraction (EC) coupling failure, or a combination of both (Jones 1996; Keeton and Binder-Macleod 2006). Our findings indicate that EC coupling failure, rather than muscle damage, is more likely the cause of PLFFD in this study. Impaired EC coupling—associated with reduced calcium (Ca^{2+}) release by the sarcoplasmic reticulum—is known to limit force production to a greater extent at low-frequency muscle activation. This could explain the significant increase in PLFFD following exercise, while high-frequency, maximal efforts such as MVCs and CMJ performance were minimally affected (Westerblad et al. 1993). In addition, we found higher PLFFD at points in time where delayed-onset muscle soreness and/or peaks in serum creatine kinase would not be expected (i.e., 24–48 h following muscle-damaging exercise) (Brancaccio et al. 2007; Baird et al. 2012).

This hypothesis is further supported by previous research demonstrating a biphasic recovery pattern in PLFFD wherein metabolic recovery occurs within 1 h post-exercise (phase 1), followed by a second, more gradual and persistent force recovery phase (Chin et al. 1997; Skurvydas et al. 2016). Kamandulis et al. (2019) similarly suggested that EC coupling failure plays a significant role in shorter term force depression, while more prolonged force depression may result from muscle damage and inflammation (Skurvydas et al. 2016; Kamandulis et al. 2019). The lack of substantial changes in CMJ performance in our study may indicate that CMJ testing is less sensitive to fatigue induced by EC coupling failure, particularly in the absence of muscle damage. For example, if one was to evaluate 'readiness to train' for the exemplar participant represented in Fig. 3, CMJ performance might suggest this athlete was 'ready' because CMJ computed variables were similar to baseline measures; however, it is clear that the ability to generate submaximal force at a given level of muscle stimulation is impaired — by ~ 30% even at 48 h post exercise.

Given the limited changes in CMJ parameters following metabolically demanding but not mechanically demanding exercise, further research is needed to clarify the exercise-dependent relationship between PLFFD and measures of neuromuscular fatigue. For example, pre-existing methods for evaluating muscle damage, such as reductions in MVC or range of motion, and increases in delayed onset muscle soreness, may offer more reliable indicators of muscle damage, potentially reducing the utility of CMJ testing when no additional value is demonstrated (Damas et al. 2016). Alternatively, assessment methods that comprehensively characterize fatigue, such as self-reported well-being, may offer a more pragmatic and sensitive option for athlete monitoring in these cases (Saw et al. 2016). In their systematic review of 56 articles, Saw et al (2016) found that subjective measures of athlete well-being were sensitive to acutely elevated and reduced training loads, whereas objective measures were generally unresponsive (Saw et al. 2016). Further, subjective measures also revealed impaired well-being in response to prolonged periods of intensive training. Given that PLFFD results from both acute and chronic training loads, relying on subjective evaluations, such as self-reported fatigue questionnaires, could offer a more efficient and sensitive alternative to performance-based measures like CMJ, with less involvement required from coaches and sport practitioners during training sessions (Urhausen and Kindermann 2002; Fowles 2006). Supporting this idea, Lombard et al. (2021) found that athletes' perceived levels of fatigue were significantly altered 24 and 48 h following a simulated soccer match, while CMJ parameters remained unchanged at all time points during the experiment (Lombard et al. 2021). However, the role of CMJ testing in relation to other measures of muscle damage and neuromuscular fatigue extends beyond the scope of this study and warrants further investigation to clarify its utility.

Limitations

One limitation of this study is that the sample consisted of recreationally active adults, while the primary audience for these findings includes researchers and practitioners in sport who might more frequently interact with highly-trained or elite athletes. The COVID-19 pandemic impacted our recruitment efforts, limiting our access to trained athletes. To better understand PLFFD in elite sport contexts, future research should build on this study by exploring recovery patterns in trained athletic populations using PLFFD and CMJ evaluations.

In addition, the use of the constant voltage stimulator in this study imposed a limitation on the amount of current we could apply during electrical stimulation. The hardware's power output restricts current to lower levels than typically used for quadriceps stimulation. This potentially limited the observable extent of PLFFD as not all motor units may have been activated during the measurement of PLFFD itself. While we were able to demonstrate a plateau in twitch force with increasing current, in many cases we were not able to offer supramaximal stimulation in the majority of our participants. Thus, while the current would have been maximal, at least prior to the metabolically demanding exercise, it would not have been supraximal in the majority of our participants, or even that it was maximal stimulation following exercise if skin impedance was increased following the exercise. Despite this limitation, we still observed a disproportionate loss of force at low frequency versus voluntary maximum muscle activation, suggesting that the underlying fatigue mechanisms were detectable even with the lower, submaximal current delivered transcutaneously. It is worth

noting that this specific technology has been employed in previous research to investigate neuromuscular function and fatigue, demonstrating its utility in similar contexts (Baptista et al. 2009; Kuenze et al. 2016). Nonetheless, using a constant current stimulator with a higher capacity, or recruiting participants with lower muscle volume (resulting in lower resistance), would allow for the delivery of stronger currents in future studies, potentially enhancing the magnitude of the observed force reduction and providing more detailed insights into changes in PLFFD and CMJ parameters following exhaustive exercise to task failure.

Conclusion

This study demonstrates that CMJ parameters remain largely unaffected following exhaustive cycling exercise, despite significant PLFFD observed for up to 60 min post-exercise. While previous studies have shown CMJ to be a reliable measure of neuromuscular fatigue following eccentric or stretch–shortening exercises, our results indicate that its utility in monitoring fatigue from non-muscle-damaging exercise may be limited.

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Author contributions Owen Lindsay: Conceptualization, methodology, formal analysis, visualization, writing – original draft, investigation, data curation, project administration. Jared Fletcher: Investigation, investigation, writing – review and editing, resources, supervision, funding acquisition.

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Data availability The data that support the findings of this study are available from the authors upon reasonable request.

Declarations

Conflict of interest The authors report there are no competing interests to declare.

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