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ORIGINAL INVESTIGATION

Alternative Countermovement-Jump Analysis to Quantify Acute Neuromuscular Fatigue

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Purpose: To examine the reliability and magnitude of change after fatiguing exercise in the countermovement-jump (CMJ) test and determine its suitability for the assessment of fatigue-induced changes in neuromuscular (NM) function. A secondary aim was to examine the usefulness of a set of alternative CMJ variables (CMJ-ALT) related to CMJ mechanics. ***Methods:*** Eleven male college-level team-sport athletes performed 6 CMJ trials on 6 occasions. A total of 22 variables, 16 typical (CMJ-TYP) and 6 CMJ-ALT, were examined. CMJ reproducibility (coefficient of variation; CV) was examined on participants' first 3 visits. The next 3 visits (at 0, 24, and 72 h postexercise) followed a fatiguing high-intensity intermittent-exercise running protocol. Meaningful differences in CMJ performance were examined through effect sizes (ES) and comparisons to interday CV. ***Results:*** Most CMJ variables exhibited intraday (n = 20) and interday (n = 21) CVs of <10%. ESs ranging from trivial to moderate were observed in 18 variables at 0 h (immediately postfatigue). Mean power, peak velocity, flight time, force at zero velocity, and area under the force–velocity trace showed changes greater than the CV in most individuals. At 24 h, most variables displayed trends toward a return to baseline. At 72 h, small increases were observed in time-related CMJ variables, with mean changes also greater than the CV. ***Conclusions:*** The CMJ test appears a suitable athlete-monitoring method for NM-fatigue detection. However, the current approach (ie, CMJ-TYP) may overlook a number of key fatigue-related changes, and so practitioners are advised to also adopt variables that reflect the NM strategy used.

Keywords: athlete monitoring, reliability, team sport, neuromuscular strategy

The countermovement-jump (CMJ) test is a practical athlete-monitoring tool used to examine neuromuscular (NM) status. Examining measurements from a CMJ test can provide insight into numerous components of NM function; however, the variables most sensitive to NM fatigue remain unclear.[1] CMJ analysis is generally limited to gross values (ie, peak, mean) relating to the concentric CMJ phase,[2] with often only jump height and peak power reported.[3] Given the complex nature of NM fatigue,[4] this approach may overlook a number of fatigue-related NM changes, or lack sensitivity and/or repeatability, contributing to the current state of uncertainty.

The high practicality and low physiological strain of a CMJ test permit repeated assessment of multiple individuals over a short period of time. Previous investigations have typically examined CMJ reliability using the information from 1 jump in each testing occasion.[3,5,6] However, averaging multiple jumps within a test session has been found to improve CMJ reliability.[7] A similar approach may therefore also improve the sensitivity of the CMJ test to NM fatigue.

Cormie et al[2,8] used temporal CMJ analysis to examine the mechanical changes related to NM training adaptations. A similar approach may permit the same for fatigue-related NM changes. These methods provide insight into eccentric-loading behaviors and the strategies used to perform a CMJ.[8] Traditional CMJ analysis typically overlooks eccentric CMJ performance; however, it is a fundamental component of stretch-shortening-cycle (SSC) movement and NM function.[9] Athletic performance consists of SSC movements,[10] with SSC fatigue related to a number of metabolic, mechanical, and/or neural factors.[9,11,12] Recovery after SSC fatigue is considered biphasic, with an immediate decrease in NM function that is recovered within 1 to 2 hours and then a secondary decrease at around 2 days that is recovered within 4 to 8 days.[11] A validated and sensitive monitoring tool should track such changes and provide valuable and immediate feedback to coaches and athletes.

Many investigations that have used the CMJ test to examine NM fatigue report only a few CMJ variables,[13–19] with a number also observing changes that appear to conflict with conventional thinking (ie, improved results in fatigued condition).[14,17,18] These curious findings, along with the biphasic SSC-recovery pattern, highlight the complexity of NM-fatigue assessment and suggest that a more thorough CMJ analysis may provide greater insight into fatigue-related NM changes.

The purpose of the current study was to determine the suitability of the CMJ test for the assessment of fatigue-induced changes in NM function. The assessment therefore began with a 3-day assessment of intraday and interday reliability followed by an analysis of the magnitude and consistency of change across individuals after a bout of fatiguing SSC exercise. A secondary aim was to examine the usefulness of alternative CMJ variables (CMJ-ALT), based on previous methods,[2,8] for postexercise fatigue detection and recovery.

Methods

Experimental Design

A 2-part experimental design was implemented to examine the suitability of the CMJ test for the detection of fatigue-induced declines in NM function. In part 1 we examined the intraday and interday reliability (days 1–5), while in part 2 we looked at the

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sensitivity to fatigue-induced changes in NM function (days 6–9; Figure 1). Participants visited the testing facility at the same time of day (±1.5 h) on 7 total occasions, featuring a familiarization, 3 separate reliability-testing days, a fatigue protocol, and then 2 days of postfatigue monitoring (Figure 1). Participants did not perform any additional exercise beyond the requirements of this investigation throughout the course of testing. The original methods design also included 20-m-sprint testing (3 trials) before the CMJ testing and then squat jump (6 trials) and drop jump (6 trials) testing during each test session. Only CMJ data are reported here.

Participants and Familiarization

Eleven male college-level team-sport athletes (mean ± SD 23.8 ± 3.9 y, 182 ± 6 cm, 80.3 ± 6.6 kg) participated in the study. Eight participants (23.0 ± 3.7 y, 184 ± 6 cm, 80.6 ± 6.2 kg) completed both reliability and fatigue-sensitivity portions of the study, whereas 3 completed just the reliability section. Ethical approval was obtained from the University of Victoria Human Ethics Review Board, with participants providing written informed consent and completing a Physical Activity Readiness Questionnaire and a familiarization session at least 7 days before study commencement. Participants adopted a high-carbohydrate diet throughout testing, consuming the same meal, at the same time, before every testing session. Familiarization consisted of a warm-up and then CMJ practice with an emphasis on the speed of jump, until demonstration of consistent CMJ technique (n = 10 ± 4 attempts). Consistency was determined by visual inspection and an assessment of peak and minimum displacement and velocity and peak power, ensuring that values were within 10% of each other over 4 consecutive jumps.

CMJ-Testing Session

Participants performed a 20-minute dynamic warm-up consisting of light jogging (~10 min), dynamic stretching, and 10- and 20-m sprints (5 each) of progressive speed completed within 5 minutes. Three minutes after sprint testing, participants performed 10 practice CMJ trials of increasing intensity, with session testing beginning 3 minutes after.

Subjects performed 6 CMJ trials with 1.5 minutes rest between. Trials were sampled at 200 Hz using the Ballistic Measurement System and software (BMS; Fitness Technology, Adelaide, Australia, Version 2012.3.7), consisting of a force plate (400 series, Fitness Technology, Adelaide, Australia) and position transducer (Celesco, PT5A-0150-V62-UP-1K-M6, Chatsworth, CA, USA). A ceiling-mounted position transducer was suspended directly above the force plate and attached to the center of a wooden dowel, which was placed on the participant's back similar to a back squat. Participants were instructed to limit dowel movement, and the position transducer was zeroed to participant height before every jump. Data were collected immediately after zeroing until the jump was completed.

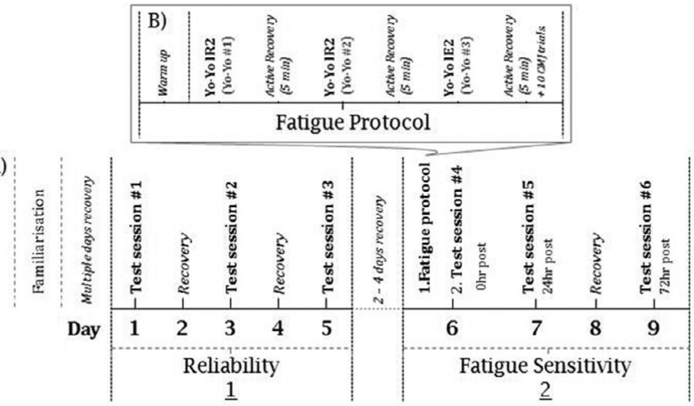


Figure 1 — (A) Schematic representation of the study timeline including familiarization, reliability, and fatigue-sensitivity sections. (B) The fatigue protocol.

Fatiguing Protocol

A 3-stage Yo-Yo fatiguing protocol (Figure 1) was performed on an outdoor concrete track to elicit a neuromuscular load similar to team-sport activities (Yo-Yo intermittent recovery level 2 [Yo-Yo IR 2] and Yo-Yo intermittent endurance level 2 [Yo-Yo IE 2] tests[20]). Briefly, the Yo-Yo IR 2 was performed twice consecutively and involved repeated 20-m shuttle runs performed at increasing velocities (10-s recoveries). The Yo-Yo IE 2, performed once, involved 20-m shuttle runs at slower velocities (5-s recoveries). Between Yo-Yo tests participants performed 5 minutes of active recovery with water provided ad libitum. After the fatigue protocol, participants performed 5 minutes of active recovery, followed by 20-m-sprint testing (3 trials) and then 10 practice CMJ trials before beginning final CMJ testing.

Variables

BMS software calculated typically derived CMJ variables (CMJ-TYP), with time-based variables using a jump-start threshold based on a >5% decrease in body mass. CMJ-ALT variables were calculated by extraction of raw CMJ data from the BMS software and then analysis through custom-designed software. All CMJ variables are described in Table 1. Force and power (mean and peak) values were converted to values relative to body mass. Force at zero velocity and area under the force–velocity trace were calculated using the force–velocity trace (Figure 2[A]), with other CMJ-ALT variables relating to the power–time trace (Figure 2[B]).

To prevent distortion of power–time-trace-derived CMJ-ALT variables, an alternative start time was determined (Figure 3[A]). The thresholds used in the alternative-start-time detection were determined through trial and error and developed to standardize and ensure that the CMJ countermovement had begun, while also minimizing the amount of removed data. To enable computation of mean force–velocity and power–time traces, the custom software modified every CMJ trial to a set number of 200 data points. Mean power–time traces were calculated through reintegration of time by calculating the mean start and end jump time, dividing this by 200 (to determine the time interval between consecutive data points), and then offsetting the start time to zero.

Statistical Analysis

The 4 most consistent CMJs from the 6 collected were used for analysis (Figure 3[B]). Selection was individualized and based on the CMJ-ALT variable mean eccentric and concentric power over time (MEccConP). This variable reflects both the total CMJ duration and the mean power produced both eccentrically and concentrically throughout the jump, and so we therefore determined it as representative of the entire jump performance. The 4 most consistent jumps were identified by subtracting the MEccConP for each individual CMJ by the mean MEccConP of the 6 trials and determining the 4 trials with the smallest difference.

Table 1 Description of Typical (TYP) and Alternative (ALT) Countermovement-Jump (CMJ) Variables

Variable	Abbreviation	Description
CMJ-TYP variables		
peak power	PP	Greatest power achieved during the jump.
mean power	MP	Mean power generated during the concentric phase of the jump.
maximum rate of power development	mRPD	Largest power increase during a 30-ms epoch.
time to peak power	TTPP	Time from jump initiation to peak power.
peak force	PF	Greatest force achieved during the jump.
mean force	MF	Mean force generated during the concentric phase of the jump.
maximum rate of force development	mRFD	Largest force increase during a 30-ms epoch.
time to peak force	TTPF	Time from jump initiation to peak force.
total impulse	TI	Force exerted concentrically multiplied by the time taken concentrically.
relative net impulse	RNI	Total impulse divided by participant's body mass.
peak velocity	PV	Greatest velocity achieved during the jump.
minimum velocity	MinV	Lowest jump velocity. Occurs during the eccentric CMJ phase.
velocity at peak power	V@PP	The velocity recorded at the time point where peak power occurs.
flight time	FT	Time spent in the air from jump take-off to landing.
flight time:contraction time	FT:CT	The ratio of flight time to contraction time. Contraction time is the duration from jump initiation to take-off.
jump height	JH	The maximum jump height achieved, calculated using peak velocity.
CMJ-ALT variables		
force at zero velocity	F@0V	The force exerted at the end of the countermovement where the jump transitions from eccentric to concentric movement (ie, velocity is at zero).
area under the force–velocity trace	FV-AUC	The area under the force–velocity trace where eccentric movement is performed (ie, the area under the left side of the trace).
eccentric duration	EccDur	Time required to perform the eccentric CMJ phase.
concentric duration	ConDur	Time required to perform the concentric CMJ phase.
total duration	TotDur	Time required to perform the entire CMJ (ie, both eccentric and concentric phases).
mean eccentric and concentric power over time	MEccConP	The power produced during both eccentric (converted to absolute values) and concentric CMJ phases, divided by the time taken (in ms) to perform the jump (ie, total duration).

The coefficient of variation (CV) was calculated using raw data. Other analyses were performed using log-transformed data, with back transformation after statistical analysis. To determine where differences had occurred, the magnitude of change was examined through effect-size calculation[21] with appropriate inferences.[22] For the fatigue analyses and preexercise time point, the results of day 3 were used and referred to as baseline. Interindividual variability in fatigue response was examined by calculating the mean individual and 90% confidence limits (CL) for the percent change between testing sessions. Comparison of the mean individual change with the interday CV was used to investigate the likelihood of detecting a fatigue-induced change.

Results

Reliability

Excluding maximum rate of force development, CMJ-TYP and CMJ-ALT variables exhibited similar intraday and interday CVs (Table 2). Comparisons of intraday reliability between testing days 1, 2, and 3 revealed trivial effect sizes, indicating an absence of systematic changes in CMJ reproducibility.

Comparisons of CMJ performance revealed 1 change of small magnitude between testing days 1 and 3 for minimum velocity (day 1, –1.80 ± 0.25; day 3, –1.84 ± 0.32), whereas other comparisons were trivial. Therefore, generally, CMJ performance did not appear to systematically change over the course of reliability testing.

Fatigue Sensitivity

Distance covered during the fatigue protocol was 8613 ± 1249 m. Mean force–velocity and power–time traces, respectively, for baseline and 0, 24, and 72 hours postexercise are presented in Figure 2[A] and [B]. Force at zero velocity shows marked differences between time points, with the highest value at baseline, the lowest at 0 hours, and 24 and 72 hours in between (Table 3). The power–time trace highlights the differences in peak power (PP) and jump duration between time points, with 0 and 24 hours showing reductions in PP and increases in duration (Table 3). At 72 hours, PP appeared to have returned to baseline, but jump duration was still extended.

At 0 hours, 14 CMJ-TYP and 4 CMJ-ALT variables displayed small to moderate changes compared with baseline (Table 3). At 24 hours, only MEccConP displayed a small change, with other differences all trivial. Nine CMJ-TYP and 3 CMJ-ALT variables

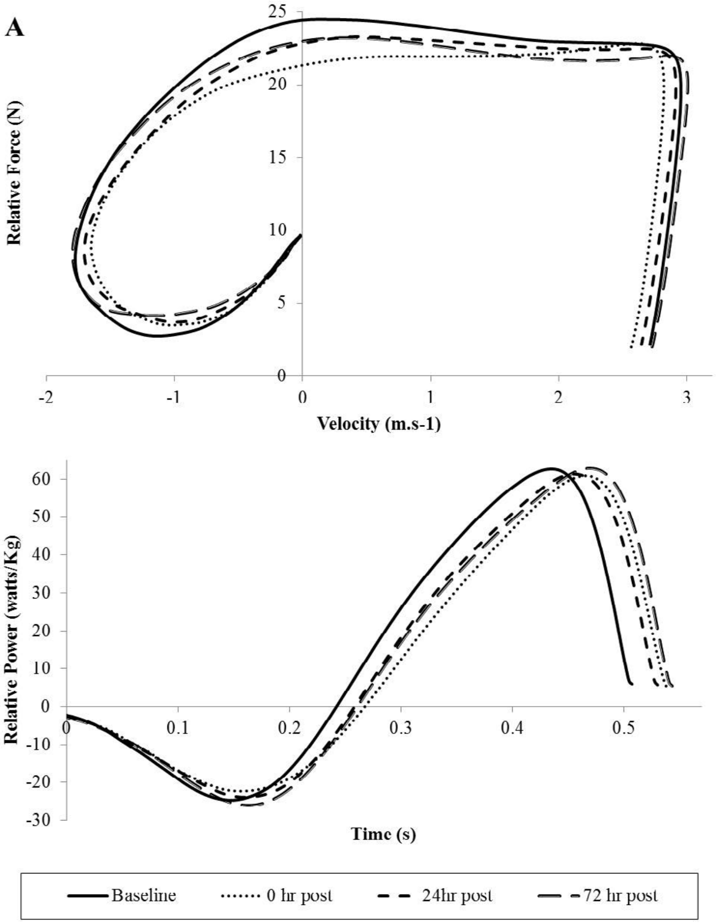


Figure 2 — (A) Force–velocity and (B) power–time trace at baseline and 0, 24, and 72 hours postexercise (n = 8; 16 CMJ trials from each participant).

displayed small changes with baseline at 72 hours (Table 3). Compared with baseline, 2 variables displayed improved values (total impulse and minimum velocity), whereas 10 variables displayed changes indicative of diminished neuromuscular function.

The mean percent change and 90% CLs at 0, 24, and 72 hours postexercise compared with baseline for select variables are presented in Figure 4, highlighting the between-participants variability in response, as well as the percent change after fatiguing exercise compared with baseline interday CV.

At 0 hours compared with baseline, 5 variables displayed mean changes and CLs greater than interday variability, while 7 other variables displayed mean changes but not CLs that were greater than interday variability. At 24 hours, flight time (FT) was the only variable to display a mean change greater than interday CV. In contrast, at 72 hours, 6 variables displayed mean changes greater than interday CV.

Discussion

The purpose of this study was to examine the reliability and sensitivity of the CMJ test to detect fatigue-induced changes in NM function. Using an intensive 3-day baseline repeatability protocol, results revealed that most CMJ test variables demonstrate high intraday and interday reliability and that changes in NM function after fatiguing exercise can be sensitively detected, with recovery of some variables taking longer than 72 hours. These findings suggest that CMJ testing could be a suitable, noninvasive method for use in athlete NM-fatigue monitoring.

Reliability

To our knowledge, this is the first study to have undertaken 3 consecutive days of controlled baseline testing on a multitude of CMJ parameters to assess reliability, with previous studies using only 1 or 2 days.[3,5,7,23,24] Attempts were made to enhance CMJ reproducibility by averaging the most similar jumps within each session in terms of power output and jump duration. This appears the first time that such an approach has been adopted with CMJ testing, and, despite the relatively small sample (N = 12), this novel approach provides insight into the practical value of such a CMJ data-manipulation processes.

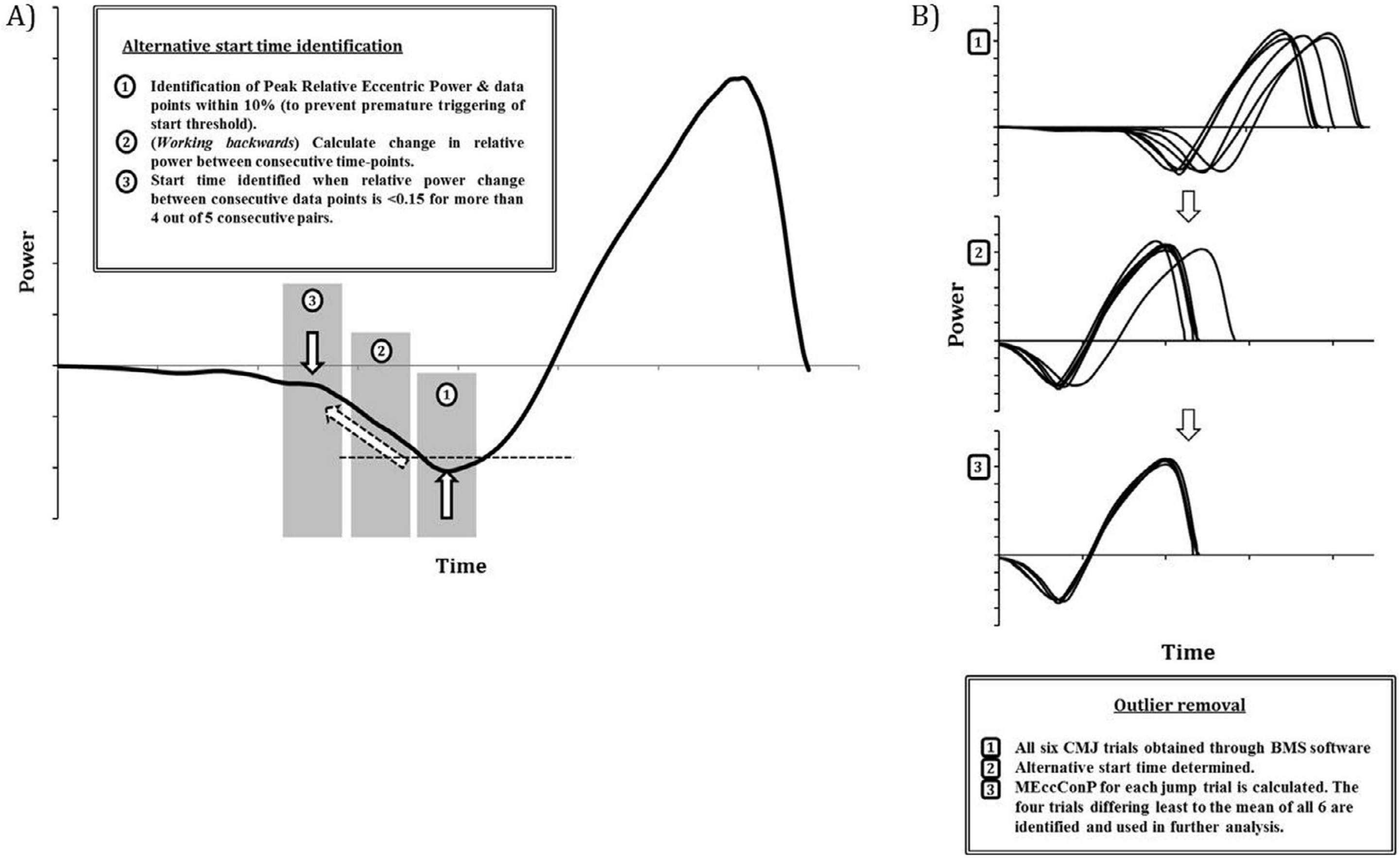
Intraday and interday CVs of CMJ variables ranged from very low to quite high (1.1–16.2%; Table 2). Previous studies have adopted a CV of <10% as indicative of a reliable test measure,[3,5,7,14,23] so, according to this criterion, most of the CMJ variables examined here can be considered reliable. Furthermore, out of the 22 CMJ variables assessed, 16 intraday and 11 interday exhibited CVs of <5%, suggesting that the CMJ test can produce highly consistent results. Our methods thus appeared to enhance CMJ-performance repeatability in college athletes. Therefore, although it is generally associated with superior performance reproducibility,[25] we hypothesize that CMJ repeatability in elite athletes may also benefit from this approach.

Notably, the variables associated with an interday CV >5% are related to the eccentric phase of the jump and time (Table 2). Other investigations report similar findings for time-related variables.[3,5,7,16,23,24] In the current study, participants were instructed to jump as high as possible, so power generation was emphasized. Variables such as PP, FT, and jump height (CV < 5%) could therefore be considered representative of the CMJ "outcome" or "output." In contrast, time- and eccentric-function-related variables (CV > 5%) relate to the movement preceding or producing these outputs and have been used previously to examine CMJ mechanics[2,8] and so may reflect the NM strategy of the jump. CMJ-movement strategy may therefore be more variable than CMJ output. It is interesting that skilled performers are thought to exhibit greater movement variability to achieve consistent performance outcomes.[26] The greater variability in NM strategy may therefore be a direct consequence of a propensity to maintain output, so examination of movement behavior may provide key insight into fatigue-induced NM changes.

Fatigue Sensitivity

The mean distance covered by participants during the fatiguing protocol was less than in elite soccer matches (10,950 ± 1044 km[27] and 10,994 ± 396.4 km[28]) but more than in elite Rugby League matches (5573 ± 1128 km[29]). The protocol therefore likely elicited a level of NM load and fatigue typically experienced by the subelite participants.

Immediately postfatigue (0 h) most CMJ variables demonstrated diminished function (Table 3). As previous investigations tend to report fewer CMJ variables,[13,15–18] it is difficult to ascertain whether such widespread fatigue-induced changes are typical. However, a "surprising" lack of change in CMJ variables was reported after an Australian Rules Football match, even though decreased MP, mean force, FT, and ratio of flight time to contraction time (FT:CT) and



Alternative start time identification

① Identification of Peak Relative Eccentric Power & data points within 10% (to prevent premature triggering of start threshold).
② (*Working backwards*) Calculate change in relative power between consecutive time-points.
③ Start time identified when relative power change between consecutive data points is <0.15 for more than 4 out of 5 consecutive pairs.

Outlier removal

1 All six CMJ trials obtained through BMS software
2 Alternative start time determined.
3 MEccConP for each jump trial is calculated. The four trials differing least to the mean of all 6 are identified and used in further analysis.

Figure 3 — Description of (A) alternative start time and (B) outlier-removal techniques.

increased PP were observed.[14] In spite of a significantly decreased peak force, increased PP and jump height were also reported after a fatiguing intermittent-running protocol.[17] Other researchers have also observed conflicting changes.[13,18]

Most variables drifted toward a return to baseline levels at 24 hours, with only MEccConP still displaying a small decrease. Fewer studies appear to have examined fatigue-induced changes in CMJ performance 24 hours postexercise. Rugby League matches decreased maximum rate of force development and PP,[16] as well as FT,[30] at 24 hours, while an Australian Rules Football match was associated with diminished PP, MP, mean force, and FT:CT.[14] Note that differences with baseline were greater at 24 hours after the Australian Rules Football match than at 0 hours, suggesting that NM function was more diminished than immediately postmatch.

Conversely, at 72 hours, a host of variables exhibited divergent responses with baseline, implying contrasting effects on recovery and, possibly, performance capacity. While CMJ output variables (ie, PP, FT, peak force) did not differ from baseline, minimum velocity and total impulse were enhanced, suggesting improved NM function, but time- and rate-related variables revealed that the CMJ took longer to perform (Table 3 and Figure 4). Therefore, although some variables demonstrated improvements, participants took longer to produce the same output and so could still be considered fatigued. We did not test after this time point and so are unable to determine precisely when baseline NM function was restored; however, recovery of FT after a Rugby League match has been reported to take 4 days,[13] while changes in FT, MP, mean force, and FT:CT after an Australian Rules Football match were recovered by 72 hours.[14] Recovery from fatiguing high-intensity intermittent exercise therefore appears to require at least 72 hours.

Also apparent in our results is the considerable between-individuals variability in response to the fatiguing protocol (Figure 4). For example, clearly detectable changes in most individuals were only evident at 0 hours and only for a select few variables. This appears to be the first time that attention has been paid to this feature of NM recovery, particularly in regard to CMJ testing; however, these results suggest that different individuals exhibit marked differences in recovery profile, thus supporting the use of individualized monitoring, as well as recovery, strategies. These CMJ monitoring strategies should include a battery of CMJ variables reflecting the CMJ output and movement strategy, as well as individualized interday CVs and fatigue-detection thresholds.

Altered Movement Strategy in Response to SSC Fatigue

Our results show an immediate decrease in CMJ performance and a trend toward recovery at 24 hours, followed by another decrease at 72 hours, thereby mirroring the recovery time course of SSC fatigue as shown previously.[9,11] SSC fatigue immediately decreases NM function through metabolic disturbances, impaired excitation–contraction coupling, and a stretch-reflex sensitivity-related

Table 2 Mean Coefficient of Variation (CV) ± SD for Days 1, 2 and 3 and the Mean ± SD for the Intraday and Interday CVs (N = 11; 12 CMJs per Participant)

Variable	Intraday CV	Interday CV
CMJ-TYP variables		
PP (W/kg)	2.3 ± 1.6	2.7 ± 1.7
MP (W/kg)	3.0 ± 1.9	2.8 ± 1.0
mRPD (W/s)	4.6 ± 1.7	7.3 ± 3.7
TTPP (s)	4.1 ± 1.7	5.4 ± 3.4
PF (N/kg)	2.8 ± 1.6	4.3 ± 2.3
MF (N/kg)	2.2 ± 1.1	3.1 ± 1.9
mRFD (N/s)	16.0 ± 8.6	16.2 ± 7.8
TTPF (s)	6.8 ± 5.5	7.7 ± 4.0
TI (Ns)	2.2 ± 1.1	2.7 ± 1.5
RNI (Ns/kg)	3.1 ± 1.4	1.6 ± 0.9
PV (m/s)	2.7 ± 1.8	2.5 ± 1.2
MinV (m/s)	4.7 ± 2.7	5.9 ± 3.3
V@PP (m/s)	2.9 ± 2.0	2.7 ± 1.7
FT (s)	1.7 ± 0.8	1.1 ± 0.4
FT:CT	4.0 ± 1.5	5.2 ± 3.2
JH (m)	5.3 ± 3.6	4.9 ± 2.4
CMJ-ALT variables		
F@0V (N)	3.9 ± 2.3	4.4 ± 2.2
FV-AUC (N/ms^2)	10.6 ± 6.0	7.4 ± 3.7
EccDur (s)	6.2 ± 3.2	8.0 ± 3.7
ConDur (s)	3.6 ± 2.0	5.1 ± 3.4
TotDur (s)	4.0 ± 2.0	6.1 ± 3.3
MEccConP ($W \cdot kg^{-1} \cdot s^{-1}$)	6.3 ± 3.2	7.9 ± 3.5

Abbreviations: CMJ, countermovement jump; TYP, typical; ALT, alternative; PP, peak power; MP, mean power; mRPD, maximum rate of power development; TTPP, time to peak power; PF, peak force; MF, mean force; mRFD, maximum rate of force development; TTPF, time to peak force; TI, total impulse; RNI, relative net impulse; PV, peak velocity; MinV, minimum velocity; V@PP, velocity at peak power; FT, flight time; FT:CT, ratio of flight time to contraction time; JH, jump height; F@0V, force at zero velocity; FV-AUC, area under the force–velocity trace; EccDur, eccentric duration; ConDur, concentric duration; TotDur, total duration; MEccConP, mean eccentric and concentric power over time.

reduction in muscle stiffness.[9,12] The subsequent quick recovery relates to restoration of metabolic factors, although low-frequency fatigue results if contractile failure has occurred.[12] Mechanisms responsible for the changes subsequent to these are less clear, with many neural and structural processes speculated to be involved.[9] Decreased reflex sensitivity is one process that is thought to protect fatigued muscle fibers from further damage.[12] This mechanism primarily affects eccentric function and so may have contributed to the increased eccentric duration and time-related variables at 72 hours. Conversely, the small improvement in minimum velocity at the same time point suggests enhanced eccentric-velocity production, possibly serving to limit concentric-performance decrement during the secondary recovery phase.

As suggested previously, changes in time-related variables may reveal a shift in NM strategy of a CMJ, so the increased time requirement at 72 hours could indicate that an alternative movement strategy was used. Previous studies have not directly reported time-related variables; however, a –7.8% change in FT:CT was reported alongside a –0.8% change in FT 24 hours after an Australian Rules Football match.[14] Increased contact time therefore appeared the primary factor in the decreased FT:CT. Strikingly similar results were observed here at 72 hours, with a –0.7% change in FT and a –7.7% change in FT:CT observed along with a 7.6% increase in total duration.

The effect of fatigue on CMJ strategy has been examined using electromyography.[31] Although CMJ strategy was unchanged immediately after fatiguing exercise, those authors suggested that more time may be required to reoptimize neural strategies and alter CMJ technique. The 72-hour time point in the current study may therefore have provided sufficient time for an alternative strategy to develop. Skilled performers are considered capable of adjusting strategy to avert decreased task output.[4] However, different NM strategies may lead to decrements in other performance factors. For example, during an Australian Rules Football match NM fatigue has been found to alter how high-speed running was performed (eg, fewer accelerations/decelerations) but not the volume. This decreased movement economy was reflected in coaches' ratings of poor performance.[15,19] The maintenance of CMJ output alongside increased jump duration in the current study may demonstrate similar changes in movement economy.

Alternative Analysis Methodology

Rather than 1 averaged value, we used 4 jumps from each participant at each time point, enhancing the sensitivity to differences compared with more traditional methods. Previous research has suggested that the use of multiple trials improves CMJ reproducibility.[7] We used multiple trials, along with a unique standardized outlier-removal procedure, to manage the influence of individual variability and limit distortion of the *true* state of NM function by *uncharacteristic* trials. To our knowledge, this is the first time such procedures have been used with CMJ testing, with the method appearing to result in highly reproducible data.

Based on previously used methods,[2,3,8] we examined fatigue-induced effects on time and eccentric function (ie, CMJ-ALT variables; Figure 2 and Table 3), finding that NM fatigue induces extensive changes in CMJ mechanics. A novel start threshold based on a continuous change in power was also used to ensure that gross CMJ movement had begun. Previous investigations have used or suggested start thresholds related to absolute[16] or relative force changes,[3,14,23] but these methods are prone to "false starts," where the onset of negative power development does not always occur instantly. This approach may therefore better standardize jump-initiation time.

Practical Applications

From a performance perspective, one might contend that if power production and jump height remain the same, then the timing of the jump may be irrelevant. Practically, however, the timing and time requirements of sporting actions are also critical to sporting success. Practitioners are therefore encouraged to consider NM fatigue as decreases in both output and/or movement economy. The CMJ test appears a suitable test to detect fatigue-induced changes in NM function; however, this requires moving away from CMJ-TYP variables and performing a more detailed analysis that reflects both CMJ output and strategy.

Table 3 Group Mean ± SD, Effect Size (ES), and Interpretation for Baseline (Day 3) and 0, 24, and 72 Hours Postexercise (N = 9; 24 CMJ per Participant)

		0 h Postexercise		24 h Postexercise		72 h Postexercise	
Variable	**Baseline (Mean ± SD)**	**(Mean ± SD)**	**ES**	**(Mean ± SD)**	**ES**	**(Mean ± SD)**	**ES**
CMJ-TYP variables							
PP (W/kg)	65.1 ± 7.9	62.8 ± 8.3	**–0.29, S ↓**	63.9 ± 7.1	–0.15, T	64.7 ± 8.2#	0.04, T
MP (W/kg)	38.0 ± 4.1	35.1 ± 4.6	**–0.69, M ↓**	37.0 ± 4.2	–0.24, T	37.6 ± 4.7#	–0.09, T
mRPD (W/s)	7977 ± 1669	7451 ± 1268	**–0.32, S ↓**	7660 ± 1407	–0.19, T	7284 ± 1054	**–0.42, S ↓**
TTPP (s)	0.655 ± 0.143	0.674 ± 0.132	0.13, T	0.671 ± 0.133	0.11, T	0.713 ± 0.093	**0.41, S ↑**
PF (N/kg)	25.8 ± 4.9	24.5 ± 3.1	**–0.27, S ↓**	25.5 ± 4.3	–0.06, T	24.9 ± 2.7	–0.19, T
MF (N/kg)	20.1 ± 2.1	19.3 ± 2.1	**–0.36, S ↓**	19.8 ± 2.4	–0.15, T	19.4 ± 1.8	**–0.34, S ↓**
mRFD (N/s)	14,926 ± 9118	12,190 ± 6008	**–0.30, S ↓**	12,958 ± 7643	–0.22, T	12,666 ± 5630	**–0.25, S ↓**
TTPF (s)	0.536 ± 0.153	0.588 ± 0.150	**0.34, S ↑**	0.530 ± 0.132	–0.04, T	0.579 ± 0.118	**0.28, S ↑**
TI (Ns)	433.4 ± 48.2	430.7 ± 53.4	–0.05, T	438.0 ± 52.8	0.09, T	447.1 ± 47.6	**0.28, S ↑**
RNI (Ns/kg)	2.79 ± 0.16	2.68 ± 0.21	**–0.69, M ↓**	2.76 ± 0.16	–0.20, T	2.75 ± 0.32	**–0.26, S ↓**
PV (m/s)	2.94 ± 0.35	2.81 ± 0.29	**–0.37, S ↓**	2.91 ± 0.31	–0.09, T	3.01 ± 0.24	0.18, T
MinV (m/s)	–1.84 ± 0.32	–1.75 ± 0.27	**0.30, S ↑**	–1.84 ± 0.33	0.02, T	–1.94 ± 0.23	**–0.31, S ↓**
V@PP (m/s)	2.85 ± 0.43	2.72 ± 0.35	**–0.29, S ↓**	2.82 ± 0.40	–0.07, T	2.94 ± 0.29	0.21, T
FT (s)	0.544 ± 0.045	0.520 ± 0.044	**–0.53, M ↓**	0.534 ± 0.046	–0.21, T	0.540 ± 0.050	–0.08, T
FT:CT	0.753 ± 0.131	0.701 ± 0.123	**–0.40, S ↓**	0.729 ± 0.117	–0.18, T	0.695 ± 0.106	**–0.44, S ↓**
JH (m)	0.44 ± 0.11	0.40 ± 0.09	**–0.34, S ↓**	0.43 ± 0.10	–0.08, T	0.46 ± 0.08	0.18, T
CMJ-ALT variables							
F@0V (N)	24.4 ± 5.0	21.7 ± 3.3	**–0.55, M ↓**	23.9 ± 4.2	–0.11, T	23.5 ± 3.7	–0.19, T
FV-AUC (N/ms^2)	27.5 ± 7.7	23.1 ± 7.3	**–0.57, M ↓**	26.5 ± 9.0	–0.13, T	28.6 ± 8.7	0.14, T
EccDur (s)	0.238 ± 0.085	0.263 ± 0.074	**0.29, S ↑**	0.253 ± 0.077	0.17, T	0.259 ± 0.074	**0.25, S ↑**
ConDur (s)	0.259 ± 0.057	0.267 ± 0.058	0.14, T	0.264 ± 0.067	0.09, T	0.276 ± 0.052	**0.31, S ↑**
TotDur (s)	0.498 ± 0.138	0.531 ± 0.128	0.24, T	0.518 ± 0.138	0.15, T	0.536 ± 0.122	**0.27, S ↑**
MEccConP (W · kg^{-1} · s^{-1})	11.13 ± 3.26	9.49 ± 2.99	**–0.50, M ↓**	10.33 ± 3.05	**–0.25, S ↓**	10.34 ± 3.27	–0.24, T

Note: Effect sizes represent comparisons with baseline values only. Values in bold are considered statistically significant.

Abbreviations: CMJ, countermovement jump; TYP, typical; ALT, alternative; PP, peak power; MP, mean power; mRPD, maximum rate of power development; TTPP, time to peak power; PF, peak force; MF, mean force; mRFD, maximum rate of force development; TTPF, time to peak force; TI, total impulse; RNI, relative net impulse; PV, peak velocity; MinV, minimum velocity; V@PP, velocity at peak power; FT, flight time; FT:CT, ratio of flight time to contraction time; JH, jump height; F@0V, force at zero velocity; FV-AUC, area under the force–velocity trace; EccDur, eccentric duration; ConDur, concentric duration; TotDur, total duration; MEccConP, mean eccentric and concentric power over time; T, trivial; S, small; M, moderate; ↑, increase; ↓, decrease.

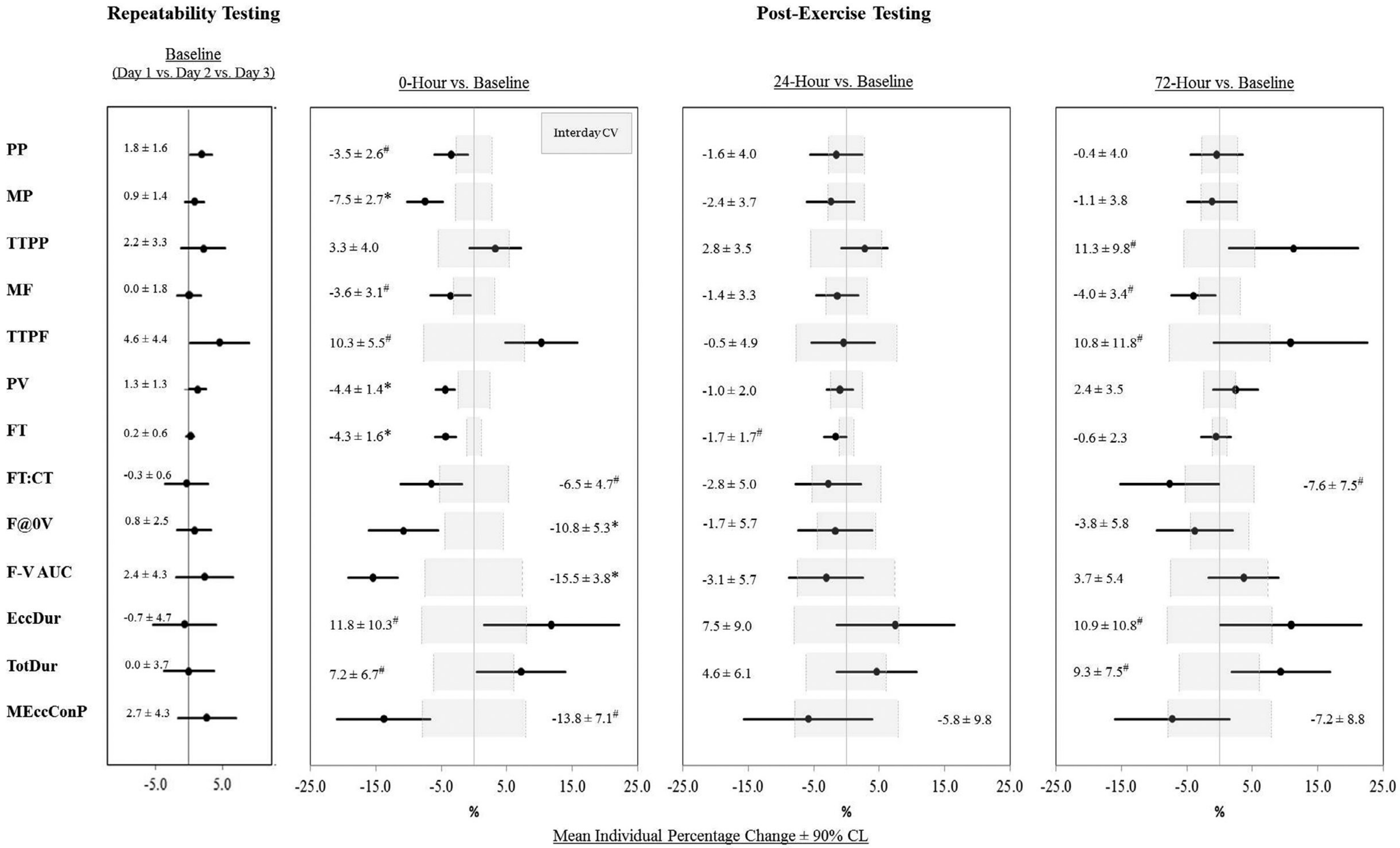


Figure 4 — The mean and 90% confidence level (CL) for the percentage change between baseline, 0 hours, 24 hours, and 72 hours postexercise for select variables and the interday coefficient of variation (CV) (n = 8; 16 countermovement jumps per participant). The interday measurement CV is shown for each parameter in light gray. *Abbreviations:* PP, peak power; MP, mean power; TTPP, time to peak power; MF, mean force; TTPF, time to peak force; PV, peak velocity; FT, flight time; FT:CT, ratio of flight time to contraction time; F@0V, force at zero velocity; F-VAUC, area under the force–velocity trace; EccDur, eccentric duration; TotDur, total duration; MEccConP, mean eccentric and concentric power over time. *Mean ± CL change ≥ interday CV. #Mean change ≥ interday CV.

Conclusions

In conclusion, the CMJ test appears a useful fatigue-monitoring tool to use in elite sport. A number of CMJ variables are associated with very high reproducibility, suggesting that the procedures used here can permit detection of even very small changes. However, when examining NM fatigue, practitioners should appreciate that the same fatiguing stimuli can elicit markedly different effects between individuals and between CMJ variables. NM fatigue may also manifest as an altered movement strategy rather than just a diminished CMJ output, so use of a full CMJ-variable battery appears most prudent for sensitive NM-fatigue detection.

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