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Contralateral muscle fatigue from slow, isokinetic contractions is not velocity-specific

Colin A. Duffett[1], Shawn A. Wiseman[1], Ashwini Punjabi[1], Kevin E. Power[1], David G. Behm[1 *]

[1]School of Human Kinetics and Recreation, Memorial University of Newfoundland, St. John's, Newfoundland and Labrador, Canada

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ABSTRACT

Non-local muscle fatigue (NLMF) describes exercise-induced fatigue of non-exercised muscles. An unexplored aspect of NLMF is whether the effects are velocity specific. In a randomized, crossover design, unilateral fatigue (4-sets of 15 maximal repetitions, separated by 15sec) was induced with low velocity ($60^0.s^{-1}$), reciprocating, isokinetic knee extensions (KE) and flexions (KF) or participants rested in the control conditions. Possible NLMF was tested with contralateral KE and KF maximal isokinetic discrete (single contraction) and repeated repetitions force and electromyography (EMG) when measured with low (12 repetitions at $60°.s^{-1}$, slow) or high (48 repetitions at $240°.s^{-1}$, fast) velocity conditions. Sixteen (10 males and 6 females) participants attended the laboratory on four occasions. Participants either rested (control) or were unilaterally fatigued prior to completing either the slow ($60°.s^{-1}$) or fast ($240°.s^{-}1$) testing conditions. The discrete KE and KF forces and EMG were not significantly different from control, with no significant relative force differences at $60°.s^{-1}$ or $240°.s^{-1}$. A significant condition effect revealed that the intervention conditions fatigue index during the KE and KF repeated maximal test significantly decreased 11% (p = .02, Effect Size: ES = 0.34) and 10% (p = .005, ES = 0.41) more respectively than the two control conditions. This study highlights that prior slow maximal isokinetic, unilateral, dominant KE and KF fatigue did not demonstrate decreases or velocity specific testing effects with singular maximal force, with some evidence of NLMF with fatigue endurance in the contralateral muscles.

1. Introduction

Fatigue is a complex, multifactorial phenomenon (Enoka & Stuart, 1992; St. Clair Gibson et al., 2003). Neuromuscular fatigue refers to the decrease in physical performance (e.g., force, torque, power) associated with an increase in the real or perceived difficulty of a task or exercise (Davis & Bailey, 1997; MacIntosh et al., 2006), regardless whether the force can be sustained (Bigland-Ritchie & Woods, 1984), and is present and progressing from the onset of the task (Bigland-Ritchie et al., 1986). Identifying the extent to which central and peripheral fatigue mechanisms interact to affect performance is a major interest in exercise research (Kirkendall, 1990; Behm, 2004). While extensive literature examines muscle fatigue in the exercised muscles (Allen et al., 2008; Gandevia, 2001), effects of fatigue can either be localized or global (Behm et al., 2021; Halperin et al., 2015; Kennedy et al., 2013; Rattey et al., 2006), meaning it can affect the exercised muscles (local) or non-exercised, non-local, muscle groups (non-local muscle fatigue: NLMF) (Behm et al., 2021; Halperin et al., 2015).

NLMF refers to a temporary force, torque, or endurance performance deficit in a contralateral, ipsilateral, inferior or superior, uninvolved, non-exercised or non-local muscle, distant from the fatigued muscle group (Gandevia et al., 1996; Graven-Nielson et al., 2002; Halperin et al., 2015). The most studied version of NLMF might be crossover fatigue, which indicates a temporary deficit in performance of the contralateral, homologous, non-exercised, limb muscles following a fatiguing protocol to the opposite limb (Doix et al., 2013; Martin & Rattey, 2007).

By testing non-local, non-exercised, homologous or heterologous muscles, peripheral fatigue defined as changes at or beyond the neuromuscular junction is primarily eliminated due to the lack of contractions at this muscle. Crossover or NLMF can highlight central fatigue effects, which refers to changes proximal to the neuromuscular junction that can result in a decreased neural drive (e.g., recruitment and discharge rate of motor units) to the

*Corresponding Author: David G. Behm, School of Human Kinetics and recreation, Memorial University of Newfoundland, Canada, dbehm@mun.ca

muscles (Bigland-Ritchie et al., 1978; 1986; Boyas & Guével, 2011; Enoka & Stuart, 1992; Gandevia et al., 1996).

While NLMF research is relatively recent, the research is conflicting. A recently published meta-analysis (52 articles; Behm et al., 2021) found only a trivial NLMF effect when examining unilateral fatigue effects on non-local discrete or single maximal voluntary contractions. An earlier narrative review paper by Halperin et al. (2015) reported that approximately half of NLMF studies reported deleterious effects with single maximal contractions (32 of 58 measures). However, Halperin and colleagues acknowledged that varying methodological considerations such as type and location of muscle (i.e., upper vs. lower body), contraction mode (isometric, cyclic, dynamic, isokinetic), intensity and volume of the fatigue intervention can influence the presence or absence of effects. The review by Halperin et al. (2015) also suggested that fatigue endurance protocols involving repetitive testing measures demonstrated more consistent impairments whereas single, maximal efforts were less consistent (Halperin et al., 2014b). This finding is in accord with the Behm et al. (2021) meta-analysis, which reported moderate magnitude deficits with NLMF endurance outcomes.

Studies using dynamic or stretch-shortening cycle contractions seemed less likely to induce NLMF effects due to recovery periods (usually 1:1 work rest ratio) as well as attenuated NLMF with stretch-shortening cycle versus constant work modes such as isometric or cyclic protocols (Halperin et al., 2015). Only three studies have examined isokinetic exercise, and they demonstrated minimal NLMF effects. Two studies (Grabiner & Owings, 1999; Othman et al., 2017) did not use concentric-concentric contractions or different velocities, while Strang et al. (2009) used concentric-concentric contractions but only at a single velocity. Repetitive, reciprocating, concentric-concentric contractions without rest intervals could exacerbate fatigue while the co-contractions associated with dynamic high-speed contractions (Desmedt & Godaux, 1979; Hallet & Marsden, 1979) may also amplify fatigue effects (Othman et al., 2017; Paillard et al., 2010). Thus, if isokinetic exercise were to be concentric-concentric such as with repetitive, reciprocating, quadriceps and hamstrings concentric contractions, would this increase the incidence of NLMF effects?

Furthermore, might slow or high velocity test contractions demonstrate a velocity specific NLMF effect? Velocity specificity indicates that training adaptations of strength/power are greatest near the training velocity (Behm & Sale, 1993; Coyle et al., 1981; Kanehisa & Miyashita, 1983). Only a single study to date has examined velocity specific effects (Othman et al., 2017) reporting NLMF but a lack of velocity specific effects when comparing isometric ($0°s^{-1}$) and high velocity ($300°s^{-1}$) fatigue protocols with youth. It is unknown if the higher firing frequencies, greater type II motor unit recruitment, altered motor unit recruitment thresholds, as well as the lower force/torque output of high velocity contractions (force-velocity relationship) (Behm & Sale, 1993) would differentially affect NLMF. Thus, the question can be asked if slow velocity fatiguing contractions can differentially affect slow or fast velocity crossover fatigue effects.

A benefit of using an isokinetic dynamometer is the control of the volume and velocity, allowing consistency in the contraction time, work/rest ratio and exercise durations. Equalization of contraction times using different velocities can be completed by increasing the number of repetitions over the same range of motion, since velocity will remain constant, may help determine whether NLMF may be velocity specific. Hence, the aim of this study was to determine if the existence or extent of lower limb NLMF or crossover (homologous muscles) fatigue is apparent with concentric-concentric isokinetic contractions and velocity dependent. More specifically, does constant, maximal intent, slow ($60°.s^{-1}$) isokinetic knee extension and flexion concentric contractions influence maximal contralateral knee extensions and flexions at slow ($60°s^{-1}$) and fast ($240°s^{-1}$) velocities (single contraction maximal torque, fatigue endurance, and electromyographic [EMG] parameters)? Based on the scant isokinetic NLMF literature (Grabiner & Owings, 1999; Othman et al., 2017; Strang et al., 2009), it was hypothesized that NLMF would be observed with repeated but not discrete (single) maximal contractions. With only one NLMF velocity specific investigation using youth as the recruited population (Othman et al., 2017), it is difficult to hypothesize based on the literature and hence this research question was considered an exploratory question. The research outcomes may provide practical insights into the order of exercises used in training or rehabilitation programs. Differential velocity effects may provide some insights into the mechanisms of NLMF.

2. Methods

2.1. Participants

Based on prior repeated measures (within subjects) using NLMF isometric maximal voluntary contraction (MVC) force data (Bogdanis et al., 1994; Halperin et al., 2014a,b), an "a priori" statistical power analysis (G*Power, Dusseldorf Germany) with an effect size of 0.5 (test family: F-tests), indicated that a minimum of 12 participants would be needed to achieve an alpha of 0.05 with a statistical power of 80%. Hence, a convenience sample of 16 healthy (absence of knee pain within the last six months), resistance trained (resistance trained at least three times a week for over two years [Halperin et al., 2014a]) participants (10 males: 172.2 ± 6.8cm, 82.1 ± 8.1kg, 24.2 ± 2.5 years; 6 females: 169.3 ± 4.6cm, 70.4 ± 11.3kg, 22.8 ± 1.8 years) were verbally explained the experimental procedures, completed the Physical Activity Readiness Questionnaire, (CSEP Path: Canadian Society for Exercise Physiology, 2011) and read and signed a letter of informed consent. Thirteen participants were determined to be right-leg dominant, while three participants were left-leg dominant (Oldfield, 1971). Resistance trained individuals were recruited as they would be familiar with producing maximal efforts against resistance reducing the force variability typically found with untrained individuals. Ethical approval for the study was granted by the Institutional Health Research Ethics Board (ICEHR: # 20200137) and conducted according to the latest version of the Declaration of Helsinki. To minimize confounding variables, subjects were requested to avoid intense exercise training a day before the testing days and avoid caffeine or other drugs within eight hours (Canadian Society for Exercise Physiology, 2011). In addition, testing was attempted to be completed at the same time on each day, and participants had a minimum rest interval between test days of 48 hours in accordance with American College of Sports Medicine recommendations for exercise recovery (ACSM, 2009).

2.2. Experimental Design

A fully randomized, repeated measure crossover design was used to examine the acute effects of unilateral, dominant, knee extensors and flexors isokinetic muscle fatigue on the performance of the contralateral (non-dominant) homologous muscles (Table 1). Participants visited the laboratory for four sessions (2 control and 2 experimental) and completed them in a random order separated by a minimum of 48 hours. The sessions consisted of (i) control-slow (no prior dominant leg fatigue: slow-isokinetic test of contralateral leg, 60°s^{-1}), (ii) control-fast (no prior dominant leg fatigue: fast isokinetic test of contralateral leg, 240°s^{-1}), (iii) slow-slow (prior slow isokinetic fatigue of dominant leg at 60°s^{-1}: slow isokinetic test of contralateral leg, 60°s^{-1}), (iv) slow-fast (prior slow isokinetic fatigue of dominant leg at 60°s^{-1}: fast isokinetic test of contralateral leg, 240°s^{-1}).

The intervention fatigue protocol of the dominant leg involved maximal force contractions completed at 60°s^{-1} and consisted of 4 sets of 15 consecutive 90° range of motion knee extension / flexion repetitions, separated by 15sec, totaling 3min of contraction time. For the testing protocols of the contralateral non-dominant leg, initially a single maximal intent effort (discrete contraction) at the prescribed angular speed (60°s^{-1} or 240°s^{-1}) for that session's condition (i.e., control-slow, control-fast, slow-slow or slow-fast) was used. To determine post-intervention fatigue resistance (endurance), the slow testing fatigue protocol of the non-dominant, non-exercised leg consisted of 12 consecutive, reciprocating, repetitions at 60°s^{-1}, ([90° range of motion / 60°s^{-1}] x 12 repetitions = 18sec) with a similar duration achieved with the high-speed protocol by using 48 consecutive, reciprocating, repetitions at 240°s^{-1} ([90° range of motion / 240°s^{-1}] x 48 repetitions = 18sec). During the experiment, isokinetic muscle torque was measured in both the dominant and non-dominant knee extensors (quadriceps) and flexors (hamstrings) muscles, muscle electrical activity by EMG in the non-dominant knee extensors (vastus lateralis: VL) and flexors (biceps femoris: BF) was recorded.

2.3. Experimental Procedures

Participants first performed a general warm up on a stationary cycle ergometer (Monark, WA, U.S.A) for 5min at 70 repetitions per min at 0.5kp resistance. They were then prepared for EMG electrode placement.

Table 1: Experimental Design

Aerobic warm-up: 5min on a stationary cycle ergometer at 70 rpm and 1 kilopond			
Conditions			
Control-Slow test	Control- Fast test	Slow Fatigue-Slow Test	Slow Fatigue- Fast test
Familiarization and test specific warm-up:			
12 KE and KF repetitions at 60°/s at 50% of self-perceived maximal intensity of DOM and Non-DOM	12 KE and KF repetitions at 240°/s at 50% of self-perceived maximal intensity of DOM and Non-DOM	12 KE and KF repetitions at 60°/s at 50% of self-perceived maximal intensity of DOM and Non-DOM	12 KE and KF repetitions at 240°/s at 50% of self-perceived maximal intensity of DOM and Non-DOM
Pre-tests			
3 KE and KF maximal isokinetic contractions @ 60°/s of DOM and Non-DOM leg	3 KE and KF maximal isokinetic contractions @ 240°/s of DOM and Non-DOM leg	3 KE and KF maximal isokinetic contractions @ 60°/s of DOM and Non-DOM leg	3 KE and KF maximal isokinetic contractions @ 240°/s of DOM and Non-DOM leg
Interventions			
5min seated rest	5min seated rest	4x15; 60°/s with 15sec rest between sets with DOM leg	4x15; 60°/s with 15sec rest between sets with DOM leg
Post-tests			
3 KE and KF maximal isokinetic contractions @ 60°/s of DOM and Non-DOM leg	3 KE and KF maximal isokinetic contractions @ 240°/s of DOM and Non-DOM leg	3 KE and KF maximal isokinetic contractions @ 60°/s of DOM and Non-DOM leg	3 KE and KF maximal isokinetic contractions @ 240°/s of DOM and Non-DOM leg
Post-intervention fatigue tests			
12 maximal contractions at 60°/s with Non-DOM knee	48 maximal contractions at 240°/s with Non-DOM knee	12 maximal contractions at 60°/s with Non-DOM knee	48 maximal contractions at 240°/s with Non-DOM knee

Note: DOM: dominant leg, Non-DOM: non-dominant leg, KE: knee extensions, KF: knee flexions

2.4. Electromyography (EMG)

EMG of the non-dominant VL and BF were monitored using self-adhesive Ag/AgCl bipolar electrodes (MeditraceTM 130 ECG conductive adhesive electrodes, Syracuse, USA) placed parallel to the muscle fibers according to the area specifications of Hermens et al. (2000) after area shaving, abrading, cleaning with isopropyl alcohol swabs, and left to dry. A ground electrode was placed on the femoral lateral epicondyle. EMG activity was collected from the mid-belly (midway between the anterior superior iliac spine to the superior edge of the patella) of the VL and BF (midway between the gluteal fold and the popliteal space) at 2cm apart (Hermens et al., 2000). Following electrode placement, electrodes were taped to minimize movement and tested for inter-electrode impedance noise (< 5kOhms).

All EMG signals were amplified (×1000) (CED 1902 Cambridge Electronic Design Ltd., Cambridge, UK) and filtered using a 3-pole Butterworth filter with cut-off frequencies of 10–1000 Hz. All signals were analog digitally converted at a sampling rate of 5kHz using a CED 1401 (Cambridge Electronic Design Ltd., Cambridge, UK) interface and recorded with sampling rate of 2000Hz using a commercially designed software program Signal 4.0 (Cambridge Electronic Design Ltd., Cambridge, UK) and stored on personal computer for further analysis. Post-test EMG were normalized to the pre-test values. Only the non-dominant (contralateral to the exercised leg) limb was monitored for EMG as the focus of the study was on velocity specific, non-local effects and the decline in dominant limb force was sufficient to document fatigue of the exercised limb.

2.5. Isokinetic Dynamometry

Following placement of EMG electrodes, participants were instructed to sit comfortably on the dynamometer seat according to manufacturer's specifications for seated knee extension/flexion (NORM; CSMI, Inc., Stoughton, MA). One manufacturer procedure that was changed for our protocol was the switch from using hand grips to placing the hands-on shoulder without use of shoulder straps. This change was made due to the possibility of NLMF effects due to upper body and arm fatigue from bracing (stabilizing). A dual crossover strap was used to secure the torso, a waist strap for the hips, and individual thigh straps for the legs. Special care was taken to minimize extraneous movement as movement could affect the force values and biomechanical moments (Weir et al., 1996). The lever arm attachment was placed just proximal to the medial malleolus and stabilized tightly against the limb with Velcro straps. The isokinetic device lever axis was positioned in line with the axis of the knee. All isokinetic chair and apparatus settings were recorded for each participant to ensure an identical setup for each session.

2.6. Specific Warm-Up

Following the dynamometer physical setup, participants completed an isokinetic specific warm-up involving full explanations in addition to familiarization repetitions. The specific warm-up performed at every session consisted of 12 unilateral knee extension and flexions contractions at $60°s^{-1}$ and $240°s^{-1}$ over 90° range of motion (ROM) (90°-0° with knee flexed at 90° as start) at 50% of self-perceived maximal contractions with the dominant leg, then repeated with the non-dominant leg. Prior to contractions at each speed, participants were informed that with isokinetic actions, the lever arm will have zero resistance until the setting velocity is reached ($60°s^{-1}$ or $240°s^{-1}$) at which point it will maintain that velocity, and torque will be measured as force exerted against the arm at that speed. This meant participants must kick (contract) at the set velocity in order to register torque. In addition, because momentum cannot be used, participants were instructed to maintain effort throughout the ROM set in order to complete 'work' during the entire protocol. Computer settings for ROM prevented hyperextension/flexion to reduce risk of injury, and rubber stoppers were placed as an extra precaution. To better understand the isokinetic principles, the computer screen, displaying torque, position, and velocity was visible for the participant. Finally, the isokinetic action was reciprocating concentric knee extension and concentric knee flexion with no eccentric phase and no rest between contractions. Participants were instructed to 'push' to extend their leg and activate their knee extensors, and 'pull' to activate their knee flexors to return the lever arm to the start position as verbal encouragement has been shown to improve performance (Lauber & Keller, 2014).

2.7. Pre-Test (Peak Isokinetic Torque)

To minimize the possibility of fatigue, five minutes following familiarization, three pre-test maximal isokinetic contractions were completed with the dominant and non-dominant leg with 30-seconds recovery between repetitions in order to measure peak torque. Participants were instructed and encouraged to exert maximally as hard and as fast as possible over the full range of motion for both the knee extensors and flexors. Participants were able to see the computer monitor to compare trials to encourage them to outperform previous trials. EMG was recorded from the non-dominant leg during non-dominant trials.

2.8. Fatigue Protocol

Five minutes following the pre-tests, with the intervention protocols (sessions: slow-slow and slow-fast) the dominant leg was initially fatigued, as cross education (unilateral training induces training effects in contralateral, untrained limb) studies have demonstrated greater effects from dominant to non-dominant limbs (Carroll et al., 2006). Prior NLMF studies using isokinetic contractions have imposed 60-175sec (< 3min) of repeated maximal contractions (Grabiner & Owings, 1999; Othman et al., 2017; Strang et al., 2009), while a number of isometric NLMF studies from this lab have utilized two repetitions of 100sec MVCs (3min 20sec) (Aboodarda et al., 2016; Halperin et al., 2014a,b; Sambaher et al., 2016). To meet or exceed both the prior isokinetic and isometric NLMF durations and ensure the development of significant fatigue, the intervention fatigue protocol in this study consisted of four sets of 15 knee extension and flexion repetitions each with no rest between repetitions. Repetitions were performed through 90° ROM at $60°s^{-1}$, with sets separated by 15sec (3min of extension and 3min of flexion), with one minute of rest total (4x15sec), totalling seven minutes for the protocol). The slow angular velocity ($60°s^{-1}$) was chosen for the fatigue intervention since higher contractile forces would be sustained by the muscle over longer duration repetitions, inducing greater physical and metabolic stress on the muscle (Allen et al., 2008; Allen, 2009; Asmussen, 1979). Higher relative contractile forces have demonstrated greater NLMF effects (Kawamoto et al., 2015; Kennedy et al., 2014). The control sessions (control-slow and control-fast) consisted of 5min of seated rest before post-tests. EMG of the non-dominant leg was monitored throughout the protocol and at any sign of activity, participants were reminded to relax that leg. Participants were verbally encouraged and able to view the computer screen demonstrating torque values to encourage them to outperform previous repetitions in order to promote maximal contractions.

2.9. Post-Test & Endurance Test

Participants were allocated 15sec between the intervention fatigue protocol of the dominant leg or 5min of seated rest for the control sessions and the post-test to refocus on the next task (post-tests). The initial post-test measure involved one maximal isokinetic contraction with the dominant leg at either 60°s^{-1} (slow-slow and control-slow conditions) or 240°s^{-1} (slow-fast and control-fast conditions) to determine the extent of fatigue intervention of the exercised leg. Then the non-dominant leg was tested similarly at 60°s^{-1} or 240°s^{-1} dependent on the testing condition to assess differences in contralateral (non-exercised) single, discrete maximal torque. Switching the dynamometer arm from one leg to the other leg took 30sec. Similarly, 15sec following the non-dominant single maximal contraction (1min post-intervention), participants completed a maximal endurance test of 12 maximal contractions at 60°s^{-1} for sessions control-slow and slow-slow, and 48 contractions at 240°s^{-1} for sessions control-fast and slow-fast with the non-dominant leg. The 240°s^{-1} protocol consists of four-fold greater repetitions to equalize total contraction time or volume of work.

2.10. Measurements and Data Analysis

Changes in isokinetic peak torque pre- and post-fatigue (or rest) with the dominant and non-dominant knee extensors and flexors were recorded, with the highest peak torque (baseline to highest force amplitude) measurement recorded. During the endurance test, changes in peak torque for the first and average of the final two contractions were used to calculate a fatigue index ([average of final two contractions peak torque / first contraction peak torque] x 100).

EMG activity of the VL and BF were also investigated pre- and post-fatigue (or rest) with post-fatigue values normalized to the pre-test MVC. A finite response high pass filter with a frequency cut-off of 20Hz was used. The data was then rectified and the root mean square (with an average of 20 data points) was calculated across 1-sec windows that included the peak force output from 0.5sec before and 0.5sec after the peak force in both muscles. A power spectral analysis was also completed to examine the median frequency (Hz) with a 3-sec window epoch that included the peak force output.

For the maximal endurance test, the EMG root mean square was measured during the first contraction and last contraction to determine the EMG output before a power spectrum analysis was conducted to determine the median frequency.

2.11. Statistical Analysis

Statistical analyses were calculated using SPSS software (Version 16.0, SPSS, Inc, Chicago, IL). This study employed a repeated measure, within subjects, cross-over design. Kolmogorov–Smirnov tests of normality were conducted for all dependent variables. Significance was defined as $p < .05$. If the assumption of sphericity was violated, the Greenhouse−Geiser correction was employed. Modified Bonferroni post-hoc tests were conducted to detect significant main effect differences whereas for significant interactions, post-hoc t-tests corrected for multiple comparisons were conducted to determine differences between values. Cronbach alpha intraclass correlation coefficients (ICCs) were measured for the pre-test trials of the Control-slow test and slow fatigue-slow tests to assess consistency of these data (Table 2). Based on Koo and Li (2016), ICC between 0.75 – 0.9 were classified as good, and over 0.9 was considered excellent. We also report the coefficient of variation (CV = [Standard Deviation / Mean] * 100) and standard error of the mean (SEM = standard deviation / square root of the sample size). Standards for CV are as follows: CV < 10% is considered very good, 10-20% is good, 20-30% is acceptable, and CV > 30% is not acceptable (Campbell et al., 2010). Cohen's "d" effect size (ES) statistics were conducted to evaluate the magnitude of the changes following various exercise protocols to the criterion of ≥ 0.80 for large; 0.50-0.79 for moderate, 0.20-0.49 for small and < 0.20 for trivial (Cohen, 1988).

To examine a single maximal contraction peak torque and EMG with slow angular velocity testing, a three-way repeated measures ANOVA comparing 2 conditions (control-slow vs. slow-slow) x 2 limbs (dominant vs. non-dominant) x 2 times (pre- vs. post-test) was used for both quadriceps and hamstrings. Similarly, a single maximal contraction peak torque with fast angular velocity testing was examined using a three-way repeated measures ANOVA comparing 2 conditions (control-fast vs. slow-fast) x 2 limbs (dominant vs. non-dominant) x 2 times (pre- vs. post-test) for both quadriceps and hamstrings. Separate ANOVAs were used for single absolute maximal peak torques with slow and fast isokinetic testing due to the inherent torque differences associated with the force-velocity muscle characteristics.

When examining the slow fatigue (endurance) test, a two-way repeated measures ANOVA comparing 2 conditions (control-slow vs. slow-slow) x 4 tests (pre-test, post-test, first and last fatigue repetitions) was used. Likewise, the same setup was used for examining the fast fatigue test. To compare the slow versus fast peak torque and EMG (normalized to the pre-test single maximal contraction peak torque or EMG) testing, a two-way repeated measures ANOVA with 2 limbs (dominant vs. non-dominant) x 4 conditions (control-slow, slow-slow, control-fast, slow-fast) was conducted for the quadriceps and hamstrings. To compare slow versus fast testing for fatigue, a fatigue index was used, analyzed with a two-way repeated measures ANOVA with 2 conditions (control and fatigue intervention) x 2 tests (slow and fast isokinetic velocity).

3. Results

The excellent intraclass correlation coefficient torque measures (r = .87-.91) are presented in Table 2.

Table 2: Cronbach alpha Intraclass Correlation Coefficients (ICC), coefficient of variation (CV) and standard error of the means (SEM).

Leg	Muscle	Peak Torque (Nm) Pre-tests	Cronbach's Alpha ICC	CV	SEM (Nm)
Dominant	Hamstrings	133.7±27.1 132.9±26.7	0.87	28.6%	7.1
Non-Dominant	Hamstrings	127.8±26.2 132.9±26.7	0.90	30.4%	7.2
Dominant	Quadriceps	189.4±36.1 193.5±46.1	0.91	28.9%	9.3
Non-Dominant	Quadriceps	189.1±37.8 185.3±46.1	0.89	26.7%	9.1

3.1. Slow Test Condition

3.1.1. Quadriceps Single MVC Peak Torque - Slow Test Condition (Table 3)

A significant interaction was seen for intervention x time (F(1,15) = 17.44, *p* = .001), revealing a significant peak torque decrease of the dominant quadriceps from pre- vs. post-test for control-slow (*p* = .001, ES = 0.27) and slow-slow test (*p* < .001, ES = 0.57) of 6% and 14% respectively.

A significant dominance x time (F(1,15) = 23.49, *p* < .001) interaction found decreases of 16% (*p* < .001, ES = 0.70) and 4% (*p* < .01, ES = .17) for pre- to post-test for dominant and non-dominant limbs, respectively (combined data from both the fatigue intervention and control conditions). A significant intervention x dominance x time interaction (F(1,15) = 9.21, *p* = .008) showed a significant 25% decrease (*p* < .001, ES = 1.04) from pre- vs. post-test for dominant quadriceps with the intervention slow test condition. Post-test dominant quadriceps MVC during the intervention condition was significantly (*p* = .008, ES = 0.53) lower than control by 13%.

3.1.2. Hamstrings Single MVC Peak Torque - Slow Test Condition (Table 3)

A significant dominance x time interaction (F(1,15) = 8.42, *p* = .011) indicated that peak torque of the dominant (exercised) and non-dominant (non-exercised) hamstrings decreased significantly 9.1% (*p* < .001, ES = .44) and 4.7% (*p* = .001, ES = 0.23) pre- vs. post-test respectively (combined data from both the fatigue intervention and control conditions). A significant intervention x dominance x time (F(1,15) = 10.57, *p* = .005) interaction illustrated pre- to post-test decreases for slow-dominant hamstrings of 14.6% (*p* < .001, ES = 0.65). When comparing post-test conditions, the dominant hamstrings peak torque post-test in the fatigue condition was 11% (*p* = .03, ES = 0.49) lower than control.

3.2. Fast Test Condition

3.2.1. Quadriceps Single MVC Peak Torque - Fast Test Condition (Table 3)

An intervention x time interaction (F(1,15) = 5.94, *p* = .03) demonstrated a significant (*p* = .005, ES = 0.30) 11% pre- to post-test decrease of the dominant quadriceps for the slow-fast intervention fatigue protocol. In addition, the dominant quadriceps post-test for the slow-fast intervention was significantly (*p* = .02, ES = 0.26) lower than control-fast post-test by 9%. An intervention x dominance x time interaction (F(1,15) = 12.77, *p* = .003) found a significant (*p* = .006, ES = 0.57) decrease of 20% for pre- vs. post-test for the dominant leg intervention.

3.2.2. Hamstrings Single MVC Peak Torque - Fast test condition (Table 3)

A significant intervention x dominance interaction (F(1,15) = 5.77, *p* = .03) exhibited a significant (*p* = .02, ES = 0.25) decrease of 8% for dominant hamstrings post-test in the intervention test vs. control. A significant interaction effect for intervention x dominance x time (F(1,15) = 9.35, *p* = .008) disclosed a significant (*p* = .001, ES = 0.55) 17% decrease in pre- to post-test dominant leg hamstrings in the intervention protocol.

3.3. Slow versus Fast Testing Conditions

3.3.1. Quadriceps Torque and EMG

There was no significant main effects or interactions for quadriceps peak torque when comparing slow vs. fast contraction effects. Furthermore, there was no significant interaction for quadriceps EMG but there was a significant main effect for time (F(2,10) = 4.45, *p* = .04). Although the main effect was significant, post-hoc analysis indicated that there was a non-significant (*p* = .20), small magnitude (14.3%, ES = 0.27) lower EMG with the pre-test versus the post-slow test (Table 4).

3.3.2. Hamstrings Torque and EMG

A significant interaction between conditions x dominance (F(1,15) = 9.54, *p* = .007) indicated a significant (*p* = .002, ES = 0.94) fatigue intervention-induced torque decrease of 11.7% in dominant hamstrings (knee flexion) performance with the interventions (slow-slow and slow-fast) vs. control (control-slow and control-fast) conditions. There was no significant interaction for hamstrings EMG but there was a significant main effect for time (F(2,10) = 7.78, *p* = .009). Post-hoc analysis revealed that there was a significant (*p* = .01), small magnitude (8.3%, ES = 0.22) lower EMG with the post-test versus the pre-test (Table 4).

Table 3: Discrete (single) maximal mean peak torque (N x m) and standard deviation (SD) of quadriceps and hamstrings during slow (60°s-1) and fast (240°s-1) tests. Percentage changes represent pre- to post-test or first to last repetition relative different.

	Peak Torque – 60°s^{-1} Test				Peak Torque – 240°s^{-1} Test			
	Quadriceps		Hamstrings		Quadriceps		Hamstrings	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Control – Single Contraction Pre-Test – Dom	189.3	37.2	133.6	27.9	98.3	37.7	81.5	29.7
Control – Single Contraction Post-Test – Dom	175.2	47.2	127.9	25.6	98.1	36.8	79.6	30.1
% Δ Pre to Post	-7.4%		-4.3%		-0.2%		-2.3%	
Control – Single Contraction Pre-Test – Non-Dom	189.1	39.1	127.7	27.1	102.3	33.6	79.0	31.3
Control – Single Contraction Post-Test – Non-Dom	181.1	42.0	119.6	25.6	99.6	38.1	73.5	30.5
% Δ Pre to Post	-4.2%		-6.3%		-2.6%		-6.9%	
Control – Fatigue Post-Test – Non-Dom Repetition #1	177.7	45.4	132.9	27.5	90.6	32.8	73.2	23.8
Control – Fatigue Post-Test – Non-Dom Last Repetition	154.2	43.1	118.2	25.1	46.2	15.4	45.3	12.7
% Δ first to last repetition	-13.2%		-11.1%		-49.0%		-38.1%	
Fatigue Intervention – Single Contraction Pre-Test - Dom	198.5	47.3	97.6	21.3	102.7	41.7	80.5	29.7
Fatigue Intervention– Single Contraction Post-Test - Dom	151.1	46.2	113.6	33.3	82.7	28.9	66.9	21.4
% Δ Pre to Post	-23.8%		16.4%		-19.4%		-16.9%	
Fatigue Intervention – Single Contraction Pre-Test – Non-Dom	185.2	47.6	129.3	25.6	99.1	37.6	79.0	26.0
Fatigue Intervention – Single Contraction Post-Test - Non-Dom	177.4	55.6	125.3	28.8	96.6	37.1	74.6	28.1
% Δ Pre to Post	-4.2%		-3.1%		-2.5%		-5.6%	
Fatigue Intervention– Post-Test – Non-Dom Repetition #1	175.5	51.6	117.2	26.1	93.6	32.6	76.5	22.8
Fatigue Intervention– Post-Test – Non-Dom Last Repetition	136.9	50.1	92.1	23.4	41.1	13.6	39.6	12.4
% Δ first to last repetition	-21.9%		-21.4%		-56.1%		-48.2%	

Note: Dom: dominant leg; Non-Dom: non-dominant leg

Table 4: Pre- and post-test EMG measures. Significant difference between control and fatigue, and between fast and slow intervention groups (p = .0009, ES = 0.63).

	Control - Slow Test			Control - Fast Test			Slow Fatigue - Slow Test			Slow Fatigue - Fast Test		
EMG Median Frequency (Hz) - Quadriceps												
	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last
Mean	73.9	76.9	62.7	81.6	75.9	55.6	72.3	70.2	66.3	77.1	80.2	56.2
SD	18.4	17.8	18.2	18.2	14.9	15	17.2	13.7	15.1	18.2	13.4	14.9
EMG Median Frequency (Hz) - Hamstrings												
	Control - Slow Test			Control - Fast Test			Slow Fatigue - Slow Test			Slow Fatigue - Fast Test		
	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last
Mean	78.4	73.9	132.4	73.6	76.3	57.6	153.1	78.8	125.7	78.4	75.6	54.9
SD	15.7	14.8	250.6	22.8	17.7	12.9	245.5	19.6	233.9	18.4	15.1	12.2
EMG Peak – Quadriceps (RMS: mV)												
	Control - Slow Test			Control - Fast Test			Slow Fatigue - Slow Test			Slow Fatigue - Fast Test		
	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last
Mean	0.7	0.6	0.7	0.4	0.4	0.5	0.6	0.5	0.7	0.4	0.3	0.4
SD	0.5	0.4	0.5	0.2	0.3	0.6	0.5	0.4	0.6	0.2	0.1	0.2
EMG Peak – Hamstrings (RMS: mV)												
	Control - Slow Test			Control - Fast Test			Slow Fatigue - Slow Test			Slow Fatigue - Fast Test		
	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last
Mean	0.3	0.4	0.5	0.4	0.3	0.3	0.4	0.3	0.4	0.4	0.3	0.4
SD	0.1	0.1	0.2	0.1	0.1	0.2	0.2	0.1	0.2	0.2	0.2	0.2

Note: Pre-test: single maximum contraction. Post First: post-test first repetition of fatigue protocol, Post Last: post-test 12th repetition of fatigue protocol, RMS: root mean square

3.4. Unilateral Fatigue Intervention Effects on Contralateral, Non-dominant, Leg Fatigue Tests

3.4.1. Contralateral (Non-dominant) Quadriceps Fatigue Index (Figure 1)

Significant main effects for time with the slow ($F(1,15) = 46.88$, $p < .001$) and fast fatigue ($F(3,45) = 43.78$, $p < .001$) tests displayed significant decreases of 18% ($p < .001$, ES = 0.67) and 53% ($p < .001$, ES = 2.1) between the first and last repetition of the contralateral, non-dominant, quadriceps fatigue tests.

A significant main effect for conditions ($F(1,15) = 6.27$, $p = .02$) revealed that the intervention conditions (slow-slow and slow-fast) peak torque during the repeated maximal test significantly decreased 11% ($p = .02$, ES = 0.34) more than control (control-slow and control-fast) (Figure 1). In addition, a significant main effect for tests ($F(1,15) = 31.26$, $p < .001$) indicated that high velocity, contralateral, non-dominant, quadriceps peak torque fatigue index decreased 37% ($p < .001$, ES = 1.77) more than slow test.

The ANOVA revealed a significant condition x time interaction ($F(9,27) = 2.77$, $p = .019$). with every condition. The pre-test quadriceps EMG median frequency either significantly ($p < .001 – p = .02$) or nearly significantly (slow-fast condition; $p = .10$) was greater than the last repetition of the fatigue protocol. A main effect for time ($F(3,9) = 16.02$, $p = .026$) for the contralateral quadriceps EMG median frequency revealed that the post-test frequency was 6.2% ($p = .01$, ES = 0.21) and 35.1% ($p = .05$, ES = 0.73) higher than first and last repetitions of the fatigue test.

3.4.2. Contralateral (Non-dominant) Hamstrings Fatigue Test (Figure 1)

Significant main effect for times for the slow ($F(3,45) = 63.29$, $p < .001$) and fast ($F(3,45) = 41.32$, $p < .001$) fatigue tests revealed significant decreases of 19% ($p < .001$, ES = 0.98) and 5% ($p = .03$, ES = 0.16) between the first and last repetition of the repetitive fatigue endurance test respectively.

A significant main effect for conditions ($F(1,15) = 8.32$, $p = .011$) displayed that the intervention conditions (slow-slow and slow-fast) peak torque during repeated maximal test decreased 10% significantly ($p = .005$, ES = 0.41) more than control (control-slow and control-fast) (Figure 1). Furthermore, analysis revealed a significant effect for tests ($F(1,15) = 14.94$, $p = .002$) revealing that high velocity peak torque endurance decreased 30% significantly ($p = .003$, ES = 1.54) more than slow test.

A main effect for time ($F(3,9) = 27.10$, $p < .0001$) for the hamstrings EMG median frequency revealed that the post-test frequency was 40.7% ($p = .01$, ES = 0.91) greater than last repetition of the fatigue protocol, while first repetition of the fatigue protocol was 34.0% ($p = .002$, ES = 1.1) higher than the last repetition. There were no significant interactions for hamstrings EMG median frequency.

4. Discussion

The most important finding in this study was that velocity specific effects were not demonstrated with relative peak torque or relative fatigue endurance changes between slow (60°s^{-1}) or fast (240°s^{-1}) testing. In accord with the hypothesis, prior unilateral fatigue of the dominant quadriceps and hamstrings by repetitive slow (60°s^{-1}) maximal isokinetic actions did not demonstrate decreases in singular (discrete) maximal peak torque in the contralateral, homologous muscles. However, there was some evidence (main effect for conditions) of NLMF with repetitive fatigue endurance (fatigue index). These findings are in agreement with a recent meta-analysis that determined that an analysis of the NLMF literature generated only trivial NLMF discrete maximal contraction differences but moderate effects with endurance testing (Behm et al., 2021).

4.1. Velocity Specificity

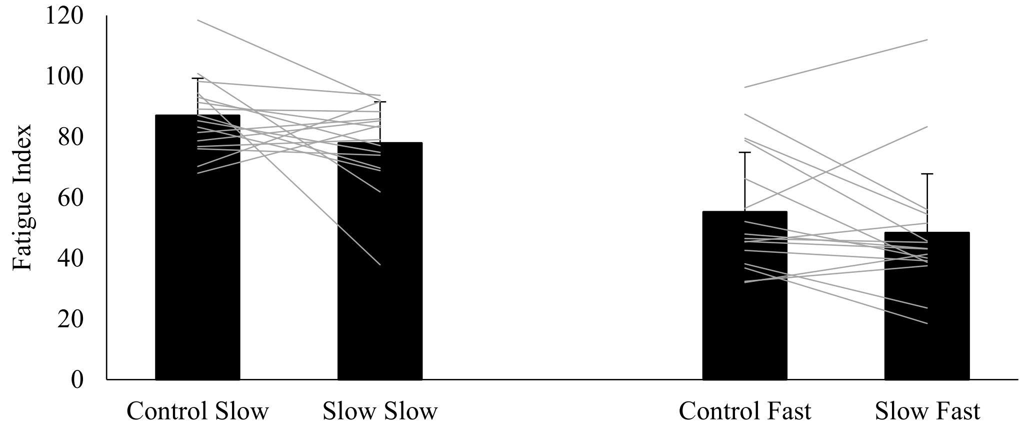
A relatively unexplored aspect of NLMF is whether effects are velocity specific. The majority of prior NLMF or crossover literature intervened and tested with maximal voluntary isometric contractions and hence did not compare varying contraction velocities. No velocity specific effects (60°s^{-1} vs. 240°s^{-1}) were demonstrated in peak torque. Velocity specific differences were observed for the non-dominant, contralateral, repetitive fatigue endurance test, with the high velocity test demonstrating a 30% (ES = 1.5) greater decrease in the fatigue index compared to the slow velocity test. This difference however was not deemed NLMF as it was not significantly different from control. It is likely the greater decrease in repetitive fatigue endurance in the high velocity protocol is due to the greater fatiguability of fast (type 2) muscle fibers at higher velocities. The only study that also compared velocity specific effects was Othman et al. (2017) who compared isometric (0°s^{-1}) and high velocity (300°s^{-1}) fatigue protocol on isometric and high velocity peak torque. In contrast to the current study, they found evidence of NLMF for both isometric and isokinetic protocols, however there was no difference between protocols, also demonstrating a lack of velocity specific NLMF effects.

4.2. Fatigue Intervention

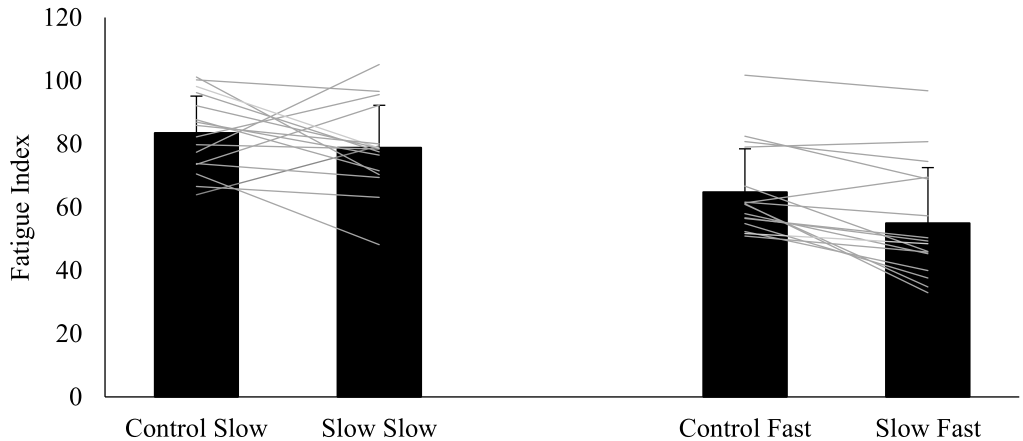
In the present study, the intervention fatigue protocol consisting of four sets of 15 unilateral isokinetic knee extensions and flexions utilized maximal intent contractions, delivering similar dominant (exercised) quadriceps and hamstrings torque deficits of 24% (ES = 1.01) and 15% (ES = 0.65) when tested at 60°.s^{-1}, with 20% (ES = 0.57) and 17% (ES = 0.55) quadriceps and hamstrings deficits when tested at 240°.s^{-1}. These fatigue-induced deficits of the exercised leg were similar to Kawamoto et al. (2014) (↓32%), Doix et al. (2013) (↓17%), Martin and Rattey (2007) (↓16%) and Othman et al. (2017) with 12.6% and 11.3% decrements at 90° and 120° respectively. In contrast, Grabiner and Owings (1999) and Strang et al. (2009) exhibited greater fatigue impairments of the exercised muscle of 39% and 19% respectively.

It has been demonstrated that higher or maximal intensity exercise (Kawamoto et al., 2015; Kennedy et al., 2014) has demonstrated greater NLMF effects than lower intensity exercise (Arora et al., 2015; Paillard et al., 2010). In addition, the amount of contraction time might play a role as fatigue accumulates over time (Bigland-Ritchie et al., 1986). When shorter and longer

A) Quadriceps



B) Hamstrings



Conditions		**Peak Torque Fatigue Index**			
		Quadriceps		Hamstrings	
		Mean	SD	Mean	SD
Control – Slow	(Rest - 60°.s^{-1})	87.01	12.6	83.5	12.01
Control – Fast	(Rest - 240°.s^{-1})	55.2	20.3	64.8	14.1
Slow – Slow	(60°.s^{-1} - 60°.s^{-1})	77.9	14.1	78.8	13.8
Slow – Fast	(60°.s^{-1} - 240°.s^{-1})	48.3	22.2	54.9	18.2

Figure 1: Fatigue Index (mean and standard deviation (SD) % decrease) for quadriceps (Figure 1A) and hamstrings (Figure 1B) peak torque between 1st and last repetition of fatigue endurance tests.

isometric durations were compared, the longer protocol induced greater decrements (Doix et al., 2013). However, for isokinetic protocols, the data is mixed even though all protocols used maximal intent contractions. With isokinetic studies, Grabiner and Owings (1999) contracted for 3min, Strang et al. (2009) used 3.8min, and the current study used 3min and did not demonstrate NLMF strength effects, whereas Othman et al. (2017) used 60sec and demonstrated effects. The present study results again call into question further methodological considerations. For example, Grabiner and Owings (1999) suggested the allowance of a passive return of the dynamometer giving the protocol a 1:1 work/rest ratio, which might have allowed a recovery effect. However, the present study and Strang et al. (2009) used concentric-concentric actions of the quadriceps and hamstrings, not allowing a full recovery of either muscle (i.e., co-contractions) and did not demonstrate deficits, while Othman et al. (2017) utilized concentric only actions of the quadriceps and demonstrated NLMF effects. It might then be possible that the velocity being used to fatigue might play a role, as isokinetic actions allow control over movement velocity. While Grabiner and Owings (1999) used slower velocity (30°s^{-1}), the current study used 60°s^{-1}, and Strang et al. (2009) used 110°s^{-1} and did not demonstrate effects, Othman et al. used a much faster 300°s^{-1} protocol and reported impairments. As mentioned earlier, the other three studies used adults, Othman et al. (2017) used children, which might be a contributor to the NLMF effects.

4.3. Fatigue Measures

The most commonly used NLMF detection method has been peak force during a singular, maximal contraction, (Halperin et al., 2015). Several studies have (Aboodarda et al., 2015; Doix et al., 2013; Martin & Rattey, 2007; Othman et al., 2017) and have not (Arora et al., 2015; Decorte et al., 2012; Elmer et al., 2013; Grabiner & Owings, 1999; Halperin et al., 2014; Halperin et al., 2014; Kennedy et al., 2015; Paillard et al., 2010; Regueme et al., 2007; Strang et al., 2009; Triscott et al., 2008; Zijdewind et al., 1998) demonstrated deficits in singular maximal contractions. A NLMF meta-analytical review (Behm et al., 2021) illustrated that studies that demonstrated NLMF of single maximal contractions generally counterbalanced those that did not, resulting in an overall trivial magnitude effect.

Although there is evidence for NLMF effects with repeated maximal contractions (Amann et al., 2013; Behm et al., 2021; Halperin et al., 2014a; Rasmussen et al., 2010; Triscott et al., 2008), the evidence for NLMF of repetitive contractions was not comprehensive in the present study as there were no significant interactions. But there were main effects for conditions with greater decreases in quadriceps and hamstrings peak torque fatigue indexes following the fatiguing intervention (slow-slow and slow-fast) compared to control conditions (control-slow and control-fast). It can then be suggested that the fatigue induced with most NLMF studies might not be sufficient to elicit a deficit in a singular maximal contraction, however prolonged or repetitive testing demands, may require more persistent neural input (e.g., inter-hemispheric and/or corticospinal inhibition: Takahashi et al., 2011) that could exacerbate global neural failure and afferent inhibition of spinal and cortical motoneurons (Behm, 2004). Furthermore, according to the mental energy deficit theory, mentally fatiguing tasks (e.g., concentration and focus necessary to maintain high contractile forces for a prolonged period) can impair subsequent physical performance, especially with repeated and/or prolonged exertion (Marcora et al., 2009; Pageaux et al., 2013, 2014). Mentally fatiguing tasks influence participants perception of the activity as more strenuous or uncomfortable (Steele, 2020), and hence, disengage sooner from the activity (Marcora et al., 2009; Pageaux et al., 2013, 2014). As persistent focus and concentration are also a requisite for performing repetitive MVCs, the mental energy involved with the fatigue intervention may have negatively impacted the repetitive, contralateral, fatigue test. Similar to the general findings of the Behm et al. (2021) meta-analysis, the present study failed to demonstrate impairments in single maximal peak torque contractions, but did provide some evidence of deficits with the peak torque fatigue index.

Neuromuscular activation as monitored by EMG activity did not demonstrate a NLMF effect but the power density spectrum median frequency did decrease in response to the fatigue test protocol (irrespective of the condition) as has been frequently reported in the literature (Ament et al., 1996; Krogh-Lund & Jorgensen, 1991; Warren et al., 2000). Reduced EMG median frequency represents decreases in action potential conduction velocities and motoneuronal rate coding associated with fatigue. (Ament et al., 1996; Krogh-Lund & Jorgensen ,1991; Warren et al., 2000).

4.4. Contraction Mode

The contraction mode has been suggested to play a role in NLMF (Halperin et al., 2015), with constant action fatiguing protocols such as isometric (Aboodarda et al., 2015; Doix et al., 2013; Halperin et al., 2014a,b; Kennedy et al., 2013. 2015; Martin & Rattey, 2007; Post et al., 2008; Todd et al., 2003), and cycling (Bangsbo et al., 1996; Bogdanis et al., 1994; Bouhlel et al., 2010; Johnson et al., 2014; Nordsborg et al., 2003; Rasmussen et al., 2010; Sidhu et al., 2014) more likely to demonstrate NLMF effects than dynamic. However, significant impairments have been demonstrated in a few dynamic studies with isoinertial and isokinetic fatigue interventions (Amann et al., 2013; Ciccone et al., 2014; Kawamoto et al., 2014; Othman et al., 2017; Šambaher et al., 2016). Of three studies examining isokinetic contractions, Strang et al. (2009) used concentric unilateral knee extensions and flexions, but at 110°.s^{-1}, and tested isometrically whereas the current study tested at slow (60°.s^{-1}) and high velocities (240°.s^{-1}). In contrast to the current study, Grabiner and Owings (1999) used slower (30°.s^{-1}) unilateral knee extensions or flexions, and Othman et al. (2017) used faster (300°.s^{-1}) unilateral knee extensions and isometric contractions. Within these three isokinetic studies, only one demonstrated NLMF effects (Othman et al., 2017). In addition, to employing higher velocity fatiguing contractions, Othman et al. (2017) reported global NLMF (i.e., knee extensors, elbow flexors, handgrip, and balance test), suggesting that NLMF may be more susceptible with youth.

A limitation was the time required to switch the isokinetic device from the dominant exercised to non-dominant non-exercised testing legs (approximately 30sec). NLMF effects seem to diminish quickly following recovery of the exercised limb, and therefore a quick transition to the non-exercised leg may be critical to monitor immediate responses. However, it can also be argued that an effect that persists for less than 1min has little practical significance. However, significant NLMF effects have been observed at 30sec (Prieske et al., 2017), 1-min (Halperin et al., 2014a) and 3min (Halperin et al., 2014b; Prieske et al., 2017) post-fatigue protocol. Furthermore, while a sample size of 16 participants was calculated from an “a priori” statistical power analysis and is a typical population number in these types of studies, the ability to detect significant differences may have been strengthened but a greater number of participants.

A major strength of this study was the inclusion of both sexes and the scope of measurements that highlighted both physical performance (i.e., maximal torque, fatigue endurance), and neural mechanisms (EMG RMS, EMG median frequency). However, the inclusion of both males and females could also be perceived as a disadvantage due to sex differences in fatigability. Females are reported to be less fatigable during low velocity contractions (Yoon et al., 2007) and this could have skewed the results.

In conclusion, this study highlighted that prior unilateral fatigue of the dominant quadriceps and hamstrings by repetitive slow ($60°s^{-1}$) maximal isokinetic actions did not demonstrate decreases in singular maximal peak torque but some NLMF evidence with repetitive fatigue endurance in the contralateral homologous muscles. In addition, velocity specific effects were not demonstrated in relative peak torque or relative fatigue endurance changes. The present findings suggest that individuals can still expect to produce a maximal contraction force of a contralateral leg following unilateral knee extensor and flexor fatiguing activities at slow or faster angular velocities. However, subsequent contralateral exercise that involves muscular endurance could be negatively impacted by prior unilateral fatiguing contractions.

Conflict of Interest

The authors declare no conflict of interests.

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A comparison of countermovement jump performance and kinetics at the start and end of an international Rugby Sevens season

Ben Lonergan[1 *], Phil Price[2], Stephanie L. Lazarczuk[3], David J. Howarth[4, 5, 6], Daniel D. Cohen[7, 8]

[1]West Ham Football Club, Physical Development Department, Romford, UK
[2]Falculty of Sport, Allied Health and Performance Science, St Mary's University, Twickenham, UK
[3]School of Allied Health Sciences, Griffith University, Gold Coast Campus, Queensland, Australia
[4]Faculty of Health, School of Sport, Exercise & Rehabilitation, University of Technology Sydney, New South Wales, Australia
[5]Connacht Rugby, Galway, Co. Galway, Ireland
[6]Irish Rugby Football Union, Dublin, Ireland
[7]Masira Research Institute, Faculty of Health Sciences, University of Santander (UDES), Bucaramanga, Colombia
[8]Mindeporte (Colombian Ministry of Sport), Centre for Sport Science, Bogotá, Colombia

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ABSTRACT

The countermovement jump (CMJ) is used to profile and monitor lower body neuromuscular performance in a variety of sports. While jump height, peak power and peak force are commonly reported CMJ variables (CMJ-TYP), several temporal and rate-limited kinetic "alternative" (CMJ-ALT) variables have shown greater response to acute and chronic load, but this has not been examined in male Rugby Sevens (7s) athletes. We evaluated changes in CMJ-ALT and CMJ-TYP variables at the start and end of a World 7s Series season. We compared mean values for CMJ-ALT and CMJ-TYP variables in three CMJs performed by elite male rugby 7s players (n = 12) close to the start and at the end of the season. Potential differences were determined with repeated measures t-tests and magnitude of change quantified using effect sizes. Comparing the start and the end of the season, there were significant differences with very large and large effect sizes in concentric peak force and in a number of CMJ-ALT variables such as concentric duration, countermovement depth, concentric impulse-100ms, concentric rate of power development, eccentric deceleration rate of force development, RSI-modified and FT:CT, with effect sizes ranging between d = 0.98 to 1.39 and p values ranging between p < 0.001 to 0.04. There was no significant change in jump height or concentric peak power. Season-long exposure to matches and training blocks led to improvements in specific CMJ kinetic variables, the majority which were temporal or rate-limited kinetic or CMJ-ALT variables, but not in jump height and peak power or eccentric deceleration impulse. When aiming to quantify chronic response to loading using the CMJ, monitoring of a limited number of 'typical' variables may lead to misleading null conclusions about the response of these athletes to long-term/season long loading. In contrast, a more comprehensive kinetic analysis may reveal improvements in aspects of neuromuscular performance.

1. Introduction

Rugby Sevens (7s) is an Olympic sport with a competitive season that lasts seven months, comprised of 10 tournaments of 2-3 days each. Rugby 7s competitions impose large running-based demands during a 14-minute game period with large high-speed running (HSR) distances per minute (19.2 ± 6.8 m.min), distances covered per minute (112.1 ± 8.4 m.min) (Suarez-Arrones et al., 2016) and maximum speed outputs (8.4m/s) (Ross, Gill, & Cronin, 2015), higher than that of the 15s game. Positional differences are reported in distance covered (69.1 ± 7.6 m.min in forwards and

*Corresponding Author: Ben Lonergan, West Ham Football Club, Physical Development Department, Romford, UK, blonergan@westhamunited.co.uk

73.3 ± 8.1 m.min in backs) and HSR per minute (3.1 m.min in forwards and 7.2 m.min in backs) (Cunningham et al., 2016).

Due to the high physical demands of the sport, competition density during tournaments, and small squad sizes, superior physical qualities may increase a team's chances of success via the potential ability to tolerate greater match outputs, faster recovery (Johnston, Gabbett, Jenkins, & Hulin, 2015), and potentially reduced injury risk (Thorpe, Atkinson, Drust, & Gregson, 2017). Due to the structure of the 7s calendar, training loads can be adapted across the season to induce specific physiological adaptations, minimise effects of travel, or emphasise recovery post-tournament (Marrier et al., 2019). In high performance settings, monitoring neuromuscular responses to load and recovery is often achieved using the countermovement jump (CMJ) (Gibson, Boyd, & Murray, 2016). The CMJ provides both commonly reported performance variables such as jump height and peak power that can be measured or estimated with a number of technologies and a range of other kinetic variables that can be derived from the analysis of force, velocity, power and displacement-time curves following force platform testing (Cormie, Mcbride, & McCaulley, 2009). Gathercole, Stellingwerff, and Sporer (2015) defined these commonly reported variables as typical (CMJ-TYP) and introduced the use of a number of other variables, mainly phase durations, and defined these as 'alternative' (CMJ-ALT). Gathercole and colleagues work extended the observations of Cormack, Newton, McGuigan, and Cormie (2008), which demonstrated that the ratio of flight time to contraction time (FT:CT) was a more sensitive indicator of neuromuscular status and marker of the response to competition, residual fatigue and recovery in elite populations (Cormack et al., 2008; Cormack, Mooney, Morgan, & McGuigan, 2013). FT:CT significantly decreased in response to match play while jump height remained stable (Cormack et al., 2008), and decreases in FT:CT during the season were associated with reduced HSR performance and altered movement strategy (Cormack et al., 2013). In addition, evidence suggests that FT:CT and other rate- or time-limited CMJ-ALT variables that have since been described often provide a deeper insight into neuromuscular responses and alterations in movement strategy not expressed in CMJ-TYP outputs. For example, CMJ-ALT variables have indicated adaptations to short term training programs (Kijowski et al., 2015), long term changes in performance qualities (Heishman, Daub, Miller, Freitas, & Bemben, 2020), residual deficits following injury (Hart et al., 2019) and deconditioning following COVID-19-induced home training (Cohen et al., 2020) while CMJ-TYP were stable following these alterations in loading.

In 7s athletes, West et al. (2013) evaluated changes in CMJ performance across a two-tournament period and reported decreases in jump height of 26% at 12 hours post-tournament one which remained reduced five days later by 8% at the start of tournament two. However, CMJ-ALT variables were not examined. This study, and others (Claudino et al., 2017), indicate that jump height can be a useful marker, but neither of these investigations included CMJ-ALT variables which may provide greater sensitivity. Nonetheless, in 7s a comprehensive and wider array of CMJ kinetic variables has not been investigated throughout the course of the season. Such an analysis may reveal neuromuscular changes that are not be expressed in CMJ-TYP variables and so could provide additional insights on team and individual training, competition and recovery responses. This study aims to quantify potential changes in CMJ-TYP and ALT variables across the World 7s series season, by comparing performance at start versus the end of a season, in male elite Rugby 7s athletes. We also examined whether the CMJ kinetic profile at the start of the season differed between forwards and backs. Finally, for descriptive purposes we compare CMJ kinetics in athletes from other sports for comparable variables, to contrast with that of the present 7s players.

2. Methods

This is a retrospective cohort analysis of CMJ assessments performed across the World Rugby 7s 2018-2019 Series. Nine testing sessions were implemented by sports science support staff during a six-month period, as part of routine athlete monitoring. The first testing session was completed one week after the first pairings of World 7s Series stages (Dubai), with the last testing session completed one week post the last World 7s Series competition (Paris). The remainder of the testing sessions were conducted as part of a normal monitoring process, one-week pre-tournament travel and during the first week back in training post-tournament completion, typically one week after returning to the UK. For the purposes of the present analysis, to examine changes across the whole season, we compared CMJ performance in test session 1 and test session 9. These tests were performed under similar conditions, 1-week post competition.

Table 1**:** Player characteristics (mean (SD)).

		Testing Point 1		Testing Point 9	
	Age (y)	**Height (cm)**	**Body Mass (kg)**	**Height (cm)**	**Body Mass (kg)**
Forwards (n = 5)	26.8 (6.0)	185.8 (7.8)	94.0 (9.7)	185.9 (7.9)	94.5 (8.0)
Backs (n = 9)	24.2 (4.7)	181.6 (6.4)	89.2 (7.6)	181.8 (6.6)	89.3 (7.1)

2.1. Participants

The team consisted of 19 male international rugby 7s players, however the present analysis only includes data from 14 players in testing session 1 and 12 players in testing session 9 (Table 1) who: 1) were with the 7s programme for at least six months, 2) had competed in a World 7s series, 3) had no current or prior (in the preceding two months) training or game time-loss lower limb injuries, and 4) performed a minimum of four CMJ assessments during the season assessed. All players had at least 2 years of training experience. Ethical approval for this study was granted by the St Mary's University, Twickenham ethics committee in line with the principles of the Declaration of Helsinki.

2.2. Procedure

All testing was conducted on the first day of the testing week at the same time in the morning before the scheduled gym-based session. Players were instructed to wear the same footwear for each testing session. The bilateral CMJ was part of a series of jump tests performed by each athlete and was always performed first after a standardised five-minute warm-up of self-selected dynamic stretches, 10 bodyweight squats, 10 lunges and 10 pogo jumps followed by three practice jumps at 60%, 80% and 100% of perceived maximal effort. Two minutes rest was then allowed before the first of three measured jumps performed on dual force platforms (Model No: PS 2141; Pasco Roseville, CA, USA) sampled at 1000 Hz using proprietary software (ForceDecks v1.2.6109, Vald Performance). All players were familiar with the CMJ testing procedures as part of pre-season physical assessments.

2.2.1. Countermovement Jump

After stepping onto the force platforms, players remained still for three seconds to measure body mass (Hart et al., 2019). Athletes performed three bilateral CMJ to a self-selected depth with hands on hips throughout and 30 seconds of rest between each jump. Athletes were instructed to "dip as quick as possible and jump as high as possible" with verbal encouragement provided to encourage maximal effort. A jump was ruled invalid if an athlete exhibited excessive knee flexion once airborne, or if the jump was not autodetected by the software as a CMJ. For example, jumps in this population are not autodetected correctly (i.e., as a CMJ) if countermovement velocity is insufficient or players do not land on the force plates.

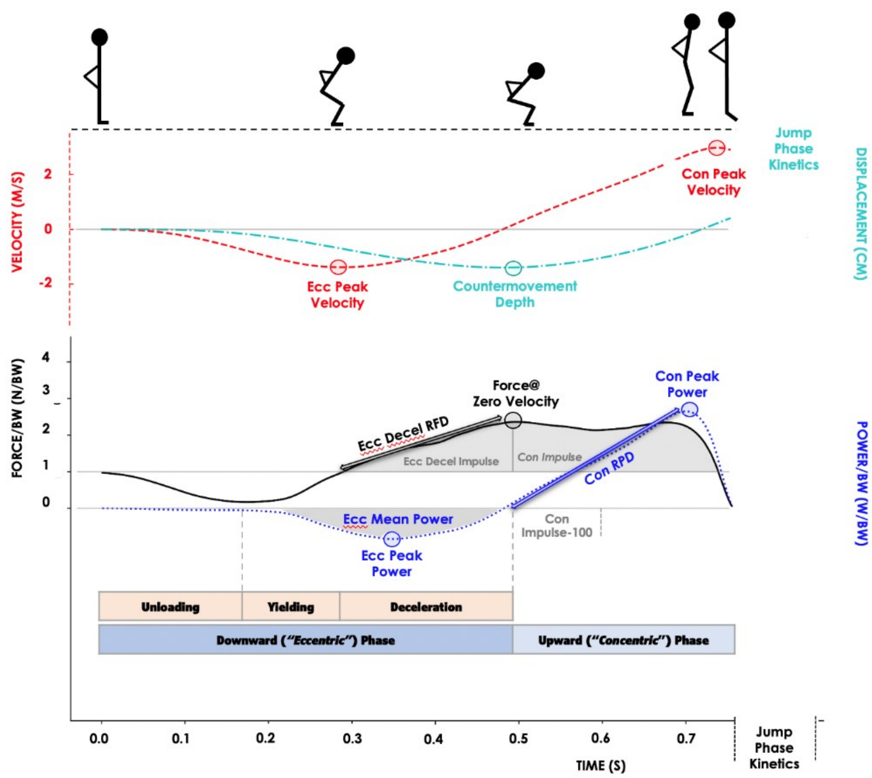

Figure 1: Countermovement jump downward and upward phase vertical ground reaction Force, Velocity, Power, and (Centre of Mass) Displacement-time curves with selected bilateral variables highlighted Force (N-Newtons) Power (W-Watts) are expressed relative to bodyweight (BW): /kg. Con = Concentric, Ecc = Eccentric; RFD = Rate of force development; RPD = Rate of power development; COM = Centre of Mass; Con Imp100 = Concentric impulse during the first 100ms following the start of the upward (concentric) phase. "Depth" refers to COM displacement. Concentric peak force not shown as due to variations in the shape of the force-time curve it occurs at different time points across the phase. As eccentric peak force typically aligns with force at zero velocity, it is not shown. Adapted from Cohen et al. (2020). The initiation of the jump (start of movement) was determined by a 20N change from body-mass quantified before the jump. The eccentric phase was defined from the start of movement to zero velocity and concentric phase from zero velocity to take-off (Kijowski et al., 2015).

2.3. Statistical Approach

Variables and phases included in the analysis are defined in Table 2 (Heishman et al., 2020) and visualised in Figure 1. We dichotomised variables reported as either typical (CMJ-TYP), i.e., CMJ output variables and those most commonly reported, or alternative (CMJ-ALT), including: FT:CT, Reactive Strength Index Modified (RSImod) and component phase durations, time-constrained or rate-related kinetics, and eccentric variables such as mean and peak power. These alternative variables are used by practitioners and have been referred to in the literature but do not appear to be commonly reported.

SPSS statistical analysis software (SPSS, version 24, Chicago, IL) was used for statistical analyses with alpha level set at 0.05. To determine if there were positional differences within the current playing group, independent t-tests were used to compare CMJ variables in the forwards (n = 5) and backs (n = 9) assessed at testing session 1. To determine if there were changes in CMJ variables between testing session 1 and testing session 9, a paired t-test was used to compare players assessed at both these testing points (n = 12); players missing a CMJ assessment at either timepoint were omitted from this analysis.

Table 2: Definition of variables (see Figure 1 for phases and positions of variables).

Variable	Definition
Overall performance	
Jump Height (Imp-Mom) [cm] TYP	Jump Height calculated from take-off velocity
RSI-modified [m/s] ALT	Jump Height (Flight Time) divided by Contraction time (eccentric + concentric duration)
Flight Time:Contraction Time ALT	Flight Time divided by Contraction Time
Upward (Concentric) phase: Zero velocity / maximum negative displacement to take-off (20N)	
Concentric Impulse [Ns] TYP	Net impulse across phase
Concentric Peak Force [N/kg] TYP	Maximum force within phase
Concentric Peak Velocity [m/s] TYP	Maximum velocity within phase
Peak Power [W/kg] TYP	Maximum power within phase
Concentric Impulse-100ms [Ns] ALT	Net impulse during the first 100-ms of phase
Concentric Duration [ms] ALT	Time from start of phase to take-off
Concentric RPD [W/s/kg] ALT	Average rate of power development (Δpower / Δtime) between start of phase to peak power
Downward (Eccentric) phase: start of movement (20N offset from body-mass) to end zero velocity / maximum negative displacement	
Eccentric Deceleration Impulse [Ns] TYP	Net Impulse during the eccentric deceleration subphase (maximum negative velocity to zero velocity)
Eccentric Duration [ms] ALT	Time from start of movement to end of the phase
Force at Zero Velocity [N] ALT	Force at the time point of zero velocity (maximum negative displacement)
Countermovement Depth [cm] ALT	Maximum negative displacement
Eccentric Peak Velocity [m/s] ALT	Maximum negative velocity during phase
Eccentric Mean Power [W/kg] ALT	Average power within phase
Eccentric Peak Power [W/kg] ALT	Maximum negative power within phase
Eccentric Deceleration RFD [N/s/kg] ALT	Average RFD (Δforce / Δtime) between start of deceleration phase to end of the phase

Note: cm = centimetres; /kg = refers to adjusted for body weight (kilograms); m = metres; ms = milliseconds; N = Newtons; RFD = rate of force development; RPD = rate of power development; s = seconds; W = Watts

Standardised effect sizes (Cohen's *d*) were determined to assess the magnitude of differences in CMJ variables between testing session 1 (start of season) and 9 (end of season). The magnitude of the effect sizes was classified as small (0.2-0.49), medium (0.5-0.79), large (0.8-1.2) and very large (>1.2).

We also calculated coefficient of variation for the variables assessed using two tests performed by the same players under similar conditions, early in the season; this analysis included 12 players who were assessed at both testing session 1 and a second testing session 4 weeks later. Evaluation of inter-day reliability would typically involve comparison of two tests closer together – separated by days or a week. Therefore, while these CVs may not qualify as a reliability analysis, they do provide some population-specific information related to the magnitude of variability (or "noise") in the metrics reported. This data, which uses the two earliest assessments, those *least* contaminated by repeated competition and training cycles, puts into context the percentage changes ("signal") determined between the start to end of season.

3. Results

In the start of season test, there were no statistical differences between forwards and backs for any variable (Table 3), therefore in the subsequent start versus end of season analysis, we included all players. Table 4 shows t-test and effect size for all variables in start versus end of season tests. In comparison to the start of season test, there were significant decreases in concentric duration ($p = 0.01$; $d = 1.39$), and countermovement depth ($p = 0.02$; $d = 1.29$) in the end of season test. There were significant increases in concentric impulse-100ms ($p = 0.04$, $d = 0.98$), concentric RPD ($p < 0.001$; $d = 1.14$), concentric peak force ($p < 0.007$; $d = 1.08$), eccentric deceleration RFD ($p = 0.01$; $d = 1.03$), RSI-modified ($p < 0.009$; $d = 1.14$), and FT:CT ($p < 0.001$; $d = 1.28$).

Table 3: Descriptive data and (mean (SD)) and comparison between forwards (n = 9) and backs (n = 5) for countermovement jump typical (CMJ-TYP) and alternative (CMJ-ALT) variables.

Variable	Forward	Backs	ES	*p*-value
CMJ-TYP				
Jump Height (Imp-Mom) [cm]	44.8 (4.8)	45.5 (4.8)	0.12	0.86
Concentric Peak Force [N/kg]	29.7 (1.9)	29.6 (3.2)	0.06	0.92
Concentric Impulse [Ns]	261.6 (18.5)	265.8 (27.2)	0.19	0.71
Concentric Peak Velocity [m/s]	2.93 (0.2)	3.03 (0.2)	0.50	0.43
Concentric Peak Power [W/kg]	58.8 (7.0)	62.4 (7.4)	0.50	0.43
Eccentric Deceleration Impulse [Ns]	137.4 (7.3)	136.5 (18.4)	0.07	0.91
CMJ-ALT				
RSI-modified [m/s]	0.72 (0.1)	0.70 (0.1)	0.14	0.82
Flight Time:Contraction Time	1.0 (0.1)	0.94 (0.1)	0.24	0.70
Concentric Duration [ms]	220.5 (22.4)	225.6 (33.7)	0.18	0.77
Eccentric Duration [ms]	406.7 (52.7)	435.6 (70.4)	0.47	0.46
Force at Zero Velocity [N]	2755.4 (217.2)	2636.4 (116.0)	0.71	0.31
Concentric Impulse-100ms [Ns]	168.3 (23.2)	163.55 (17.0)	0.24	0.71
Concentric RPD [W/s/kg]	386.0 (88.7)	410.7 (132.1)	0.22	0.89
Eccentric Mean Power [W/kg]	7.3 (0.6)	6.9 (0.8)	0.54	0.39
Eccentric Deceleration RFD [N/s/kg]	163.1 (36.6)	169.0 (67.2)	0.11	0.86
Eccentric Peak Velocity [m/s]	-1.5 (0.1)	-1.5 (0.2)	0.14	0.83
Eccentric Peak Power [W/kg]	25.3 (4.2)	30.2 (12.2)	0.59	0.32
Countermovement Depth [cm]	-30.4 (5.7)	-30.9 (5.6)	0.09	0.89

Note: cm = centimetres; ES = effect size; Imp-Mom = Impulse-Momentum calculation; /kg= variable expressed relative to bodyweight; ms = milliseconds; m = metres; N = Newtons; RFD = rate of force development; RPD = rate of power development; RSI = reactive strength index; s = seconds; W = Watts.

Table 4: Comparison of countermovement jump typical (CMJ-TYP) and alternative (CMJ-ALT) variables in start versus end of season tests.

Variable	Start of Season Mean (SD)	End of season Mean (SD)	ES (95% CI)	*p*-value	% Change	CV (95% CI)
CMJ-TYP						
Jump Height (Imp Mom) [cm]	45.18 (5.86)	45.48 (3.69)	0.06 (-0.80, 0.92)	1.0	1%	3.5 (3.1, 5.5)
Concentric Peak Force [N/kg]	29.63 (2.57)	33.24 (4.14)	1.05 (0.13, 1.96)	0.007*	12%	3.3 (2.9, 5.2)
Concentric Impulse [Ns]	263.89 (22.62)	250.95 (24.25)	-0.55 (0.32, -1.42)	0.454	-5%	2.1 (1.9, 3.4)
Concentric Peak Velocity [m/s]	2.99 (0.19)	2.90 (0.17)	-0.46 (0.44, -1.37)	0.845	-3%	1.6 (1.5, 2.6)
Concentric Peak Power [W/kg]	60.77 (7.12)	63.59 (5.24)	0.46 (-0.42, 1.32)	1.0	5%	1.9 (1.7, 3.1)
Eccentric Deceleration Impulse [Ns]	136.95 (13.80)	130.43 (11.44)	-0.52 (-1.38, 0.36)	1.0	-5%	5.7 (5.1, 9)
CMJ-ALT						
RSI-modified [m/s]	0.71 (0.11)	0.83 (0.11)	1.14 (0.17, 2.01)	0.009*	17%	3.2 (2.9, 5.1)
Flight Time:Contraction Time	0.95 (0.12)	1.11 (0.13)	1.28 (0.34, 2.22)	0.002*	17%	2.7 (2.4, 4.3)
Concentric Duration [ms]	223.30 (27.87)	185.72 (26.10)	-1.39 (-2.35, -0.44)	0.01*	-17%	3.4 (3.1, 5.4)
Eccentric Duration [ms]	422.44 (61.79)	373.25 (63.24)	-0.79 (-1.68, 0.10)	0.138	-12%	3.5 (3.1, 5.6)
Force at Zero Velocity [N]	2690.48 (171.64)	2928.35 (410.26)	0.82 (-0.13, 1.64)	0.97	9%	3.8 (3.4, 6)
Concentric Impulse-100ms [Ns]	165.72 (19.14)	189.33 (29.18)	0.98 (0.05, 1.86)	0.042*	14%	4.6 (4.1, 7.3)
Concentric RPD [W/s/kg]	399.47 (109.73)	545.60 (146.60)	1.14 (0.21, 2.05)	0.002*	37%	7.1 (6.4, 11.3)
Eccentric Mean Power [W/kg]	7.11 (0.68)	6.59 (0.91)	-0.65 (-1.53, 0.23)	0.503	-7%	4.4 (3.9, 6.9)
Eccentric Deceleration RFD [N/s/kg]	166.30 (52.93)	242.50 (94.98)	1.03 (0.08, 1.90)	0.01*	46%	11.0 (9.9, 17.5)
Eccentric Peak Velocity [m/s]	-1.49 (0.18)	-1.45 (0.13)	0.26 (-0.61, 1.11)	1.0	-3%	4.7 (4.2, 7.4)
Eccentric Peak Power W/kg]	27.97 (9.36)	28.99 (4.34)	0.15 (-0.72, 1.00)	1.0	4%	9.9 (8.9, 15.7)
Countermovement Depth [cm]	-30.63 (5.37)	-24.97 (3.42)	1.29 (0.32, 2.19)	0.02*	-18%	4.0 (3.6, 6.3)

Note: * = significant difference ($p < 0.05$) between start of season test and end of season test (in the 12 players who performed both assessments); cm = centimetres; CV = coefficient of variation calculated using data from 12 players who performed both the start of season test and a second test 4 weeks later under the same conditions (1 week post competition); ES = effect size; Imp-Mom = Impulse-Momentum calculation; /kg= variable expressed relative to bodyweight ms = milliseconds; N = Newtons; s = seconds; RFD = rate of force development; RPD = rate of power development; RSI = reactive strength index; s = seconds; W = Watts

4. Discussion

To our knowledge the present retrospective study conducted in elite rugby 7s is the first analysis to examine potential changes in both CMJ-TYP and CMJ-ALT variables between the start and end of a season and to describe a detailed kinetic profile of these athletes. Comparing CMJ performance at the beginning versus the end of season, we, found that while CMJ-TYP variables jump height and peak power were stable, over this period there were significant changes of a large magnitude in CMJ-ALT variables including concentric impulse 100ms, concentric rate of power development, concentric duration, eccentric deceleration rate of force development and RSI-modified, and in the CMJ-TYP variable concentric peak force. The finding that CMJ-ALT variables show larger magnitude and statistically significant changes while CMJ-TYP are stable aligns with the conclusions of previous studies regarding the greater sensitivity in detecting acute, residual and chronic responses to load. In these studies, CMJ-ALT variables such as phase durations, and time-limited or rate, force, power or impulse variables, were more sensitive markers of the neuromuscular response to the input of intense exercise or competition i.e., neuromuscular fatigue (Cormack et al., 2008; Gathercole et al., 2015) or of training i.e., positive adaptations (Kijowski et al., 2015). In the present analysis, this implies that by monitoring only CMJ-TYP variables practitioners might have incorrectly concluded that CMJ performance and neuromuscular status was stable across a season, whereas CMJ-ALT variables revealed team-level seemingly favorable neuromuscular responses to competition and conditioning between the start and end of the season.

As well as a tool for monitoring responses to training and competition load and adaptations to targeted training, CMJ kinetics have also been used to “profile” elite athlete populations. They have also been used to determine their underlying neuromuscular characteristics and strategies that may contribute to performance (Laffaye, Wagner, & Tombleson, 2014). CMJ-TYP variables such as jump height and concentric peak power and peak force are frequently reported due to associations with key physical qualities such as acceleration (Loturco et al., 2019; Morris, Weber, & Netto, 2020) and maximum velocity performance (Loturco et al., 2015). CMJ-ALT variables provide additional information by describing and quantifying the underlying neuromuscular qualities, temporal variables and strategies with which performance outputs are generated.

To provide context for the present data, Table 5 shows selected CMJ kinetic variables of other elite athletes, including sprinters (Tawiah-Dodoo & Graham-Smith, 2020), rugby league players (McMahon, Jones, & Comfort, 2019; McMahon et al., 2020) and elite footballers (Cohen et al., 2020) alongside the current cohort. RSI-modified for rugby 7s athletes is comparable to that of elite sprinters, with lower values for concentric peak power and eccentric peak power respectively (Laffaye et al., 2014) but larger values than elite rugby league and professional football for the variables presented. In our start of season analysis, there were no significant differences between forwards and backs in any CMJ variables. In our start of season analysis, there were no significant differences between forwards and backs in any CMJ variables. However, backs did show moderately higher concentric peak velocity and concentric peak power, eccentric peak power while eccentric mean power and force at zero velocity was moderately higher in forwards. As there were only five backs within the sample, our study may have been underpowered for such a comparison. This conclusion is supported by the findings of McMahon et al. (2020) who noted significantly higher (moderate to large effect size) jump height, RSImod, concentric peak and mean power in rugby league backs than forwards.

In the present analysis, concentric peak force was the only CMJ-TYP variable to display a significant change between start of season and end of season tests, with small non-significant improvements in jump height and peak power also observed. Gathercole et al. (2015) also reported that amongst CMJ-TYP, concentric peak force showed the greatest sensitivity to a 19-week training block in elite snowboard cross athletes. Corresponding to this study and in contrast to the minimal changes observed in CMJ-TYP variables, we observed significant increases of a large magnitude in a range of time related CMJ-ALT variables such as FT:CT, concentric rate of power development and eccentric deceleration rate of force development, of 17%, 37% and 46% respectively (Table 3).

While no other studies have examined changes in these alternative variables across a 7s season, Mitchell, Pumpa, Williams, and Pyne (2016) (season-long testing period) and Gibson et al. (2016) (three weeks testing period) found no change in jump height in 7s athletes. Mitchell et al. (2016) observed a significant decline in peak power in forwards, but due to the use of a linear transducer to determine power in this study rather than force platforms this data may not be directly comparable. However, a study involving a comprehensive kinetic analysis of force platform CMJ variables across a five-week pre-season training block in elite university basketball players reported a similar pattern observed here in the current study (Heishman et al., 2020). Significant increases in RSI-modified (0.71 to 0.83) and FT:CT (0.95 to 1.11) were reported, but no significant change in jump height (45.2 cm versus 45.5 cm). The present study therefore adds to the literature showing that the temporal, kinetic or strategy CMJ-ALT variables may provide greater sensitivity to the positive neuromuscular responses to periods of competition and training compared to ‘CMJ-TYP’ variables.

RSI-modified or its equivalent, FT:CT, is considered an indicator of lower limb explosiveness (rapid force development), stretch shortening cycle function and reactive qualities (Mitchell et al., 2016). Improvements in RSI-modified/FT:CT alongside stable jump height represents improved neuromuscular efficiency whereby the same performance output (jump height) is produced in a shorter time. This is driven by reductions in the contraction time components (eccentric and concentric duration). Interestingly, the concentric phase showed a significant and large magnitude decrease while the eccentric duration decrease was of moderate magnitude but not significant. Our analysis provides clues as to possible kinetic changes underpinning the improved neuromuscular efficiency globally represented by RSI mod/FT:CT.

The lack of change in peak velocity in this cohort, alongside large significant improvements in concentric peak force, RFD and time limited impulse variables supports the suggestion that RSI-modified is more strongly associated with strength than speed capabilities (Mitchell et al., 2016). We observed a clear pattern whereby time-constrained impulse, force, and power variables showed large changes, whereas their equivalent that represents a peak or overall, for the same phase or kinetic characteristic was stable, or declined.

Overall concentric impulse and eccentric deceleration impulse both showed non-significant moderate magnitude declines while there were large magnitude significant increases in concentric impulse 100ms (impulse in the first 100ms of the concentric phase) and eccentric deceleration rate of force development. Kijowski et al. (2015), reported similar patterns in response to a four-week plyometric/strength program following jump height and concentric peak power were relatively stable whereas there were significant increases in concentric rate of power development and eccentric deceleration rate of force development (Kijowski et al., 2015).

Concentric impulse 100ms has not been specifically examined longitudinally or part of group studies examining responses, but in a rehabilitation case report Taberner et al. (2020) highlighted its greater sensitivity to neuromuscular fatigue relative to overall concentric impulse. The value of characterising not only the magnitude of concentric impulse but also its “shape” has been previously highlighted by Mizuguchi, Sands, Wassinger, Lamont, and Stone (2015). The significant increase in concentric impulse 100ms we observed, represents an increase in early concentric phase force production and change in impulse shape that was not reflected in impulse across the concentric phase.

As impulse is determined by the magnitude of force and the time over which it is applied, increased values would be limited by the reduction in the time and range over which force was applied, demonstrated by the reduced countermovement depth (center of mass displacement). This would also explain the divergent response also observed in the two variables used to quantify the kinetics during this phase (Kijowski et al, 2015; McMahon et al., 2019; West et al., 2013). Eccentric deceleration rate of force development and eccentric deceleration impulse displayed a significant large magnitude increase and a moderate magnitude, non-significant decrease, respectively.

Interestingly, while there was a significant, large magnitude decrease in concentric duration and countermovement depth, eccentric duration only showed a moderate magnitude but non-significant decrease. This is perhaps counterintuitive; however, eccentric and concentric duration are not entirely equivalent in terms of the range or displacement over which they are calculated: concentric duration ends at toe-off (in plantar flexion) whereby center of mass displacement is higher than in the starting position (flat footed). Furthermore, from an adaptation perspective, eccentric duration comprises 3 subphases, which have been shown to respond differently to load (Cohen et al., 2020; Taberner et al., 2020). We suggest future work should report the duration of these subphases, to better define neuromuscular load-response.

It is worth noting that while eccentric deceleration impulse is recognised as a more reliable variable than eccentric deceleration RFD (Howarth et al., 2021), eccentric deceleration RFD asymmetries (Hart et al., 2019) and total eccentric deceleration RFD have been shown to be more sensitive markers of prior lower limb injury (Taberner et al., 2020). The present sample were well familiarised with the test and have a substantial training age, factors associated with better reliability, particularly in CMJ-ALT eccentric variables such as eccentric deceleration RFD (Howarth, Cohen, McLean, & Coutts, 2021). Furthermore, as highlighted by Howarth et al. (2021) determining the value of a variable in monitoring, requires consideration, not only of its the reliability (noise) but also its responsiveness to load (signal). The coefficient of variation’s we determined between the start of season and a test 4 weeks later (Table 4) are comparable with that of Howarth et al. (2021) in an inter-day reliability analysis in 36 elite Rugby (15’s) players across the first two days of preseason. This study also showed that the more sensitive rate-limited and phase duration CMJ-ALT variables have higher coefficient of variations than CMJ-TYP variables and whole phase impulses. Nonetheless, the magnitude of change observed in these variables far exceeded their coefficients of variation and SDs, suggesting these are meaningful changes in these variables.

It is important to note that towards the latter part of the season (and prior to the end of season test) in preparation for Olympic qualifications players were exposed to an increase in plyometrics and change of direction training was programmed to ensure peaking during regional qualification. As such, the changes observed may not reflect a typical 7s end of season loading profile.

Table 5: Comparison of selected CMJ variables across different sports.

	Jump Height (m)	RSI-modified	Concentric Peak Power (W/kg)	Eccentric Peak Power (W/kg)
Rugby 7s (Current Study)	0.45 ± 3.69	0.83 ± 0.11	63.59 ± 5.24	-28.99 ± 4.34
Elite Sprinters (Cohen et al., 2020)	0.57 ± 0.03	0.83 ± 0.07	75.00 ± 2.60	-33.36 ± 7.20
Rugby League (Claudino et al., 2017; West et al., 2013)	0.37 ± 3.99	0.52 ± 0.05	55.02 ± 4.91	-14.64 ± 11.90
Professional Football (McMahon et al., 2020)	0.40 ± 5.12	0.49 ± 0.07	56.41 ± 6.23	-20.04 ± 4.78

Nonetheless, positive adaptations related to the season as a whole and this final competition and training block were expressed in the time-constrained and rate variables, with concentric impulse 100ms, concentric rate of power development and eccentric deceleration rate of force development, suggested to be indicators of better stretch-shortening cycle function (Cormie et al., 2009; Kijowski et al., 2012).

While we cannot define the precise mechanisms underlying the alterations in CMJ-ALT variables observed, previous work suggests that strength and plyometric-specific training increases in eccentric deceleration rate of force development might be attributed to changes in muscle-tendon length, stiffness, muscle calcium sensitivity, and muscle pre-activity (Bohm, Mersmann, & Arampatzis, 2015; Kijowski et al., 2012). Consistent exposure to targeted resistance training is shown to produce changes in lower limb tendon properties such as increased stiffness (Bohm et al., 2015), and potentially an improved stretch-reflex sensitivity and increased muscle tendon stiffness during the eccentric phase, thereby increasing elastic energy utilization (Avela, Kyröläinen, Komi, & Rama, 1999). Irrespective of the mechanism, the large reduction in countermovement depth (*d* = 1.29, -18%) suggesting reduced knee flexion and time spent developing eccentric and subsequently concentric impulse indicates a more mechanically efficient triple extension, but only a trivial or small improvement in "output", i.e., jump height.

This study should be interpreted considering a few limitations. First, no "true" baseline measure was taken prior to the first tournament and although our defined start of season test was a week post-first tournament after a de-load period, neuromuscular changes could have already occurred with training and game exposure. Furthermore, logistics prevented us from obtaining an ideal reliability measure early in the season separated by several days or 1 week rather than four weeks that we were able to implement. Due to this and the small sample size of the main analysis, these findings should be confirmed in larger samples and using an inter-day reliability assessment implemented earlier in the season. Future research should also investigate the association between changes in specific CMJ variables and external workload over shorter time periods. We recommend that these types of analysis should be conducted within other elite sports, in order to confidently identify the variables that best quantify positive and negative adaptations to sports and position-specific loading patterns, as our results may be specific to the competition and training demands of Rugby 7s.

In summary, the comparison between the beginning and end of the season, Rugby 7s athletes showed stability in typically reported "performance" CMJ variables such as jump height and peak power, but large improvements in "alternative" kinetic and temporal variables (concentric impulse 100ms, reactive strength index modified, FT:CT, concentric peak force, concentric rate of power development, concentric duration, eccentric deceleration rate of force development and CMJ depth). This appears to show a positive neuromuscular change in athletes across the season, with an increased ability to express reactive and explosive qualities via improvements in rate- or time-limited measures of force, impulse and power, potentially driven by shorter phase durations manifesting in large improvements in RSI-modified and FT:CT. Use of these variables suggested that, at least within the 7s schedule, specific conditioning can produce ongoing enhancement of underlying neuromuscular performance characteristics. Therefore, as previously described in the context of short-term fatigue and recovery cycles, a comprehensive kinetic analysis which includes CMJ-ALT variables also enhances the detection of positive responses to the input of training and match loads over longer periods, whereas if only typical outputs are considered practitioners may not identify specific neuromuscular changes and may falsely conclude that their conditioning prescription has been ineffective.

Conflict of Interest

Daniel D. Cohen has been a consultant to Vald Performance, the suppliers of the force platform system used in the study.

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The reliability and validity of different jump-test performance metrics for fatigue monitoring in amateur boxing

Callum Blades[1, 2 *], Mick Wilkinson[2]

[1]Department of Sport, Exercise and Rehabilitation, Faculty of Health and Life Sciences, Northumbria University, UK
[2]School of Sport, Faculty of Education, Health and Wellbeing, University of Wolverhampton, UK

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ABSTRACT
Jump testing has become widespread practice in sport science for monitoring athletes' fatigue. The purposes of this study were to determine whether the number of trials performed influenced the reliability of jump-test performance metrics, as well as establish the construct validity of these jump-test performance metrics for monitoring fatigue in amateur boxing. After institutional ethical approval, seven novice (stature 1.81 ± 0.08 m, mass 82.7 ± 12.4 kg, age 20.9 ± 0.8 years, training <6 months) and seven experienced amateur boxers (stature 1.74 ± 0.12 m, mass 71.3 ± 13.5 kg, age 22.0 ± 3.4 years, training >18 months) participated. All boxers completed familiarisation and three experimental trials, involving a standardised warmup and eight jump-tests. These jump-tests included countermovement and squat jumps, performed bilaterally and unilaterally as well as vertically and horizontally. For each jump-test, 12 performance metrics were calculated using the maximum, mean or median height or distance, from combinations of the four attempts performed per jump-test, with and without one initial practice. Trial two also involved 3 x 2 min rounds of sparring to induce fatigue. Reliability was calculated for novice and experienced boxers separately using typical error between trials one and two, which ranged from 1.5 to 19 cm across the performance metrics. Construct validity was determined by a 2 x 2 within and between group ANOVA (novice v experienced, trial two v three). Only unilateral vertical squat jump height could discriminate experienced from novice boxers after a fatiguing sparring bout. Jump height of experienced boxers was lower than novices by 2.0 ± 0.2 cm (p = 0.01, 95% CI [1.1, 3.0] cm) when using the mean of two attempts after one practice. As typical error was 1.3 cm, results suggest that this jump-test and performance metric appear reliable and valid for monitoring fatigue in amateur boxing.

1. Introduction

Fatigue monitoring is widespread in sport science to avoid the development of non-functional overreaching, track long term improvements over time and inform training program periodisation (Halson, 2014). Amateur boxing is a high intensity intermittent sport where boxers perform 2-3 min rounds of exercise at a blood lactate averaging 13.5 ± 2 mmol/L, interspersed with 1 min rest periods of insufficient duration to enable complete recovery (Delvecchio, 2011). These rounds are performed during training, via sparring, as well as within competitive bouts, meaning that boxers accumulate substantial levels of neuromuscular fatigue from generating upwards of 2,643 N of force per punch (Delvecchio, 2011). The reduction in body mass that occurs before competitive bouts is also associated with a significant decline in neuromuscular system performance (Zubac et al., 2020). Consequently, it is necessary to identify effective monitoring batteries that are specific to the detection of neuromuscular fatigue in amateur boxing.

Effective fatigue monitoring batteries require reliable and valid tests (Pyne et al., 2014). A reliable test produces consistent results under standardised conditions (Ortega et al., 2008), while

*Corresponding Author: Callum Blades, School of Sport, Faculty of Education, Health and Wellbeing, University of Wolverhampton, UK, C.Blades@wlv.ac.uk

a valid test will correctly measure the concept of interest (Castro-Piñero et al., 2010). Although reliability is determined using test-retest protocols (Ortega et al., 2008), validity can be confirmed through either criterion or construct approaches (Castro-Piñero et al., 2010). Criterion validity is the extent to which a test correlates with a gold standard, while construct validity is the extent to which a test discriminates ability or predicts performance (Castro-Piñero et al., 2010). As there is no accepted gold standard test of fatigue (Lambert & Borresen, 2010), construct validity must be used alongside test-retest reliability to confirm the effectiveness of tests within an amateur boxing fatigue monitoring battery.

Jump tests are currently a popular field-based measure used in fatigue monitoring batteries (Taylor et al., 2012). The most common jump tests include countermovement jump (CMJ), squat jump (SJ) and horizontal jump, with all three possessing good levels of test-retest reliability (Markovic et al., 2004; Moir et al., 2009; Thomas et al., 2017). While a meta-analysis also infers strong construct validity of the CMJ for monitoring fatigue (Claudino et al., 2017), the validity of both the SJ and horizontal jump are less clear. While research confirms SJ height and soccer players training load were positively related throughout a season (Sams et al., 2018), it remains disputed as to whether SJ height provides greater reliability and validity to CMJ height for fatigue monitoring (Gathercole et al., 2015). The validity and reliability of all jump tests are further confounded by different metrics being calculated in the literature, with studies using the maximum height from two recorded jumps (Oliver et al., 2015), the maximum height from three recorded jumps (Wiewelhove et al., 2017), the mean height from three recorded jumps (Maulder & Cronin, 2005) and the maximum height from three recorded jumps after two practices (Thorpe et al., 2015). Consequently, further investigation is necessary to establish whether the validity and reliability of each jump test is affected by the number of recorded and practice attempts being used to calculate the metric of jump performance.

In addition to validity and reliability, the specificity of a test to the sport remains an important, but often overlooked, requirement of an effective test (Reilly et al., 2009). Considering this, a key physiological determinant of amateur boxing is the expression of unilateral lower body force horizontally (Chaabène et al., 2015). Despite this, mainly bilateral and vertical jumps have been investigated within the literature for fatigue monitoring (Maulder & Cronin, 2005; Oliver et al., 2015; Thorpe et al., 2015; Wiewelhove et al., 2017). Theoretically, horizontal and unilateral jumps should be more specific to amateur boxing, but this requires investigation in the context of fatigue monitoring. Therefore, the aim of this study was to examine the test-retest reliability and construct validity of various metrics of jump-test performance for fatigue monitoring in amateur boxing.

2. Methods

2.1. Design

A repeated measures parallel group design was used, with two groups comprising either novice or experienced amateur boxers. Each group completed one familiarisation trial and three experimental trials, with familiarisation using identical procedures to experimental trials. Familiarisation was separated from the experimental trials by 48 h, with 24 h of inactivity also separating each experimental trial. All trials commenced with 5 min of jogging at a pace standardised by a metronome to 132 beat/min, prior to four attempts at 12 different jump tests. From these attempts, 12 metrics of jump performance were calculated for each jump test. These metrics were calculated using the maximum, mean and median height/distance from different attempt combinations, with the first attempt being either recorded or a practice. The test-retest reliability of each jump performance metric derived from the jump tests was calculated between experimental trials one and two. Approximately 10 min after completing the jump tests in experimental trial two, boxers performed 3 x 2 min rounds of full contact sparring to induce fatigue. Construct validity was subsequently determined by comparing the decline in jump performance metrics between novice and experienced boxers over experimental trials two and three.

2.2. Participants

The study received institutional ethical approval from the Northumbria University Health and Life Sciences Research Ethics Committee and was conducted according to the Declaration of Helsinki. Fourteen male amateur boxers from Northumbria University Boxing Club provided their written informed consent to take part, after receiving a full verbal and written study explanation. Each boxer was unpractised at jump testing, free of lower extremity injury and had successfully passed an England Boxing medical for sparring. Seven boxers qualified as novice (stature 1.81 ± 0.08 m, body mass 82.7 ± 12.4 kg, age 20.9 ± 0.8 years), possessing under 6 months of training history and no inter-club sparring or competitive amateur boxing experience. Likewise, seven boxers qualified as experienced (stature 1.74 ± 0.12 m, body mass 71.3 ± 13.5 kg, age 22.0 ± 3.4 years), possessing over 18 months of training history and competitive experience including at least three inter-club sparring or competitive boxing bouts. Independent sample t-tests confirmed no difference between the groups in stature ($p = 0.22$), body mass ($p = 0.13$) or age ($p = 0.39$).

2.3. Procedure

Boxers commenced all trials by jogging for 5 min around a 10 m^2 square that was marked out by cones. The speed of jogging was standardised by a metronome to 132 beat/min, by instructing boxers to coincide their steps with the beat. The 12 jump tests were completed in the fixed order of bilateral vertical CMJ (BV-CMJ), left/right leg vertical CMJ, bilateral vertical SJ (BV-SJ), left/right leg vertical SJ, bilateral horizontal CMJ (BH-CMJ), left/right leg horizontal CMJ, bilateral horizontal SJ (BH-SJ), left/right leg horizontal SJ. Four attempts were completed for each jump test, with 15 s recovery between attempts and an additional 3 min of recovery between the vertical and horizontal jumps. For each unilateral jump, either the left or right leg was performed first according to random number generation.

All vertical jumps were recorded to 0.1 cm using an Opto Jump (Microgate, Bolzano, Italy), connected to a laptop computer

(Idea Pad 510, Lenovo, North Carolina, USA) running Opto Jump Next (Microgate, Bolzano, Italy). Boxers started with their feet approximately shoulder width apart and hands placed on hips. During the BV-CMJ, boxers squatted to a self-selected depth (established during familiarisation) before immediately jumping vertically for maximum height. For the BV-SJ, boxers squatted to a 90° knee angle that was measured by a goniometer (Cranlea, Birmingham, UK), before jumping vertically for maximum height following a 3 s pause with no countermovement. During both CMJ and SJ jumps, boxers were instructed to maintain knee and hip extension during flight, with slight knee and hip flexion permitted upon landing. Jumps were excluded if the boxers' hands did not remain on hips, or flexion of the hips or knees occurred during the flight phase. The left/right leg vertical CMJ and SJ were also performed identically to their bilateral counterparts, with the sole exception of requiring boxers to balance on their respective leg for 3 s prior to, and immediately after, jumping.

Horizontal jumps were recorded as the distance between a start line marked on the floor and the boxer's heel upon landing, measured to 1 cm using a tape measure (PowerWinder, Stanley, Slough, UK). Boxers started behind the start line with their feet approximately shoulder width apart and hands placed on hips. During the BH-CMJ, boxers squatted to a self-selected depth (established during familiarisation) before immediately jumping horizontally for maximum distance. For the BH-SJ, boxers squatted to a 90° knee angle that was measured by a goniometer (Cranlea, Birmingham, UK), before jumping horizontally for maximum distance following a 3 s pause with no countermovement. Jumps were excluded if the boxer's hands did not remain on hips or the feet did not land in a parallel stance. The left/right leg horizontal CMJ and SJ were also performed identically to their bilateral counterparts, with the sole exception of requiring boxers to balance on their respective leg for 3 s prior to, and immediately after, jumping.

The full contact sparring within experimental trial two was supervised by an England Boxing level two coach who provided maximal encouragement. Sparring occurred between two boxers in the same England Boxing recognised weight class, that also qualified for the same study group (i.e., novice v novice or experienced v experienced). A 7.32 m^2 ring (Competition Boxing Ring, Geezers, Norfolk, UK) and 453.6 g gloves (Sparring Gloves, ProBox, Gillingham, UK) were used, with boxers performing three rounds of 2 min exercise and 1 min rest. Immediately prior to sparring, boxers were permitted 10 min to undertake their own traditional pre-sparring warmup.

2.4. Statistical Analysis

Statistical analysis was performed using SPSS v26 with significance set at $p < 0.05$. After verification of underpinning assumptions, paired sample t-tests revealed no significant differences between the left and right leg for the vertical CMJ (p = 0.34), vertical SJ (p = 0.99), horizontal CMJ (p = 0.72) or horizontal SJ (p = 0.86). Therefore, only the left leg data were used and are hereby referred to as unilateral (i.e., UV-CMJ, UV-SJ, UH-CMJ and UH-SJ). From the four attempts completed per jump test, 12 metrics of jump performance were calculated using the maximum, mean and median height or distance achieved from different combinations of attempts, with the first attempt either being recorded or a practice (see Table 1). The test-retest reliability of each jump performance metric, from all the jump tests, was calculated using typical error (the standard deviation of the individual difference scores between trials ÷ square root of two) (Hopkins, 2000). Construct validity was determined using a 2 x 2 between and within group analysis of variance (ANOVA) between the novice and experienced boxers over trials two and three. For jump performance metrics where a significant group by time interaction effect was detected, Bonferroni adjusted confidence intervals were calculated on the difference between novice and experienced boxers' scores in trials two and three.

Table 1: Metrics of vertical jump height and horizontal jump distance that were calculated from four attempts at each jump test.

Metric	Attempt				Calculation
	1	2	3	4	
MAX 1	✓				Maximum height/distance from one recorded attempt.
MAX P+1	P	✓			Maximum height/distance from one recorded attempt after one unrecorded practice.
MAX 2	✓	✓			Maximum height/distance from two recorded attempts.
MAX P+2	P	✓	✓		Maximum height/distance from two recorded attempts after one unrecorded practice.
MAX 3	✓	✓	✓		Maximum height/distance from three recorded attempts.
MAX P+3	P	✓	✓	✓	Maximum height/distance from three recorded attempts after one unrecorded practice.
MEA 2	✓	✓			Mean height/distance from two recorded attempts.
MEA P+2	P	✓	✓		Mean height/distance from three recorded attempts after one unrecorded practice.
MEA 3	✓	✓	✓		Mean height/distance from three recorded attempts.
MEA P+3	P	✓	✓	✓	Mean height/distance from three recorded attempts after one unrecorded practice.
MED 3	✓	✓	✓		Median height/distance from three recorded attempts.
MED P+3	P	✓	✓	✓	Median height/distance from three recorded attempts after one unrecorded practice.

Note. ✓ = recorded attempt used in metric calculation, P = unrecorded practice attempt not used in metric calculation.

Table 2: Test-retest typical error of 12 metrics of jump height/distance calculated from eight jump tests, which were performed over two trials separated by 24 h of inactivity.

Metric	BV-CMJ (cm)	BV-SJ (cm)	UV-CMJ (cm)	UV-SJ (cm)	BH-CMJ (cm)	BH-SJ (cm)	UH-CMJ (cm)	UH-SJ (cm)
MAX 1	3.5	2.9	**1.7**	2.0	13	14	19	18
MAX P+1	3.0	3.1	2.3	1.4	13	11	19	17
MAX 2	3.2	2.5	1.9	1.6	12	11	15	17
MAX P+2	**1.5**	2.3	2.6	**1.3**	16	**10**	15	15
MAX 3	1.7	**2.2**	2.2	1.6	14	**10**	**13**	15
MAX P+3	2.0	2.8	2.2	1.5	**11**	**10**	**13**	16
MEA 2	2.9	2.5	1.8	1.6	**11**	12	17	16
MEA P+2	1.8	2.4	2.4	1.7	14	12	17	**13**
MEA 3	2.2	2.5	2.0	1.7	12	12	16	14
MEA P+3	2.0	2.5	1.9	1.6	13	11	14	15
MED 3	2.7	2.5	2.0	1.7	13	11	17	14
MED P+3	2.0	2.7	2.1	1.6	16	**10**	**13**	15

Note. **Bold** = lowest typical error per jump test, B = bilateral, U = unilateral, V = vertical, H = horizontal, CMJ = countermovement jump, SJ = squat jump. Refer to table 1 for metric calculations.

3. Results

The test-retest typical error of all metrics of jump performance, calculated from each jump test, are presented in Table 2. The lowest typical error recorded for each jump test was 1.5 cm (BV-CMJ), 2.2 cm (BV-SJ), 1.7 cm (UV-CMJ), 1.3 cm (UV-SJ), 11 cm (BH-CMJ), 10 cm (BH-SJ), 13 cm (UH-CMJ) and 13 cm (UH-SJ). The metrics of jump performance that most frequently produced the lowest typical error were the MAX P+2, MAX 3 and MAX P+3, with each metric producing the lowest recorded typical error for three jump tests. The MED P+3 produced the lowest typical error for two jump tests, with MAX 1, MEA 2 and MEA P+2 each producing the lowest typical error for one jump test.

Only three jump tests demonstrated construct validity by detecting a significant decrease in jump performance after sparring between trials two and three, as well as an interaction effect from boxers being categorised as novice or experienced (see Figure 1). For the BV-SJ, experienced boxers jump height was lower than novice boxers after sparring by 3.1 ± 1.0 cm (p = 0.03, 95% CI [0.5, 5.7] cm) for the MEA 2 and 3.0 ± 0.9 cm (p = 0.03, 95% CI [0.3, 5.4] cm) for the MED 3. Additionally, experienced boxers jump distance was lower than novice boxers after sparring on the UH-CMJ by 13 ± 3 cm (p = 0.04, 95% CI [1, 25] cm) for the MAX 3. Finally, experienced boxers jump height was also lower than novice boxers after sparring on the UV-SJ by 1.3 ± 0.3 cm (p = 0.04, 95% CI [0.1, 2.6] cm) for the MAX P+3, 2.0 ± 0.2 cm (p = 0.01, 95% CI [1.1, 3.0] cm) for the MEA P+2, 1.8 ± 0.5 cm (p = 0.01, 95% CI [0.1, 2.9] cm) for the MEA P+3, and 0.1 ± 0.1 cm (p = 0.02, 95% CI [0.4, 3.1] cm) for the MED P+3.

4. Discussion

The aim of this study was to examine the test-retest reliability and construct validity of various jump-test performance metrics for fatigue monitoring in amateur boxing. The jump performance metrics that most frequently produced the lowest typical error were the MAX P+2, MAX 3 and MAX P+3. Construct validity for monitoring fatigue was demonstrated by the BV-SJ MEA 2 and MED 3, the UH-CMJ MAX 3, plus the UV-SJ MAX P+3, MEA P+2, MEA P+3 and MED P+3. However, for the construct validity of these jump performance metrics to be considered meaningful, the 95% CI should exclude the respective typical error (i.e., the signal should exceed the noise of the test). The jump performance metric closest to achieving this was the UV-SJ MEA P+2, with all but 0.2 cm of the 95% CI [1.1, 3.0] cm being above the 1.3 cm typical error.

Unilateral jumps (UJ) appear more reliable and valid for fatigue monitoring than bilateral jumps (BJ). This is supported by the UV-SJ demonstrating the greatest potential for detecting construct validity beyond the respective typical error. Although UJ have previously been used to monitor limb asymmetries in athletes (Lockie et al., 2014), this study was the first to investigate their effectiveness at fatigue monitoring. The bilateral deficit provides one mechanism for UJ to more effectively monitor neuromuscular fatigue than BJ. The bilateral deficit describes a phenomenon whereby the force output from one leg during BJ is lower than the force output from one leg during UJ (Bobbert et al., 2006). This was evident during electromyography studies reporting greater neural activation of the quadriceps and hamstrings in one leg during UJ compared to BJ (Pappas et al., 2007). UJ may therefore be able to better stimulate neural drive than BJ, theoretically making it more sensitive to fatigue.

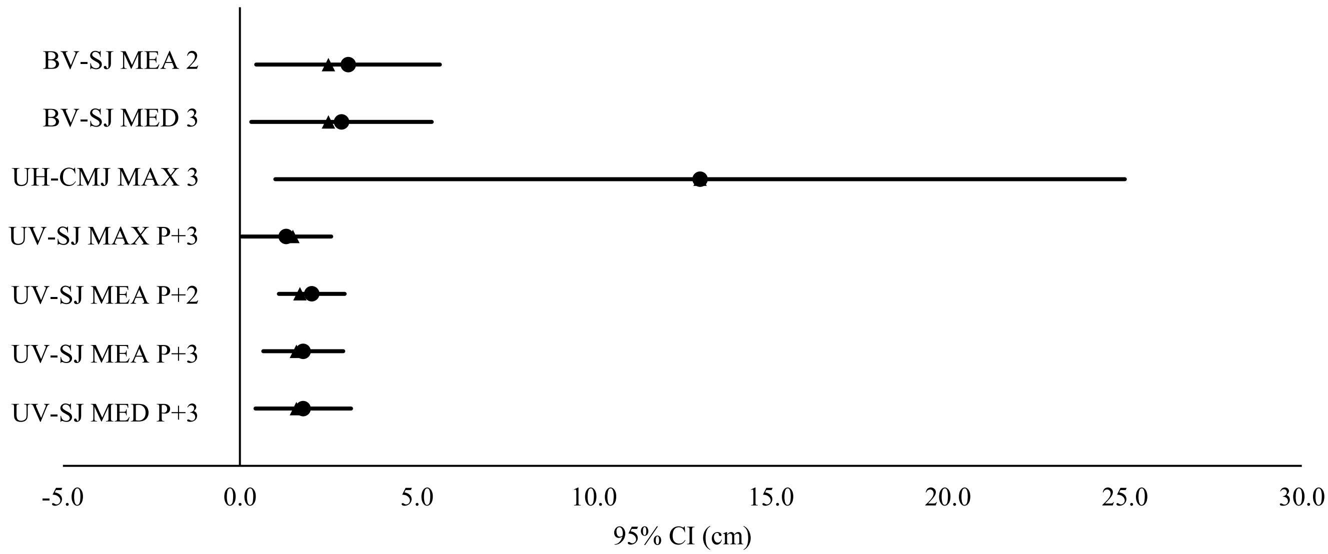

Figure 1: Forest plot of 95% confidence intervals (95% CI) showing the difference between novice and experienced boxers' jump height/distance from immediately prior to 24 h post sparring. All 95% CI indicate that experienced boxers' jump height/distance was lower than novices 24 h after sparring. *Note.* ● = mean difference, ▲ = test-retest typical error, B = bilateral, U = unilateral, V = vertical, H = horizontal, CMJ = countermovement jump and SJ = squat jump. Refer to Table 1 for metric calculations.

However, further research on the effectiveness of UJ for fatigue monitoring is needed before conclusive recommendations for use can be made.

Present findings also suggest that vertical jumps (VJ) are more reliable and valid for fatigue monitoring than horizontal jumps (HJ). This is because VJ consistently produced lower test-retest typical error than HJ. Furthermore, six of the seven jump performance metrics that demonstrated construct validity for fatigue monitoring were calculated from VJ tests. These findings concur with the wider literature reporting good validity of vertical CMJ and SJ for monitoring fatigue (Gathercole et al., 2015; Loturco et al., 2017; Oliver et al., 2015). However, the validity of HJ may have been expected because of greater biomechanical specificity to boxing movements (Delvecchio, 2011). One explanation for the poor validity and reliability of HJ, compared with VJ, may be the kinematic and kinetic differences that occur (Senshi et al., 2005). Kinematically, HJ produce higher anterior trunk lean, ankle dorsiflexion and knee extension than VJ (Senshi et al., 2005). This results in lower knee extension torque than is achieved during VJ (Senshi et al., 2005). Such biomechanical differences initiate different ground reaction forces (GRF), with VJ GRF directed almost entirely vertically, but HJ GRF directed horizontally and vertically (Seyfarth et al., 1999). Although the present study is limited by not measuring GRF, it can be speculated that VJ height may therefore be more valid for monitoring neuromuscular fatigue because all the neural drive is directed vertically and could therefore be better reflected in the resulting jump height. Whereas, during the HJ some of this neural drive may be lost as vertical GRF propulsion, which may not always therefore be reflected in jump distance. Further research is required to test this hypothesis though.

Present findings further indicate that the SJ appears more effective at fatigue monitoring than the CMJ. This was evident from six of the seven jumps that demonstrated construct validity for fatigue monitoring being SJ variations. This finding contradicts past evidence reporting that the CMJ and SJ were equally valid for monitoring fatigue (Loturco et al., 2017). This past research did however use force plates for determining jump height (Loturco et al., 2017), which are more accurate than the Opto Jump used in the present study (Glatthorn et al., 2011). Despite this, stretch shortening cycle (SSC) utilization and the length tension relationship (LTR) provide two explanations for SJ appearing superior to CMJ for fatigue monitoring. The SSC contributes additional force to increase jump height via factors such as tendon elasticity, in addition to neural drive (Nicol et al., 2006). Meanwhile, the LTR describes the variable force output that is produced at different muscle lengths, and by extension jump descent depth. The SJ eliminates the LTR by standardising descent depth to 90°, plus the SSC by pausing for 3 s. Consequently, it becomes less influenced by factors outside of neural drive and so may better reflect neuromuscular fatigue than CMJ height (Nicol et al., 2006).

Using three jump attempts appears best practice for fatigue monitoring. This is supported by the MAX P+2, MAX 3 and MAX P+3 metrics most frequently producing the lowest typical error, plus six of the seven jump performance metrics that demonstrated validity for fatigue monitoring also using three attempts. This finding supports multiple studies reporting that three jump attempts provided valid fatigue monitoring (Thorpe et al., 2015; Wiewelhove et al., 2017). Furthermore, the MEA P+2 demonstrated greatest potential for detecting changes greater than typical error, suggesting averages may be superior to maximum jump height. This is supported by the average of three attempts correlating significantly with footballers' training load, inferring validity for monitoring fatigue (Thorpe et al., 2015). Therefore, practitioners are encouraged to perform one practice UV-SJ, before using the average height from two recorded attempts to most effectively monitor fatigue in amateur boxing.

Opto Jump was used to measure jump height in this study because the system is highly portable and widely utilised in applied practice. While the Opto Jump demonstrates excellent test-retest reliability and validity in comparison to a gold standard force plate (Glatthorn et al., 2011), it should be noted that force plates remain the gold standard measure of jump performance because they enable an analysis of jump strategy via the force-time record that is not always reflected in the jump outcome of height/distance (Buckthorpe et al., 2012). Caution is therefore needed when comparing the findings of this applied study against results obtained in laboratory conditions using a gold standard force plate.

5. Conclusion

Based on the results of this study, practitioners seeking to monitor fatigue in amateur boxing should utilise a unilateral squat jump that is performed vertically. One unrecorded practice attempt should firstly be performed at this jump test, before taking the mean of two subsequent recorded attempts.

Conflict of Interest

The authors declare no conflict of interests.

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Characterisation of physiological performance measures in arid and humid military operational environments

Edward T. Ashworth[1 *], James D. Cotter[2], Andrew E. Kilding[1]

[1] Sport Performance Research Institute of New Zealand, Auckland University of Technology, New Zealand
[2] School of Physical Education, Otago University, New Zealand

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ABSTRACT

Military personnel often deploy into hot environments that impose substantial strain on physical and cognitive performance. Hot environments can present as arid or humid and occur in different terrains, requiring different operational approaches. The aim of this study was to characterise the physiological, cognitive and perceptual strain experienced by military personnel during typical operations in arid and humid environments. Nine pack-fit military personnel participated in two heat-stress tests to exhaustion, one in an arid environment (44°C, 21% humidity) and the other in a humid environment (33°C, 78% humidity). Participants walked at 5 km.h-1 while physiological, cognitive and perceptual measures were recorded. Tests were terminated volitionally, or by excessive core temperature or heart rate. The operational environments induced similar physiological strain, resulting in no difference in time to exhaustion (p = .155). The humid environment saw a greater elevation in core temperature (+0.3°C, p < .001) and heart rate (+5 b.min-1, p < .001). Skin temperature was greater in the arid environment (+0.4, p < .001) as was sweat evaporation (+0.3 L.h1, p = .045). Baseline performance predictors only provided moderate predictions of performance, whereas changes in perceptual measures provided the best performance predictors during the exercise, specifically perceptions relating to thermal sensation (β = -.65 - -.80) and sleepiness (β = -.79 - -.87). No differences in cognitive performance were observed (p > .075). The humid operational environment elicited a greater thermal strain that may threaten safety, and impair performance, to a greater degree than the arid environment. Perceptual measures of thermal sensation and sleepiness were the best predictors of test termination and could likely be used to monitor thermal tolerance in field settings.

1. Introduction

Military personnel deployed abroad are often exposed to different environments from that which they typically live and train in (Parsons et al., 2019). Regions with tropical climates are predisposed to conflict as weather patterns that affect food production can lead to civil unrest, which in extreme cases leads to conflict and international military intervention (Humphreys, 2005; Koubi, 2019). Climate change is already exacerbating resource competition and conflict and will worsen. Therefore, military operations in extreme environments are expected to rise (CNA, 2007; Reuveny, 2007; Smith, 2007; Brzoska & Fröhlich, 2016).

Hot environments pose a unique challenge to military operations as military-specific factors, such as carrying heavy loads and wearing protective gear, increase endogenous heat production and restrict heat loss (Taylor, 2015), thereby impairing work capacity and predisposing military personnel to exertional heat illness (Casa et al., 2012). Exertional heat illness can present as heat syncope, heat exhaustion, and in extreme cases heat stroke, which can cause organ damage, and in some cases death (Carter et al., 2005; Howe & Boden, 2007; Goforth & Kazman, 2015). Therefore, understanding the effects and mitigation of heat stress is important for military performance and safety in such environments.

*Corresponding Author: Edward Ashworth, Auckland University of Technology, New Zealand, eashworth@health.ucsd.edu

Hot environments are typically characterised by either very high ambient temperatures and low humidity (i.e., arid), or high ambient temperatures and high humidity. Arid conditions are typical of desert environments and have been encountered recently by numerous international militaries in Afghanistan and the Middle East (Armed Forces Health Surveillance Branch, 2019). Humid environments are often found in jungle environments, and have been encountered in tropical regions of Asia (Forster, 1951; Haisman, 1972). Heat stress differs between these environments, with the high ambient temperature in arid environments causing heat gain via sensible exchanges (Nadel, 1979), while the vapour pressure in humid environments minimises sweat evaporation (Akerman et al., 2016; Gonzalez et al., 1974). Given that evaporative heat loss is the main avenue for heat loss during moderate and heavy physical activity in humans, a greater thermal challenge is likely to occur in humid environments (Maughan et al., 2012; Muhamed et al., 2016).

In military contexts the environmental characteristics and terrain influence the carried loads and protective clothing requirements of each soldier (Eddy et al., 2015; Larsen et al., 2011), which may inadvertently augment the effects of hot environments (Boffey et al., 2019; McLellan, 2001). For example, arid environments consist primarily of open areas where air support is more often available, and soldiers often move alongside vehicles. Consequently, the carried pack is relatively light, but as open conflict is more likely, more body armour is worn, further restricting heat loss from the torso (Johnson et al., 1995). Conversely, a humid jungle environment often requires self-sufficiency, requiring a larger pack. However, as camouflage and stealth play a greater role, less body armour may be worn.

Given the environmental differences in the presentation of heat and the expected mission objectives dictating a unique gear loadout it is likely that the environments place different physiological strain on soldiers. Understanding these differences allows training plans prior to deployment to be tailored for each environment. Additionally, identification of physiological variables that influence or predict subsequent performance in the heat is important to help inform safety outcomes and assist both deployment selection and real-time monitoring of military personnel in the field. Therefore, the aims of the current study were two-fold. Firstly, to determine physiological responses to military activity in arid and humid environments, and secondly, to determine factors that may predict performance both prior to, and during, exercise in arid and humid environments.

2. Methods

2.1. Participants

A randomised cross-over design was used, with 9 participants completing two heat-stress tests (HSTs); one HST in a humid environment (33°C, 75% relative humidity (RH) [27 g.m-3 absolute humidity]) and the other in an arid environment (46°C, 10% RH [7 g.m-3 absolute humidity]). Temperatures were matched on wet-bulb globe temperature (~30°C WBGT). During each HST several physiological, perceptual, and cognitive assessments were conducted (Figure 1). Each HST was conducted at least one week apart. University (AUTEC: 17/420) and New Zealand Defence Force (6755/1) ethical approval was obtained, and informed consent obtained in writing from all participants as per the Declaration of Helsinki. Nine pack-fit military personnel (8 males, 1 female) volunteered to participate in the study (age 32.6 ± 9.4 y, body mass 81.1 ± 10.0 kg, 2.4 km run time 9:40 ± 1:11 min:s, estimated $\dot{V}O_2$ 54.2 ± 6.1 mL.kg^{-1}.min^{-1}).

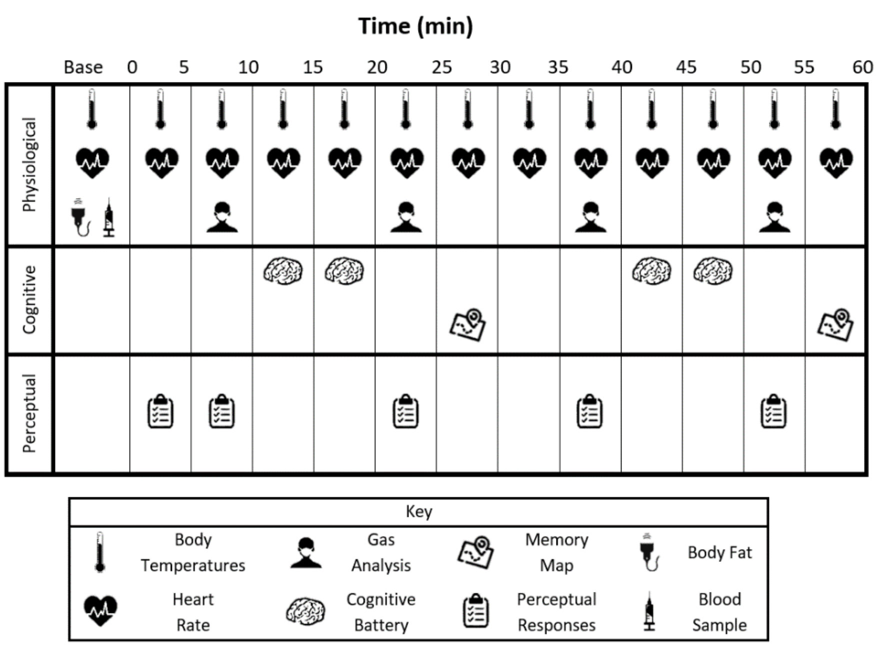

Figure 1: Schematic of tests conducted over the first 60 min in each heat-stress test. From 60 to 120 min measures were taken in the same order.

2.2. Heat-Stress Test

Heat-stress tests were conducted at the same time of the day for each participant. Participants were asked to avoid strenuous activity for the 24 h preceding each HST and were asked to record their food intake so that it could be replicated for the subsequent trial. Each HST was carried out in an environmental chamber (Design Environmental, Simultech Australia, Australia), beginning with 10 min of seated rest, followed by walking on a treadmill (Platinum Club Series, Life Fitness, Illinois, USA) at a fixed speed of 5 km.h^{-1} for 2 h or until termination criteria were met. Termination criteria were voluntary termination or ethical end points being reached for core temperature (> 39.3°C) (Aoyagi et al., 1995) or heart rate (> 95% age-predicted maximum for 1 min) (Tanaka et al., 2001). Time to exhaustion (TTE) was taken as the time at test termination. Participants were dressed according to the environment they would be operating in. For the arid environment participants wore body armour (~10 kg), a small backpack (~15 kg), helmet, and hiking shoes (total ensemble 31.1 ± 2.3 kg) (Figure 2). For the humid environment participants wore load-carrying webbing (~ 8 kg), a large backpack (25 kg), a jungle hat, and jungle boots (total ensemble 36.4 ± 2.1 kg) (Figure 2). In both environments participants also carried a rifle (~3 kg, included in total ensemble weights) and wore military uniform comprised of long-sleeved shirt and trousers. Fluid intake was allowed *ad libitum* up to a maximum of 2 L.h^{-1}, as per military rations, and was recorded.

2.2.1. Baseline Measures

Prior to the start of each trial, a resting urine and a blood sample were obtained from each participant. Urine was used to assess hydration status from urine specific gravity (USG) (Atago, Japan). There was no euhydration requirement to begin each trial. Blood was obtained by venepuncture of an antecubital vein, without stasis, into a 6 mL K_2EDTA vacutainer (Becton Dickinson and Co, USA). Vacutainers were then centrifuged (1500g for 15 min at 4°C) and the separated plasma was stored at -80°C until heat-shock protein analysis. Body fat was assessed via ultrasound (12L, Vivid S5, GE Healthcare, Chicago, IL) of the abdomen, 2 cm lateral to the umbilicus (Leahy et al., 2012; Marfell-Jones & Lindsay, 2006), given that subcutaneous adipose tissue thickness at the abdomen has been shown to correlate strongly with body fat measured by DEXA (Leahy et al., 2012; Wagner, 2013). Participants were weighed both semi-nude and fully dressed (i.e. all protective equipment on), pre- and post- HSTs, for calculation of whole-body sweat rate (*(semi-nude weight change + fluid consumption) ÷ walking time*) (Buono et al., 2009). Evaporated sweat rate was calculated by observing the difference between the undressed and dressed weight, thereby accounting for sweat absorbed by the clothing (*[semi-nude weight change – fully dressed weight change] ÷ walking time*) (Amos et al., 2000).

2.2.2. Continuous Measures

Core body temperature was recorded rectally, using a flexible thermistor (Hinco Instruments, Australia) self-inserted ~10 cm beyond the anal sphincter. Skin temperature was measured on the right-hand side of the body at the chest, bicep, thigh, and calf using skin temperature probes. Rectal and skin temperature were logged at 1 Hz (SQ2020, Grant Instruments, Cambridge, UK). In preparation for analysis, rectal and skin temperature readings were filtered due to noise caused by connections with the logger and occasional skin temperature probes losing contact with the skin due to the humid microenvironment. A filter was applied to remove readings that changed by more than 0.1°C.s^{-1}. Then a low-pass Butterworth filter of 0.02 Hz was applied to the data. Missing data were filled with linear interpolation.

Figure 2: Gear loadouts for the humid (left) and arid (right) environments for each heat-stress test.

Mean skin temperature was calculated using the following formula (Ramanathan, 1964):

$$T_{Sk} = 0.3T_{Chest} + 0.3T_{Bicep} + 0.2T_{Thigh} + 0.2T_{Calf}$$

If a thermistor became askew or off the skin, the equation was modified to proportionally compensate the weights of the three remaining sensors to maintain the summation of coefficients to 1.0, as has been done previously (Ashworth et al., 2021).

Cardiac frequency was measured from ventricular depolarisation using a heart rate monitor (Polar RS800CX, Kempele, Finland), with values recorded every 5 min.

The slope of each continuous measure was calculated by the change from walking onset to exercise termination divided by walking time.

2.2.3. Periodic Measures

Several measures were taken periodically throughout each HST. Perceptual measures were taken every 15 min, involving ratings of perceived exertion (RPE) (15-point scale ranging 6-20 arbitrary units (AU)), thermal discomfort (1-10 AU), thermal sensation (1-13 AU), feeling (-5 - +5 AU) and sleepiness (1-9 AU). Respiratory gas analysis was conducted for 4 min every 15 min with participants breathing through a mouthpiece connected to a calibrated, automated system (Trueone 2400, Parvo Medics, Utah, USA). Rates of oxygen uptake ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) and the respiratory exchange ratio (RER) were measured to evaluate substrate use during exercise. Carbohydrate oxidation ($g.min^{-1}$) was calculated from the following equation (Jeukendrup et al., 2005):

$$4.21\ \dot{V}CO_2 + 2.962\ \dot{V}O_2$$

Change scores for these measures were taken as the difference between the first and last measurement of the variable within each participant within each session. Due to the greater carried load, walking in the humid condition was predicted to incur a 6% higher metabolic rate (and therefore also rate of heat production), based on published calculations (Pandolf et al., 1977).

2.2.4. Cognitive Testing

A series of cognitive assessments were completed during each HST. Each battery lasted ~10 min and commenced at 10, 40, 70 and 100 min, unless test termination occurred prior. Simple reaction time was assessed using an electronic tablet (Nova 2 Lite, Huawei, Shenzhen) application (Reaction Time Tests for Science, Andrew Novak, 2016), which required participants to respond to a red circle appearing on a screen. Discrimination reaction time was assessed in a similar manner, with participants again responding to a red circle, but also avoiding responding to blue and black circles that appeared. A serial arithmetic task was used to assess cognitive throughput (Kase, 2009) to determine information processing speed. This required subtracting either 7 or 9 from a 4-digit number as many times as possible within one minute. A digit span task was used to assess working memory (Hocking et al., 2001). Participants were required to memorise a series of numbers read out to them, and then repeat them back, but in the reverse order. The test began with 3 digits being read out and increased by 1 digit after correctly recalling numbers twice at a given level, with the test ending once an incorrect sequence was repeated twice at the same level. Due to a lack of familiarisation, the first test for all non-reaction time cognitive tasks was removed from analysis. Following completion of this cognitive testing battery a NASA task-load index (TLX) was given to participants to indicate how they perceived the tasks to be, specifically in relation to mental, temporal and physical demands, as well as performance, effort and frustration (21-point scale).

Furthermore, a declarative memory task was also conducted using a memory map. The task involved memorising a simplified, fictional urban town plan, regarding a predefined route, the roads travelled along, landmarks and directions. The task was presented to participants at 25 and 85 min for 2 min, alongside a list of predetermined questions they would be required to answer. Following removal of the memory map participants were required to retain the information for ~30 min. At 55 and 115 min the predetermined questions were read aloud, and participants answered orally.

2.2.5. Blood Analysis

Thawed plasma samples were analysed for extracellular heat-shock protein 70 (HSP70) using a commercially available HSP70 High Sensitivity Enzyme-Linked Immunosorbent Assay (ELISA) kit (ab133061, Abcam, Cambridge, UK) run according to the manufacturer's instructions. The intra assay coefficient of variation for HSP70 was 4.9%.

2.3. Statistical Approach

Data analysis was conducted in two phases: the first compared the change in physiological variables over time between the two environments, while the second involved a linear regression for each variable and performance in each environment. All analyses were conducted in R version 3.6.1 (R foundation for Statistical Computing, Vienna, Austria).

To compare variables between environments, linear mixed models were fitted for each variable. Environment, time, and order (whether the arid or humid heat-stress test was conducted first) were used as fixed effects, with participant as the random effect. The model-generated estimated means are reported, with either standard deviation or 95% confidence intervals and p-values where appropriate. The alpha level was 0.05. For data with multiple time points, *post hoc* tests, with Bonferroni correction, were conducted using a time by environment interaction.

For regression analyses, predetermined variables of interest were selected and inputted into a linear regression model along with the performance outcome; walking time. Before running regression analysis each variable was checked for normality using a Shapiro-Wilk test, and homoscedasticity by plotting residuals. Data that did not meet normality were either log transformed or reciprocated prior to regression analysis, which overcame issues of non-normality. The lm.beta function, from the QuantPsyc package, was used for analysing each regression. Data are reported as both standardised (β) and unstandardised (B) regression coefficients, with a 95% confidence interval shown. The strengths of the standardised regressions were classified by the following correlation guidelines: very weak < 0.2, weak 0.2-0.4, moderate 0.4-0.6, strong 0.6-0.8, and very strong 0.8-1.0 (Evans, 1996).

3. Results

3.1. Environmental Differences

The actual temperature and humidity during the humid trials was 33.4 ± 0.6°C and 78 ± 2% RH (28 $g.m^{-3}$ absolute humidity), while in the arid trials it was 44.3 ± 0.5°C and 21 ± 2% RH (13 $g.m^{-3}$ absolute humidity), providing WBGTs of 31.1°C and 31.5°C, respectively. Baseline characteristics of body mass, body fat, USG and sleep quality were not different between environments (all $p > .262$).

No differences were observed in TTE between the two environments (Humid: 73.1 ± 12.8 min; Arid: 82.3 ± 22.0 min; $p = .155$) (Figure 3). Of nine HSTs in the humid environment, 5 (56%) were terminated due to rectal temperature rising beyond the ethical threshold limit, one due to heart rate, and the remaining three were voluntarily terminated. In the arid environment HST, 4 (44%) were terminated due to rectal temperature, one due to heart rate, and the remaining four were voluntarily terminated.

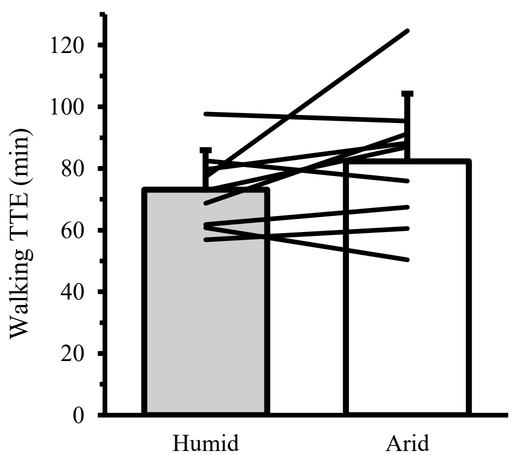

Figure 3: Walking time to exhaustion (TTE) in a simulated pack march in humid and arid environments in full military protective equipment. Individual responses are displayed by individual black lines.

3.1.1. Physiological Differences Between Environmental Conditions

While no significant differences were evident at rest or in the slope of rectal temperature between environments, during exercise rectal temperature was higher in the humid environment ($p < .001$; Table 1, Figure 4). When extrapolated to determine how long it would be before rectal temperature reached 40°C, exercise in the humid environment was projected to last 95 min, compared to 120 min in the arid environment (Figure 4). Conversely, the arid environment had a ~0.5°C higher skin temperature across the trial, despite no baseline differences, or differences in the rate of rise in skin temperature (Table 1). Heart rate in the humid environment was elevated by a time-averaged ~5 $b.min^{-1}$ in comparison to the arid environment, although other differences in heart rate were minimal (Table 1). Although overall sweat rate was not significantly different between conditions, evaporated sweat rate was ~40% greater in the arid environment (Table 1). No differences were observed in any measure of hydration (Table 1).

The $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$ all increased significantly throughout the trial (all $p < .001$). Between conditions, a 10% greater $\dot{V}O_2$ was present in the humid condition (Humid: 19.8 ± 2.5 $mL.kg^{-1}.min^{-1}$; Arid: 18.0 ± 2.2 $mL.kg^{-1}.min^{-1}$; $p < .001$), which was close to the 6% predicted, and was supported higher $\dot{V}_E$ (Humid: 47.0 ± 12.1 $L.min^{-1}$; Arid: 42.6 ± 9.8 $L.min^{-1}$; $p < .001$) and $\dot{V}CO_2$ (Humid: 1.40 ± 0.21 $L.min^{-1}$; Arid: 1.28 ± 0.18 $L.min^{-1}$; $p < .001$). Estimated substrate partitioning was comparable between conditions, based on respiratory exchange ratio (Humid: 0.88 ± 0.04; Arid: 0.88 ± 0.05; $p = .848$), and showed a trend for faster oxidation of carbohydrate in humid conditions (Humid: 1.2 ± 0.3 $g.min^{-1}$; Arid: 1.1 ± 0.4 $g.min^{-1}$; $p = .063$).

3.1.2. Perceptual Differences

All perceptions worsened throughout each condition (all $p < .001$). RPE was slightly but significantly elevated in the humid environment compared to the arid environment (Humid: 12.9 ± 2.6; Arid: 12.4 ± 2.8; $p = .040$). However, there were no differences between environments for thermal discomfort, thermal sensation, sleepiness or feeling state (all $p > .186$).

3.1.3. Cognitive Differences

No differences in cognitive performance existed between environments (all $p > .220$) or over time (all $p > .075$). Similarly, cognitive perception was not different between the environments in the task-load index (all $p > .075$), although increases in mental, physical, and temporal demand, as well as effort and frustration all occurred over time in both environments (all $p < .011$) (Figure 5).

3.2. Regression

Both standardised and unstandardised regression coefficients between individual measures and walking TTE are presented in Table 2. Baseline measures were generally poor/weak predictors of TTE. During exercise the change in physiological values produced moderate to strong relationships, although the variability was pronounced. Perceptual changes were the strongest indicators in both conditions.

Table 1: Physiological and perceptual responses during a simulated pack march in full military protective in humid (33°C, 78% RH) and arid (44°C, 21% RH) environmental conditions.

Variable	Humid	Arid	*p*-value
Rectal Temperature (°C)			
Average	38.1 ± 0.8	37.8 ± 0.7	**< .001**
Resting	36.9 ± 0.8	36.9 ± 0.7	.967
Slope (°C.h^{-1})	1.7 ± 0.3	1.6 ± 0.3	.462
Skin Temperature (°C)			
Average	36.2 ± 0.7	36.6 ± 0.8	**< .001**
Resting	34.1 ± 0.7	34.2 ± 0.8	.423
Slope (°C.h^{-1})	1.9 ± 0.7	2.0 ± 0.7	.642
Heart Rate (b.min^{-1})			
Average	146 ± 21	141 ± 23	**< .001**
Resting	76 ± 14	76 ± 13	.880
Slope (b.min^{-1}.h^{-1})	39 ± 13	40 ± 14	.893
Sweat Rate (L.h^{-1})	1.2 ± 0.1	1.3 ± 0.1	.187
Evaporated Sweat Rate (L.h^{-1})	0.6 ± 0.6	0.9 ± 0.4	**.045**
Rate of Fluid Consumption (L.h^{-1})	0.6 ± 0.3	0.7 ± 0.5	.577
USG Pre	1.011 ± 0.006	1.016 ± 0.007	.069
USG Post	1.017 ± 0.009	1.017 ± 0.010	.827

Note: slopes are calculated from exercise onset, and not resting values.

4. Discussion

The first aim of this study was to compare the physiology of each environment. Results showed the humid environment to be marginally more stressful, with higher core temperature, higher heart rate and a greater oxygen requirement. The understanding of these differences allows for specific preparation ahead of deployment, including heat acclimation, equipment design and mission planning. The second aim was to assess the strength of physiological variables at predicting performance in hot environments. To this end several factors were found in each environment that predicted performance, including factors unique to each environment.

4.1. Performance

Despite differences in environmental conditions, gear loadouts and physiological responses, there was no difference seen in performance between arid and humid environments (Figure 3), with minimal differences in the reasons for test termination. Together these similarities indicate the overall thermal strain in both environments was similar, likely due to the comparable WBGT, originally developed to quantify heat stress (Yaglou & Minard, 1957). However, the WBGT does not account for the difference in clothing and protective equipment worn by soldiers. It was expected that the larger and heavier pack carried in the humid environment would exacerbate endogenous heat production while also impairing evaporative heat loss and thereby cause earlier test termination (Dorman & Havenith, 2009). However, it is possible that the combination of body armour and backpack in the arid environment may have comparatively restricted heat loss from the chest (Johnson et al., 1995), helping to nullify the effects of a heavier pack in the humid condition.

4.2. Body Temperatures

Higher rectal temperatures were observed in the humid environment than the arid environment (Table 1, Figure 4). While this is likely partially accounted for by the additional metabolic heat production caused by the heavier carried load (Dorman & Havenith, 2009), there was also a reduced evaporated sweat rate, with the same absolute sweat rate, suggesting reduced evaporative heat loss. Despite no statistical difference in the rate of rise in rectal temperature, extrapolation of the data revealed that rectal temperature would reach 40°C 25 min faster in the humid environment (Figure 4). While military personal can likely still perform beyond this threshold safely (Ely et al., 2009; Lee et al., 2010; Veltmeijer et al., 2015), it represents a limit at which heat stroke is known to occur, and therefore safety guidelines suggest that exercise should be

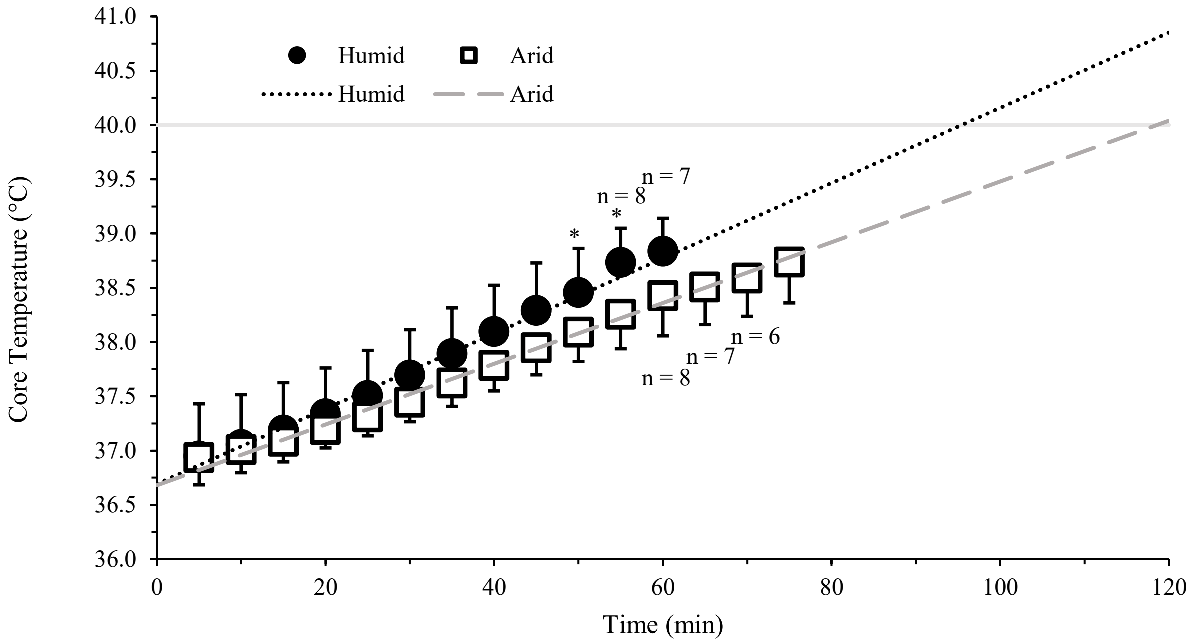

Figure 4: Rectal temperature during a simulated pack march in either a humid (33°C, 78% RH) or arid (44°C, 21% RH) environment. Trendlines display the predicted means based on recorded data, only for when *n* = 9. Data are plotted as mean ± standard deviation for *n* = 9 unless otherwise stated (data are stopped once *n* < 6 and is noted when it changes). **p* < .05 between conditions at individual time-points.

restrained beyond this threshold (Goforth & Kazman, 2015; Smith et al., 2016). Indeed, reducing core temperature below 40°C rapidly after exercise drastically reduces the mortality risk (Casa et al., 2012). However, in real-world military contexts, heat stress is often not alleviated and rectal temperature continues to rise even after the cessation of exercise, placing soldiers in danger, even if exercise is stopped (Giesbrecht et al., 2007; Smith et al., 2017). In the humid environment a 40°C rectal temperature would have been seen only 20 min after the average termination time, highlighting the imminent danger of exercise in humid environments. However, it should be noted that the 95 min mark where rectal temperature is calculated to reach 40°C in the humid condition falls outside of the 95% confidence interval (Table 1), suggesting internal cues can help reduce risk by terminating exercise in both environmental conditions. Therefore, when operating in these environments, particularly humid environments, continuous physiological monitoring of soldiers may be valuable to ensure activities are conducted safely (Buller et al., 2018; Parsons et al., 2019; Tharion et al., 2013), as is understanding methods for rapidly cooling individuals (Carter et al., 2007; Casa et al, 2012; Epstein et al., 2012).

The strength of the relationships between rectal temperature and performance is strengthened by the ethical termination of trials when core temperature exceeded 39.3°C, although, as mentioned above, internal cues such as central fatigue likely also lead to test termination (Nybo & Nielsen, 2001, Tucker et al., 2004). The stronger relationship between rectal temperature slope and performance in the humid environment may also be explained by this, where 56% of heat-stress tests were terminated due to high core temperature, compared to only 44% in the arid environment. Nonetheless, this ethical limit was put in place as it was deemed unsafe for core temperature to rise any further, and is the point where physical activity should be restrained in the field, if possible (Goforth & Kazman, 2015; Taylor et al., 1997). High rates of rise in core temperature have previously been identified to increase hyperthermia risk and heat-illness symptoms (Armstrong et al., 2010; Maughan et al., 2012), highlighting the desire for a reduced rate of rise in core temperature (Hunt et al., 2016). Therefore, to prioritise safety, core temperature should be monitored. Although less practical, the ability to monitor core temperature during exercise, either using a heat tolerance test prior to departure or real-time monitoring of soldiers in the field (Buller et al., 2018; Epstein et al., 2017), provides a much stronger predictor of performance (Table 2).

The arid environment induced a higher skin temperature (Table 1), likely through heat gain from the environment that occurs when temperatures exceed 35°C (Nadel, 1979). This is in line with recent findings from Lei et al (2020) which showed that, at a constant absolute humidity, elevating temperature increases skin temperature, without affecting other thermoregulatory variables. In the current study however, core temperature was increased in the humid condition as absolute humidity in the humid environment was 4 times greater than in the arid environment. The elevation in skin temperature impairs heat loss as it minimises the core-to-skin temperature gradient (Chou et al., 2018). The lower humidity in the arid environment facilitates heat loss (Akerman et al., 2016), explaining the lower rectal temperature despite a higher skin temperature. The higher

Table 2: Regression analysis predicting walking time (TTE) using baseline and exercising predictors for a simulated heat-stress pack march in humid (33°C, 78% RH) and arid (44°C, 21% RH) environments. Data are displayed as standardised (β) or unstandardised (B) coefficients with a 95% confidence interval.

	Humid		Arid	
	β	B	β	B
Baseline Characteristics				
Aerobic Fitness	.18 (-.55, .75)	0.4 (-1.5, 2.2)	.58 (-.13, .90)	2.1 (-0.5, 4.7)
Resting Rectal Temperature (°C)	-.31 (-.80, .44)	-9 (-32, 15)	-.15 (-.74, .57)	-15 (-103, 74)
Resting Skin Temperature (°C)	-.28 (-.80, .47)	-5 (-21, 11)	-.30 (-.80, .46)	-9 (-36, 17)
Resting Heart Rate (b.min^{-1})	-.23 (-.78, .51)	-0.2 (-1.0, 0.6)	.18 (-.55, .75)	0.3 (-1.2, 1.8)
Body Fat (mm)	-.19 (-.79, .59)	-0.1 (-0.5, 0.3)	-.39 (-.86, .43)	-0.4 (-1.3, 0.5)
Body Mass (kg)	.39 (-.37, .84)	0.5 (-0.5, 1.5)	.15 (-.57, .74)	0.3 (-1.7, 2.3)
USG	-.30 (-.80, .46)	-0.5 (-2.3, 1.1)	.18 (-.60, .78)	0.6 (-2.5, 3.7)
HSP70 (ng/mL)	-.14 (-.74, .58)	-0.03 (-0.08, 0.03)	-.40 (-.84, .36)	-0.01 (-0.05, 0.06)
Exercising Characteristics				
Rectal Temperature Slope	-.73 (-.94, -.12)	-32 (-59, -5)	-.54 (-.89, .19)	-36 (-86, 14)
Skin Temperature Slope	-.24 (-.78, .51)	-4 (-20, 12)	-.56 (-.89, .16)	-19 (-43, 6)
Heart Rate Slope	-.61 (-.91, .08)	-0.6 (-1.3, 0.1)	-.23 (-.78, .51)	-0.4 (-1.8, 1.0)
Sweat Rate	.74 (.07, .95)	22 (-4, 49)	.48 (-.26, .87)	31 (-19, 80)
Fluid Consumption Rate	.40 (-.36, .84)	16 (-17, 49)	-.35 (-.82, .41)	-14 (-49, 21)
Thermal Sensation Change	-.65 (-.92, .02)	-5 (-11, 0)	-.80 (-.96, -.30)	-13 (-21, -4)
Sleepiness Change	-.79 (-.95, -.26)	-5 (-9, -2)	-.87 (-.97, -.48)	-10 (-15, -5)
RPE Change	.17 (-.56, .75)	1 (-6, 9)	-.37 (-.83, .39)	-4 (-13, 5)

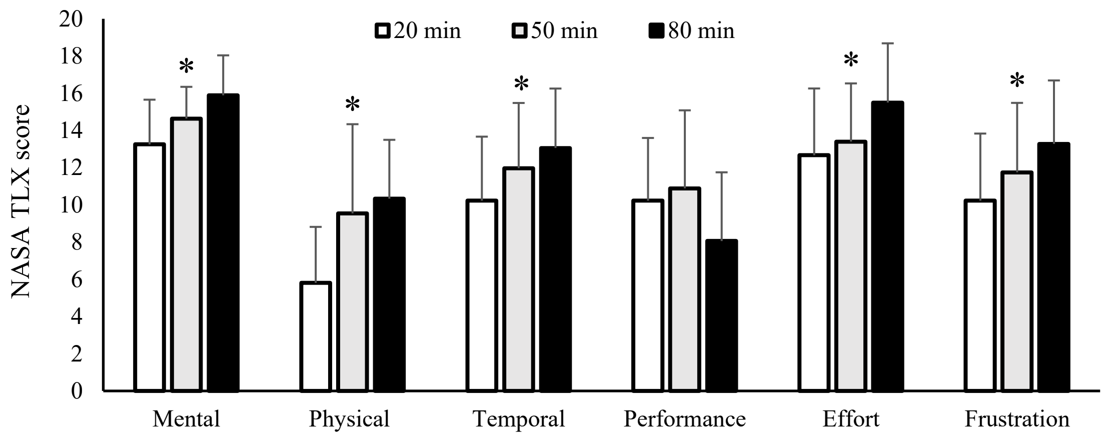

Figure 5: Pooled responses from both humid and arid heat-stress tests to the NASA task-load index following completion of a cognitive battery. *indicates a significant effect of time, regardless of the environment.

skin temperature in the arid environment likely explains the stronger relationship with performance, which was of moderate strength, compared to only a weak relationship in the humid environment. Furthermore, skin temperature may directly influence the perceptual relationships with performance, which were among the strongest predictors of performance in both environments (Table 2), consistent with previous findings (Flouris & Schlader, 2015; Schlader et al., 2013). Whether the higher skin temperature in the arid environment partially explains the stronger relationships between perceptual changes and performance in the arid environment, however, is uncertain as a lack of perceptual differences existed between environments (Table 1). Perceptions are produced by the brain integrating numerous physiological signals to generate behavioural responses to help cope with environmental stress (Fleming & James, 2014; Morante & Brotherhood, 2008; Periard et al., 2014; Schlader et al., 2011). Therefore, as a response to exercise becoming uncompensable, thermoregulatory behaviour leads to the termination of the test (Cheung & McLellan, 1998; Gonzalez-Alonso et al., 1999; Pimental et al., 1987). Thereby having a lower skin temperature could delay the rate at which perceptual feelings worsen, allowing prolonged performance before voluntary termination, although there were only marginally more voluntary terminations in the arid environment. The absence of relationship between rating of perceived exertion and performance may highlight military mental toughness, hypothesised to place individuals in danger as they disregard internal cues to cease exercise (Buller et al., 2018; Epstein et al., 2012; Howe & Boden, 2007; Parsons et al., 2019). If valid, overcoming these internal cues exacerbates the danger of these environments as continuing to exercise further elevates core temperature which can ultimately be fatal (Parsons et al., 2019). Understanding that in these environments the accumulated heat gain from both endogenous and exogenous sources, and not simply exercise intensity alone, is the primarily cause of fatigue and casualties, may help develop monitoring strategies (Macpherson, 1962). The data in the current study found that directly addressing heat in perceptual monitoring, by enquiring of how hot or sleepy individuals are feeling, provides an indication of how much longer an individual can safely exercise for.

4.3. Cardiovascular

A higher heart rate was seen during the heat-stress test in the humid environment (Table 1). In the humid environment, cardiovascular variables were better predictors of performance, whereas baseline aerobic fitness was a better predictor in the arid environment (Table 2). Furthermore, fitter individuals are known to be able to tolerate a higher core temperature (Cheung & McLellan, 1998), therefore the withdrawal of participants due to having a high core temperature, which occurred more frequently in the humid environment, limits aerobic fitness influencing the time to exhaustion.

During exercise, elevations in cardiac output, facilitated by an increase in heart rate, are required to ensure both cutaneous and skeletal muscle circulations receive adequate blood supply (Cramer & Jay, 2016; Gonzalez-Alonso & Calbet, 2003). A larger underlying blood volume facilitates higher stroke volume and a more widespread distribution of blood, allowing heat loss while maintaining performance (Gonzalez-Alonso et al., 1998; Taylor, 2000). A greater blood volume may be more important in humid environments as sweat evaporation is restricted by high humidity (Maughan et al., 2012), thereby causing insensible fluid loss, where dehydration occurs without beneficial heat loss (Eichna, 1943; King et al., 2016; Taylor, 2017). As central blood volume declines a greater strain is placed on the cardiovascular system (Charkoudian, 2016; Gonzalez-Alonso et al, 1998), limiting peripheral blood flow. As the perfusion of cutaneous circulations is reduced, heat transfer becomes limited, thereby causing increases in core temperature (Casa et al., 2012; Gonzalez-Alonso et al., 1998; Kenefick et al., 2010; Nadel et al., 1980). Alternatively, a greater reliance may be placed on convective heat loss mechanisms, thereby requiring an increased cardiac output to elevate cutaneous blood flow (Chou et al., 2018; Kenney et al., 2014; Tebeck et al., 2019), shown by an elevated heart rate in the humid environment (Table 1). The importance of limiting the cardiovascular demand is further illustrated by the strong ability of the change in heart rate to predict performance (Table 2). When the cardiovascular system can no longer increase cardiac output to support perfusion of both skeletal muscle and cutaneous circulations blood flow is reduced, first to cutaneous, and then to skeletal muscle circulations (Gonzalez-Alonso & Calbet, 2003; Gonzalez-Alonso et al., 2008; Kenney et al., 2014). Without the muscular blood flow to sustain oxygen requirements for exercising muscle intensity is reduced (Tucker et al., 2004), which in this experiment meant test termination. Heart rate monitoring is one of the simplest real-time monitoring methods available (Eggenberger et al., 2018), and by assessing the rate of rise in heart rate it allows evasive steps to be taken to prevent exhaustive limits being reached by the individual.

4.4. Sweat Rate

No differences in sweat rate were seen between the environments, although evaporated sweat was significantly reduced in the humid environment (Table 1), likely due to the vapour pressure gradient being reduced by the humidity, preventing sweat evaporation (Maughan et al., 2012). As sweat is unable to evaporate, core temperature rises (McLellan & Aoyagi, 1996; Sawka et al., 1993), underlying the elevated rectal temperature in the humid condition (Figure 4), whereas the evaporation of sweat in the arid environment would have helped maintain a lower rectal temperature (Figure 4) (McLellan et al., 1992). Sweat rate changes were closely linked to performance in both environments (Table 2). In the humid environment sweat rate strongly predicted performance (Table 2), while evaporated sweat rate had a weak negative relationship. This suggests sweating facilitates performance, but only if the sweat evaporates. If sweat does not evaporate then heat is not lost from the body, and water loss merely adds to dehydration (Cheung & McLellan, 1998; Taylor, 2017). Conversely, despite conditions favouring the evaporation of sweat, the arid environment had only a moderately strong relationship between sweat rate and performance, (Table 2). As sweat could more readily evaporate, it is likely that this was not a limiting factor, and therefore other variables were more directly linked to performance.

4.5. Metabolic

The metabolic strain during the heat stress test was greater in the humid environment, illustrated by larger oxygen uptake and carbon dioxide production. The greater pack weight in the humid environment likely accounts for some of this difference as more muscular work is required to carry the pack (Knapik, 1997). Indeed, the relatively greater $\dot{V}O_2$ in the humid environments occurred close to the expected relative value based on load carrying energy expenditure predictions (Pandolf et al., 1977). Furthermore, lighter individuals are known to have a greater relative metabolic demand when carrying heavy absolute loads (Bilzon et al., 2001). Therefore, the increased oxygen requirement from the additional relative workload likely creates a strong relationship between body mass and performance, as this would also add to metabolic heat production (Table 2).

No relationship was found between HSP70 and performance (Table 2), although most participants showed minimal plasma concentrations that were often below the detection limit of the ELISA assay. Low serum concentrations of HSP70 are not uncommon, especially at rest (Njemini et al., 2011; Walsh et al., 2001), with some studies reporting wide variations in concentrations between individuals (Lee et al., 2015). It is acknowledged that the practicality of measuring HSP70 in a real-world military context is limited due to the cost, invasiveness and laboratory expertise required to obtain results. Therefore, based on these constraints, the large variability, and our non-significant findings, HSP70 does not appear to be a worthwhile or accessible measure for predicting soldier performance in the heat.

4.6. Cognitive

Minimal changes in cognitive performance existed both within and between environments. Many of the tasks used in the cognitive assessments were relatively simple, which have been shown to be largely unaffected by heat (Hancock & Vasmatzidis, 2003; Mazloumi et al., 2014). However, research has shown load carriage (Caldwell et al., 2011; Eddy et al., 2015) and physical fatigue (Vrijkotte et al., 2016) to impair simple cognitive processes. Despite the self-reported mental demand of tasks increasing across the trial (Figure 5), no differences in cognitive performance existed. It is possible participants felt more strained when doing the tasks, but could still allocate sufficient cognitive resources to the task to complete them accurately (Lambourne & Tomporowski, 2010). In real-world military contexts, soldiers may experience greater thermal stress, physical fatigue and more complex tasks, which could impair cognition.

4.7. Conclusion

While physiological responses to military specific physical activity in humid and arid environments share many similarities, significant differences do exist and should be accounted for. Specifically, the expected environmental parameters and gear loadout of the humid environment appeared to increase heat production, while also impairing cooling due to limited sweat evaporation resulting in increased core temperature and heart rate, which lead to impairments in soldier performance. While many physiological variables predicted performance, perceptual variables were the strongest predictors. The lack of relationship between the difficulty of exercise and performance suggests monitoring questions should focus on the heat, not the exercise, to ensure soldier safety and wellbeing. Understanding the dangers of heat and improving coping mechanisms and monitoring strategies will help minimise soldier casualties.

Conflict of Interest

The authors declare no conflict of interests.

Acknowledgment

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