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

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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 ($60^{\circ}.s^{-1}$), 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 $60^{\circ}.s^{-1}$, slow) or high (48 repetitions at $240^{\circ}.s^{-1}$, 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 ($60^{\circ}.s^{-1}$) or fast ($240^{\circ}.s^{-1}$) testing conditions. The discrete KE and KF forces and EMG were not significantly different from control, with no significant relative force differences at $60^{\circ}.s^{-1}$ or $240^{\circ}.s^{-1}$. 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

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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: $172.2 \pm 6.8\text{cm}$, $82.1 \pm 8.1\text{kg}$, 24.2 ± 2.5 years; 6 females: $169.3 \pm 4.6\text{cm}$, $70.4 \pm 11.3\text{kg}$, 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 (Meditrace™ 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 ($\times 1000$) (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) ($90^\circ\text{-}0^\circ$ 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 ($4 \times 15\text{sec}$), 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 ($[\text{average of final two contractions peak torque} / \text{first contraction peak torque}] \times 100$).

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 ($\text{CV} = [\text{Standard Deviation} / \text{Mean}] * 100$) and standard error of the mean ($\text{SEM} = \text{standard deviation} / \text{square root of the sample size}$). Standards for CV are as follows: $\text{CV} < 10\%$ is considered very good, 10-20% is good, 20-30% is acceptable, and $\text{CV} > 30\%$ 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	0.87	28.6%	7.1
Non-Dominant	Hamstrings	132.9±26.7	0.90	30.4%	7.2
Dominant	Quadriceps	127.8±26.2	0.91	28.9%	9.3
Non-Dominant	Quadriceps	132.9±26.7	0.89	26.7%	9.1
		189.4±36.1			
		193.5±46.1			
		189.1±37.8			
		185.3±46.1			

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 ($p = .0009$, $ES = 0.63$).

EMG Median Frequency (Hz) - Quadriceps												
	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	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 \times 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).

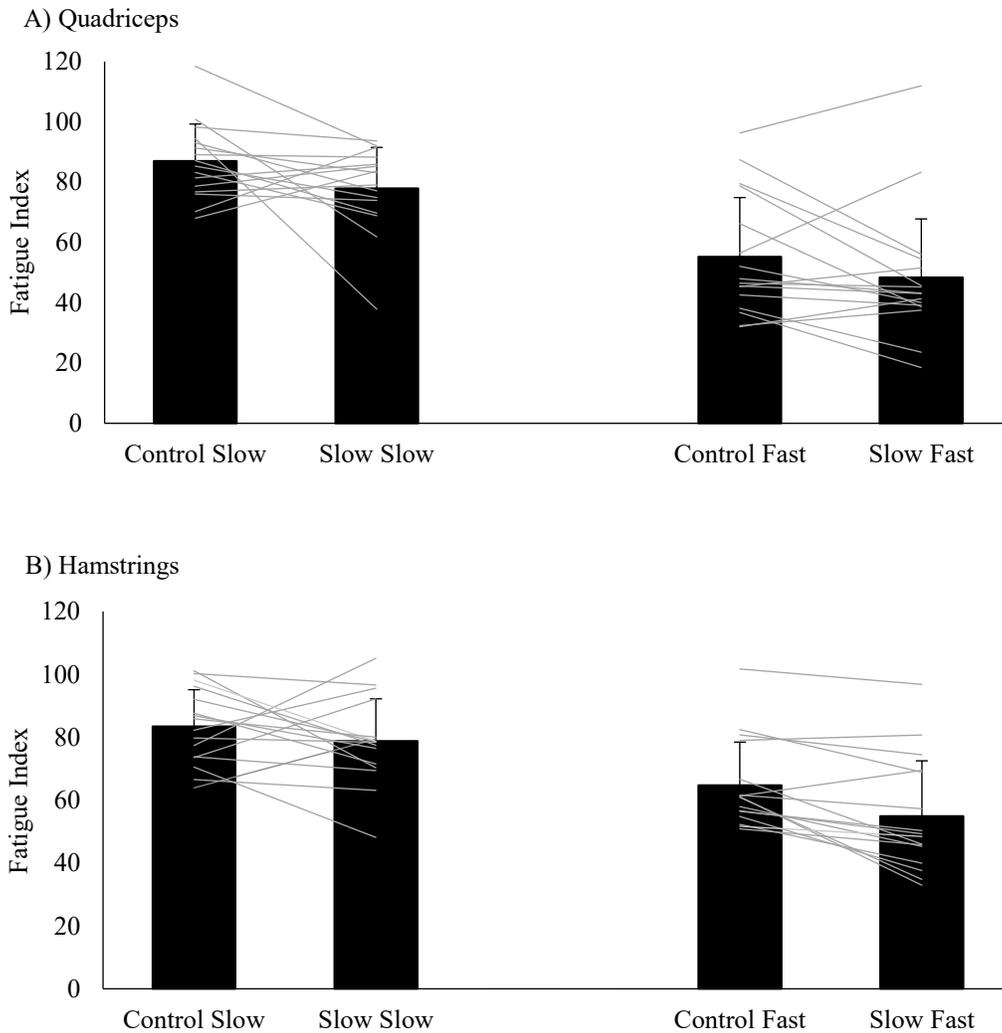
4.1. Velocity Specificity

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) ($\downarrow 32\%$), Doix et al. (2013) ($\downarrow 17\%$), Martin and Rattey (2007) ($\downarrow 16\%$) 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



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

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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; Zijdwind 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; Bouhrel 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

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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

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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, & Bembem, 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.

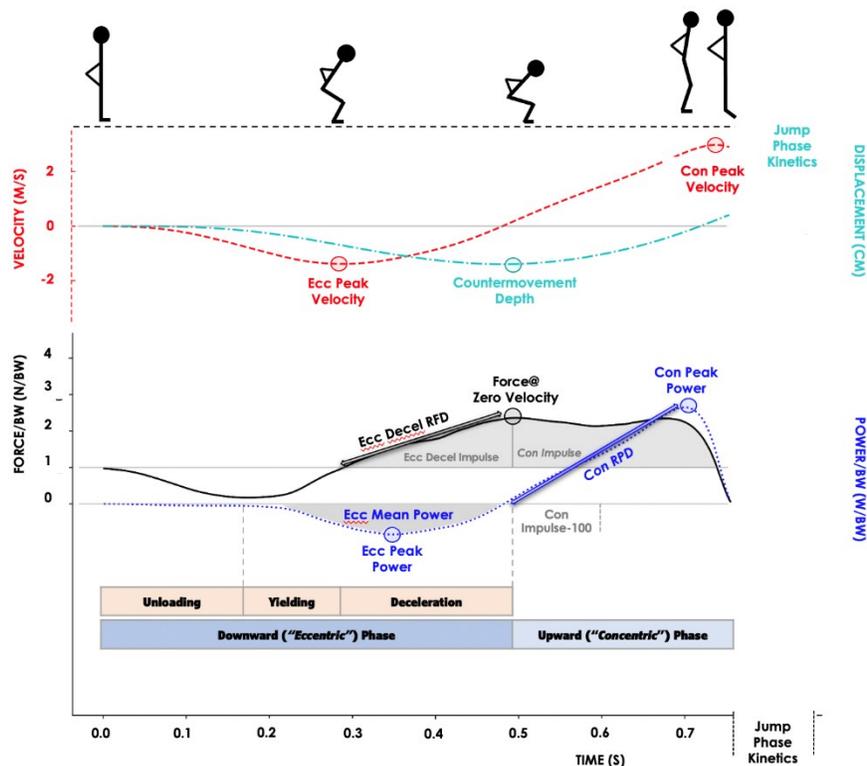


Figure 1: Counter movement jump downward and upward phase vertical ground reaction Force, Velocity, Power, and (Centre of Mass) Displacement-time curves with selected bilateral variables highlighted Force (N-Newtons) Power (W-Watts) are expressed relative to bodyweight (BW): /kg. Con = Concentric, Ecc = 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 (Δ power / Δ time) 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 (Δ force / Δ time) 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-Doodoo & 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 end 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, RSI_{mod}, 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, Pampa, 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

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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

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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 m² 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 m² 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.

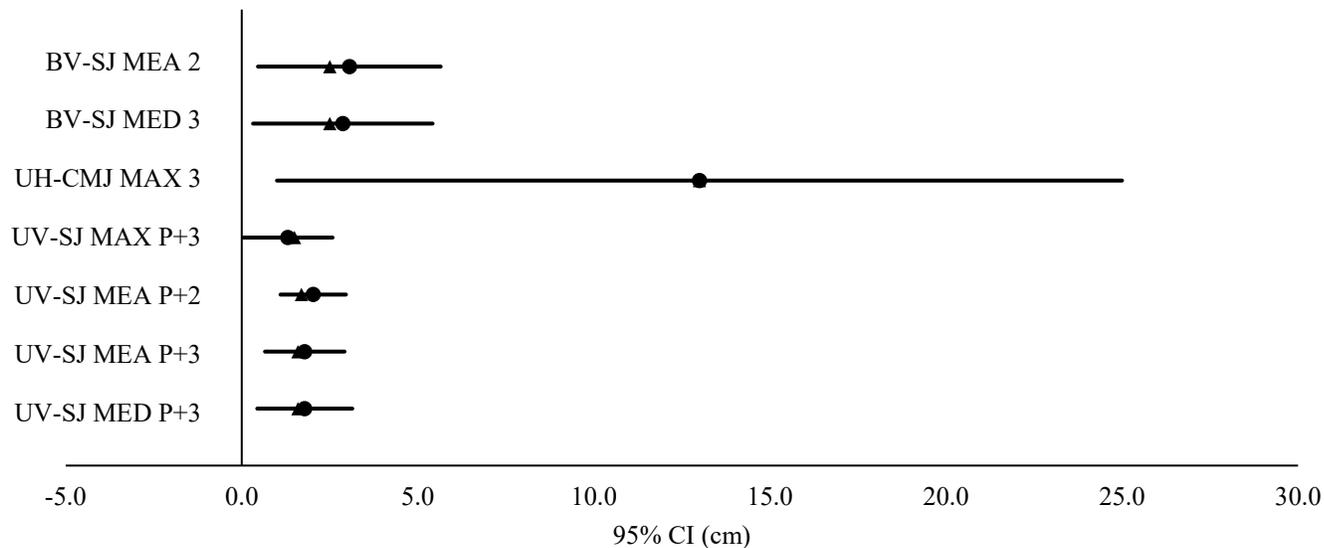


Figure 1: Forest plot of 95% confidence intervals (95% CI) showing the difference between novice and experienced boxers' jump height/distance from immediately prior to 24 h post sparring. All 95% CI indicate that experienced boxers' jump height/distance was lower than novices 24 h after sparring. *Note.* ● = 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

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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.h⁻¹, $p = .045$). 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 ($\beta = -.65 - -.80$) and sleepiness ($\beta = -.79 - -.87$). 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.

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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).

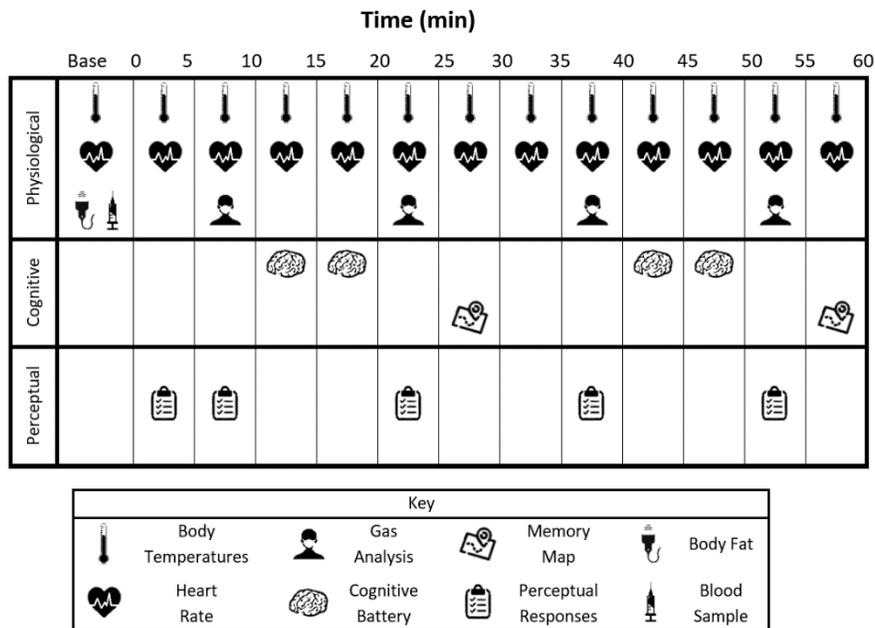


Figure 1: Schematic of tests conducted over the first 60 min in each heat-stress test. From 60 to 120 min measures were taken in the same order.

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 K₂EDTA 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 ($(\text{semi-nude weight change} + \text{fluid consumption}) \div \text{walking time}$) (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 ($[\text{semi-nude weight change} - \text{fully dressed weight change}] \div \text{walking time}$) (Amos et al., 2000).

2.2.2. Continuous Measures

Core body temperature was recorded rectally, using a flexible thermistor (Hinc 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 ($g \cdot min^{-1}$) 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 $33.4 \pm 0.6^\circ\text{C}$ and $78 \pm 2\%$ RH ($28 \text{ g}\cdot\text{m}^{-3}$ absolute humidity), while in the arid trials it was $44.3 \pm 0.5^\circ\text{C}$ and $21 \pm 2\%$ RH ($13 \text{ g}\cdot\text{m}^{-3}$ 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.

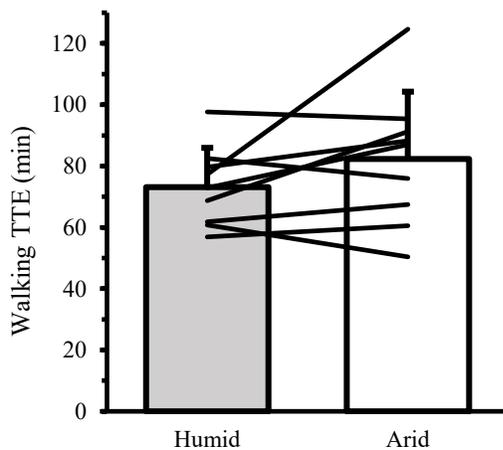


Figure 3: Walking time to exhaustion (TTE) in a simulated pack march in humid and arid environments in full military protective equipment. Individual responses are displayed by individual black lines.

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 $\sim 0.5^\circ\text{C}$ 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 $\sim 5 \text{ b}\cdot\text{min}^{-1}$ 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 $\sim 40\%$ greater in the arid environment (Table 1). No differences were observed in any measure of hydration (Table 1).

The $\dot{V}\text{O}_2$, $\dot{V}\text{CO}_2$ and \dot{V}_E all increased significantly throughout the trial (all $p < .001$). Between conditions, a 10% greater $\dot{V}\text{O}_2$ was present in the humid condition (Humid: $19.8 \pm 2.5 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; Arid: $18.0 \pm 2.2 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $p < .001$), which was close to the 6% predicted, and was supported higher \dot{V}_E (Humid: $47.0 \pm 12.1 \text{ L}\cdot\text{min}^{-1}$; Arid: $42.6 \pm 9.8 \text{ L}\cdot\text{min}^{-1}$; $p < .001$) and $\dot{V}\text{CO}_2$ (Humid: $1.40 \pm 0.21 \text{ L}\cdot\text{min}^{-1}$; Arid: $1.28 \pm 0.18 \text{ L}\cdot\text{min}^{-1}$; $p < .001$). 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: $1.2 \pm 0.3 \text{ g}\cdot\text{min}^{-1}$; Arid: $1.1 \pm 0.4 \text{ g}\cdot\text{min}^{-1}$; $p = .063$).

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 JSES | <https://doi.org/10.36905/jses.2022.02.04>

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

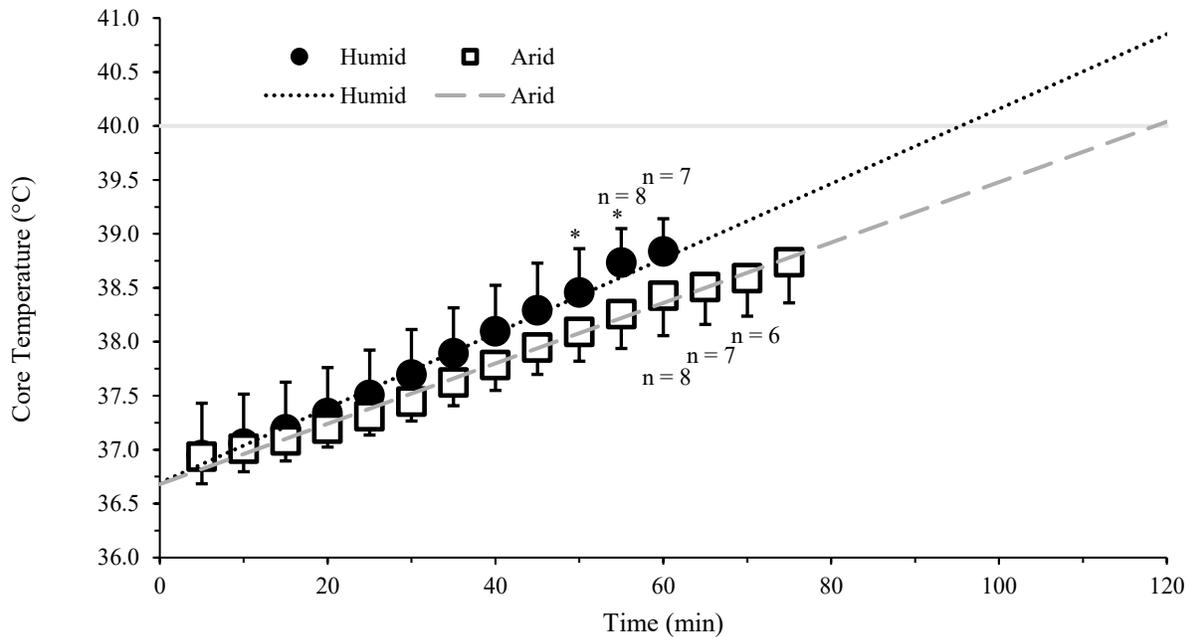


Figure 4: Rectal temperature during a simulated pack march in either a humid (33°C, 78% RH) or arid (44°C, 21% RH) environment. Trendlines display the predicted means based on recorded data, only for when $n = 9$. Data are plotted as mean \pm standard deviation for $n = 9$ unless otherwise stated (data 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)

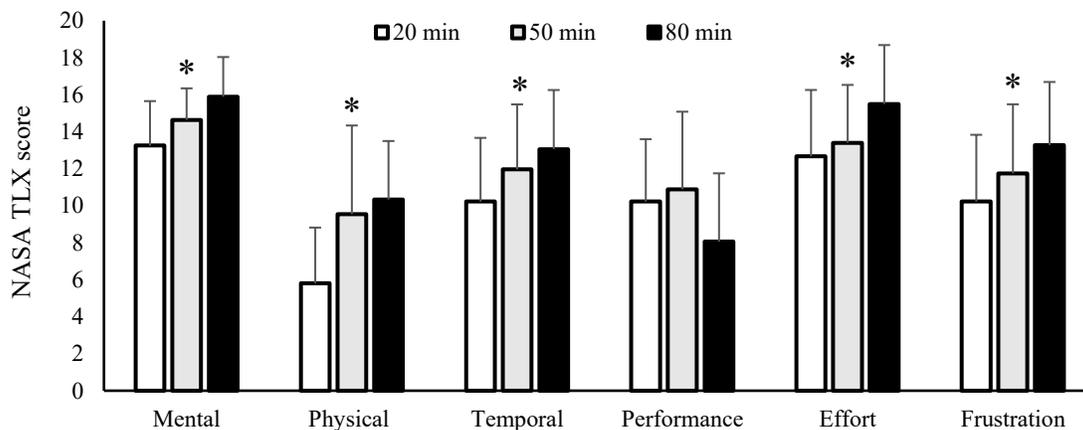


Figure 5: Pooled responses from both humid and arid heat-stress tests to the NASA task-load index following completion of a cognitive battery. *indicates a significant effect of time, regardless of the environment.

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 primary 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

Not applicable.

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The characteristics of within match play acceleration and deceleration activity in international hockey

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ABSTRACT

This investigation identified the common characteristics of both acceleration and deceleration in senior male international field hockey matches. The aim was to identify these characteristics on a positional basis. The activity of 24 players across 10 matches was investigated. Each participant wore an individual GPS unit (STATSports APEX), operating at 10 Hz. Based on match data, we identified all acceleration and deceleration efforts. Additional information relating to that effort was extracted such as distance, magnitude and duration per effort, time between efforts. The largest proportion of acceleration (71%) and deceleration (61%) events were completed within a 3-3.99m.s⁻¹ range. There was a greater proportion of deceleration efforts (11%) than acceleration efforts (6%) observed at magnitudes >5m.s⁻¹. Up to 54% of all acceleration efforts were within a distance of 2-7m and 93% of deceleration efforts were ≤5m. Defenders completed acceleration efforts of a shorter distance (6.20m) as compared to both midfielders (7.59m) and forwards (7.54m), with no difference in magnitude identified. The parameters identified in this investigation can aid in the prescription and monitoring of training for international hockey players. In training, players should experience accelerations and decelerations of similar distances and magnitude to those experienced during match play. These data can be compared to training drill data to ensure players are being afforded the opportunity to complete efforts of similar magnitude and distance in the training environment. However, further investigation relating to the contextual environment in which these events are accumulated is warranted.

1. Introduction

The physical output profiles of international hockey players during match play have been established in a comprehensive manner. It is intermittent in nature with a large proportion of activity completed in low to moderate speed zones (64%) (James et al., 2021). Match play is interspersed with intense short periods of play presenting opportunities to reach maximal velocities of 8.75m/s and peak intensities of 199–223 metres per minute, achieved in 1-3 minutes, which is similar to results found in the Australian football (Casamichana et al., 2018; Cunniffe, Grainger, et al., 2021; Delaney et al., 2017; Delves et al., 2019; Johnston et al., 2020). High intensities are enabled in field hockey due to

unlimited rotations (Linke & Lames, 2017), a four-quarter match format and the use of the “self-pass” (Tromp & Holmes, 2011) rule, however, fluctuations are apparent from quarter to quarter (Haro et al., 2021; Ihsan et al., 2017; Morencos et al., 2018) and within rotations (Linke & Lames, 2017; Lythe & Kilding, 2013).

Due to pitch constraints in field hockey, 230 m² per player compared to 320 m² in soccer (Olthof et al., 2018), hockey players reach high intensities through short, high magnitude acceleration efforts while accumulating limited max velocity efforts (Casamichana et al., 2018; Ihsan et al., 2017; Morencos et al., 2018). The ability to accelerate is a crucial physical characteristic of high-level field hockey players due to the emphasis on repeat sprint ability, for which acceleration plays a large role (Spencer et

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al., 2004). Repeat sprint ability has been widely investigated within field hockey. Spencer et al. have documented up to 17 occasions of at least 3 sprint efforts, with less than 20 seconds of recovery between efforts, per team in one match. However, the definition of sprinting utilised was “maximal effort with a greater extension of the lower leg during forward swing and a higher heel lift relative to striding”. This reliance on identifying efforts visually, could cause high magnitude acceleration efforts to be mistakenly categorised as repeat sprint efforts, which in recent times, are more commonly identified using microtechnology to identify efforts that reach certain velocity thresholds. A further consideration in field hockey physical output profiling is that tournaments pose unique demands on players, with five matches played in seven days, typically reducing perceived wellness which impacts upon physical output (Ihsan et al., 2017). It has been established that accelerations and decelerations are major contributors to post-match muscle damage (Gastin et al., 2019) and may be a large contributor to the disturbed physiological and neuromuscular pattern displayed by players post-match and during a tournament (Beato & Drust, 2021; Harper & Kiely, 2018). This may be because high rates of force development are required for acceleration (di Prampero et al., 2005) and in contrast to constant velocity running, acceleration also demands greater neural activation of the muscles (Mero & Komi, 1987). As players change velocity, even when their velocity is low, athletes require a great deal of metabolic energy, not just during the most intense phases of the match (sprinting and high-speed running) (Osgnach et al., 2010) with frequent changes of velocity reported to have an increase metabolic cost of 6-20% even at low magnitudes (Seethapathi & Srinivasan, 2015). Furthermore, a correlation between post-match creatine kinase levels and the number of high intensity decelerations completed during match play in hockey has been established, potentially linked to the high eccentric demands of these actions (McMahon & Kennedy, 2021). Thus, there is a high potential for both accelerations and decelerations to cause a disturbed physiological state. This potentially disrupts the performance potential of a hockey player, highlighting the need to track these actions.

Each position within the team has a specific physical output profile – forwards and midfielders compete at higher relative intensities and complete more repeat sprint bouts than defenders, while additionally, fatigue patterns are also distinctly different between positions (Morencos et al., 2018). Morencos et al. (2018) have established that acceleration and deceleration may be the two metrics most sensitive to fatigue in field hockey, due to these metrics displaying a reduction in volume during competition while high speed running was maintained. This is important as a key aspect of field hockey physical performance is repeat performances in a short period of time. Consequently, tracking these variables may provide an insight into the fatigue levels of players. However, according to Harper and Kiely (2018) acceleration and deceleration efforts impose significantly different demands on the physiological systems of the body despite being viewed as equivalent loading parameters. This may be attributed to the magnitude, duration, and frequency of each type of action (Beato & Drust, 2021).

There is presently limited research regarding acceleration or deceleration efforts in field hockey despite the highly metabolically challenging and fatiguing nature of these efforts. Morencos et al. has established that fatigue is present across quarters in club level field hockey with moderate and high-intensity accelerations showing a decline ($11.4 \pm 3.9\%$) in later quarters (Morencos et al., 2018). The acceleration bands utilised were moderate $2-2.9\text{m}\cdot\text{s}^{-2}$ and high $>3\text{m}\cdot\text{s}^{-2}$ which is consistent with the data proposed for acceleration bands in elite male field hockey (Dwyer & Gabbett, 2012). Chesher et al. (2019) have established the typical characteristics of deceleration efforts in elite field hockey. A peak magnitude of $-13.6\text{m}/\text{s}^2$ was noted alongside an average magnitude of $-4.25-4.35\text{m}/\text{s}^2$ across 5 matches. A $-0.11\text{m}/\text{s}^2$ decrement between halves was also identified (Chesher et al., 2019). However, these values refer to match play in elite international hockey, utilising two halves instead of four quarters. Currently, there are no available data relating to the typical distance per effort, the magnitude of efforts and the typical counts across positions in the current match format in international hockey. Identifying typical loading patterns for these two metrics may provide parameters for the monitoring of the accelerations and decelerations experienced by international field hockey teams relating to match play. These parameters can inform the national teams junior ages group physical development pathway physical training, by providing a benchmark for senior international level match play. Additionally, practitioners, at senior level can determine whether prescribed drills in training closely mimic the acceleration and deceleration demands of international matches with a consideration of playing position.

This investigation sets out to identify the acceleration and deceleration profile of elite field hockey players across positions in terms of frequency, duration, magnitude, and rest intervals in the updated match format of four quarters.

2. Methods

2.1. Participants

To be included in this investigation, players had to be an international hockey player and injury-free. Twenty-four players met the inclusion criteria and were split into four positions: defenders (mean relative to bodyweight back squat 1 repetition max (1RM) = 1.48, mean 5m time = 1.02 seconds), outside backs (1RM = 1.42, 5m time 1.02 seconds), midfielders (1RM = 1.36, 5m = 1.04 seconds), and forwards (1RM = 1.35, 5m = 1.03 seconds).

2.2. Apparatus

Each participant wore an individual GPS unit (STATSports APEX, firmware 2.50), operating at 10 Hz, for 10 international matches as part of their normal monitoring as members of the international field hockey squad. Institutional ethics approval was obtained from the Faculty of Research Ethics and Integrity committee (University College Dublin - LS – 17- 85) in accordance with the Helsinki Declaration. Before the

commencement of the studies and monitoring of players, all participants provided written informed consent.

The reliability and validity of these units have previously been reported. They display a high level of validity in a team sport setting (Beato et al., 2018), as well as excellent inter and intra unit reliability (Beato & Keijzer, 2019). They report a small error of around 1–2% compared to the criterion distances during 400-m, 128.5-m team sport-based circuit, 20-m trials, and maximal velocity (Beato et al., 2018). Crang et al. (2021) have stated these “devices generally possessed suitable reliability and consistency for threshold-based accelerations and decelerations”. GPS data handling procedures, Horizontal Dilution of Precision and match details are as reported in Cunniffe et al. (2021).

2.3. GPS Metrics

Accelerations were any effort that reached 3.0 m/s² for a minimum duration of 0.5 seconds while decelerations were noted as a reduction in velocity greater than 3.0 m/s² over a minimum duration of 0.5 seconds (Dwyer & Gabbett, 2012; Morencos et al., 2018; Romero-Moraleda et al., 2020). These efforts were derived solely from GPS data rather than the inertial sensors contained within the GPS units. Utilising the STATSports Apex Pro Series Software, all acceleration and deceleration efforts were identified and extracted alongside the following characteristics: the magnitude of the change of velocity during the effort, total effort duration, total effort distance and time since the last effort was completed. These are typical thresholds utilised in multiple investigations relating to accelerations and decelerations across multiple sports (Harper et al., 2019). By cross referencing the raw gps data with the timestamp within the match footage, the primary investigator was able to verify, or dismiss, potential outliers based on magnitude, duration, and distance.

2.4. Statistical Analysis

Linear mixed models (LMM) were utilised to examine the influence of position on the characteristics of acceleration and

deceleration during match play. The approach used in the construction and use of LMMs replicates the approach previously reported by Cunniffe et al. (Cunniffe, Connor, et al., 2021; Cunniffe, Grainger, et al., 2021). The dependent variables were distance per effort, duration per effort, magnitude per effort and time between efforts.

3. Results

Table 1 outlines the mean number of acceleration and deceleration efforts completed across positions during an international match. There were no significant differences for the number of efforts completed between positions for either accelerations or decelerations ($p > 0.05$). Within positions, there was no significant difference identified between the number of accelerations ($p = 0.14$) and decelerations ($p = 0.74$) completed with and without accounting for time on pitch. Table 2 outlines the mean distance, duration, magnitude, and time since the last occurrence of each effort by high-intensity action type across positions.

No significant differences were identified between positions for magnitude per effort of either accelerations or decelerations ($p > 0.05$). Differences identified between positions regarding distance per effort can be found in Table 2. Regarding within position comparisons, accelerations were greater in distance but not magnitude per effort than decelerations for all positions ($p < 0.05$) (Table 2). There were no significant differences identified for time between efforts for between position comparison for either accelerations or decelerations type ($p > 0.05$).

Over half (54%) of acceleration efforts were between 2-7m long. 24% of acceleration efforts were between 10-20m in distance. 3% of accelerations were >20m with a max effort of 36m (Figure 1). Less than 1% of deceleration efforts were >10m. 93% of deceleration efforts were ≤5m (Figure 2). Figure 3 outlines the total percentage of efforts in each 1m.s² band for acceleration and deceleration efforts relative to magnitude. Figure 4 outlines similar data categorised by position. Figures 3 and 4 can be found in table format in the supplementary materials.

Table 1: Average, standard deviation (SD), median and range of acceleration and deceleration efforts during match play by position.

Position	Type	Count ± SD	Median	Range
Defender	Acceleration	46 ± 9	44	30 - 58
Defender	Deceleration	61 ± 8	64	45 - 73
Forward	Acceleration	57 ± 16	54	35 - 94
Forward	Deceleration	56 ± 23	47	30 - 112
Midfielder	Acceleration	52 ± 13	54	29 - 74
Midfielder	Deceleration	56 ± 12	57	30 - 74
Outside Back	Acceleration	54 ± 9	56	39 - 63
Outside Back	Deceleration	65 ± 19	65	40 - 101

Table 2: Average and standard deviation of distance per effort, magnitude per effort, duration per effort and the time between each occurrence by position.

Position	Type	Distance (m)	SD	ES	Magnitude (m.s ²)	ES	SD	Duration (seconds)	SD	Time Between (seconds)	SD
Defender	Acceleration	6.20*†‡	4.62	1.23	3.70		0.61	2	1	23	16
Defender	Deceleration	2.17	1.46		-3.85*	0.22	0.73	2	1	20	16
Forward	Acceleration	7.54*	5.49	1.12	3.81		0.72	2	1	21	17
Forward	Deceleration	2.85	2.12		-3.99*	0.24	0.81	2	1	19	16
Midfielder	Acceleration	7.59*	5.43	1.20	3.78		0.68	2	1	21	16
Midfielder	Deceleration	2.77	1.94		-3.97*	0.26	0.80	2	1	20	15
Outside back	Acceleration	6.97*	5.27	1.19	3.76		0.71	2	1	21	16
Outside back	Deceleration	2.48	1.75		-3.95*	0.26	0.73	2	1	19	15

Note: *Significantly different to deceleration value within position. †Significantly different to midfielders. ‡Significantly different to forwards. Effect sizes are for differences for within position comparisons for distance per effort and magnitude per effort.

4. Discussion

This investigation outlines the common features of both acceleration and deceleration activities in senior male international field hockey match play. The typical distance, duration, and magnitude per effort across positions have been established. Defenders completed accelerations which were of shorter distance per effort, but similar magnitude compared to midfielders and forwards highlighting the unique positional nature of acceleration demands. Accelerations were of longer distance while decelerations were of greater magnitude for all positions. The largest proportion of acceleration and deceleration events were completed in the 3-3.99m.s⁻¹ range. 54% of all acceleration efforts were completed within a distance of 2-7m. 93% of deceleration efforts were ≤ 5 m. These findings provide a clearer understanding of how senior international field hockey players accumulate accelerations and decelerations in the revised, current match format and may inform the future training practices of elite hockey teams.

There was no significant difference in the number of either high-intensity actions completed between positions, despite having different tactical roles, which have been shown to influence movement patterns (Casamichana et al., 2018; Cunniffe, Grainger, et al., 2021; Morencos et al., 2018). This is especially noteworthy in relative terms given the different quantity of total time played by each position. The availability of unlimited rotations typically reduces the time forwards are active within a match as it has been shown that increased rest between on pitch stints may improve technical and physical performance (Lythe & Kilding, 2013). This in turn may lead to less absolute physical output and energy expenditure, therefore enabling higher intensity activity to occur. This may explain the findings of Morencos et al. (2018), who reported that forwards completed a greater number

of accelerations per-minute, yet not in the present investigation. This may be due to the increased physical capacity of international level players compared to club level players (Jennings, 2012), investigated by Morencos et al. (2018) with international players across positions able to exhibit and maintain greater high-intensity activities. This is further evidenced by the findings of Chesher et al. (2019) who did not report any differences between positions for decelerations completed at international level.

Typically, in other field sports, players exhibit greater frequencies of high-intensity deceleration efforts compared to acceleration efforts (Harper et al., 2019) and Morencos et al. (2018) reported a higher frequency of deceleration efforts per minute in elite club level field hockey for both defenders and midfielders. In contrast, in this investigation, there was no disparity between the number of efforts of each high-intensity action within positions. This replicates the findings of Chesher et al. (2019). This potentially highlights the stability of acceleration and deceleration efforts as a marker for monitoring field hockey players output longitudinally and for performance analysis purposes. Additionally, how these efforts are accumulated is warranted as given the different tactical roles of each position they may be accumulated in different tactical context. An exploration of a field hockey players physical output within match phases such as counter-attacking or deep defending, may offer further insight into how accelerations and decelerations are accumulated and why there is no discrepancy between the number of efforts completed between positions.

Within position contrasts identified that deceleration activities exhibited greater magnitudes (small ES) compared to acceleration activities for all positions. Deceleration efforts may produce higher magnitude efforts as they are frequently unplanned and unpredictable, as often, they are in response to an opposition

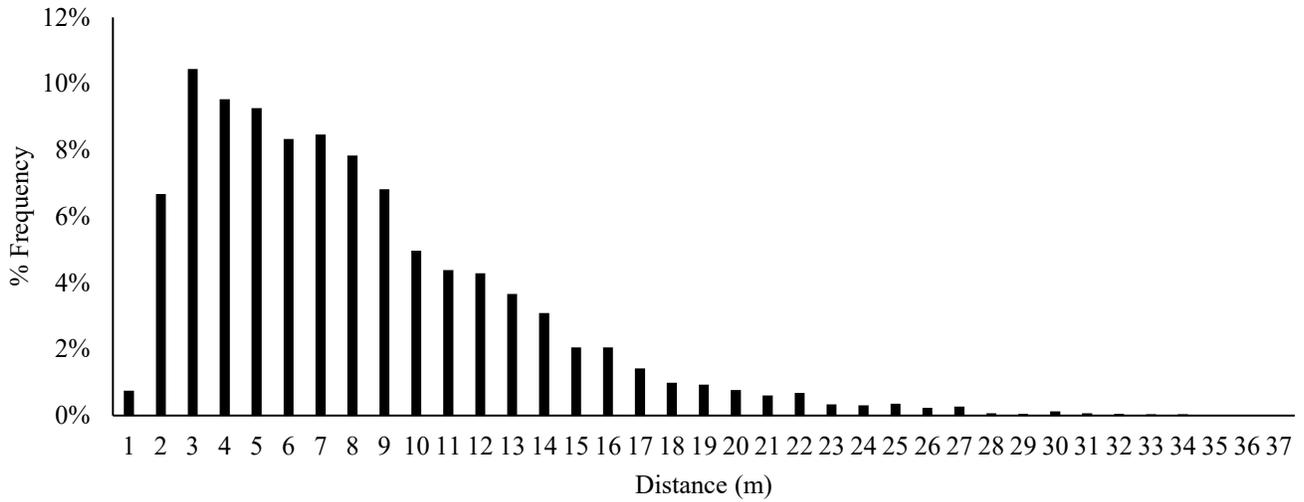


Figure 1: Percentage frequency of acceleration efforts by distance (m) across all players.

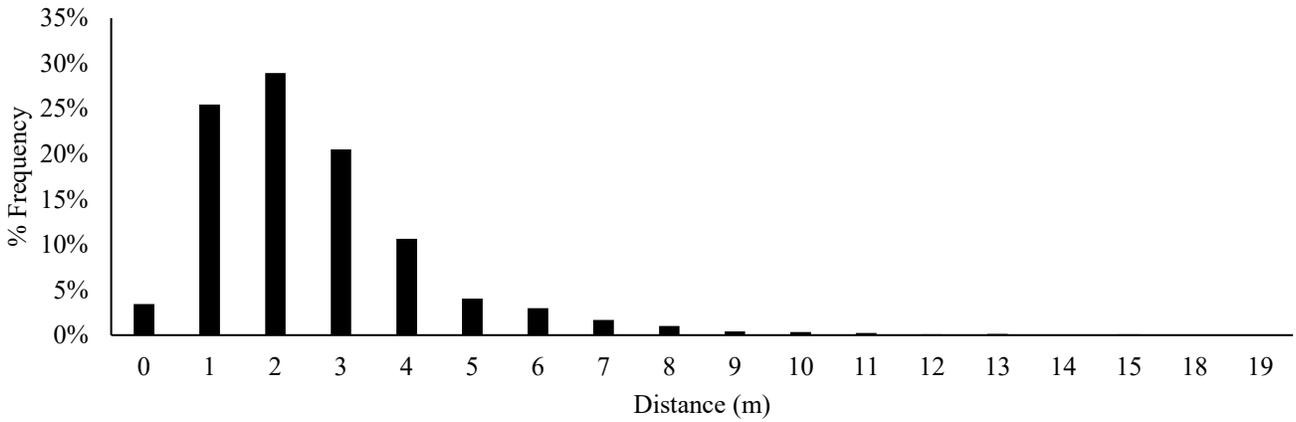


Figure 2: Percentage frequency of deceleration efforts by distance (m) across all players.

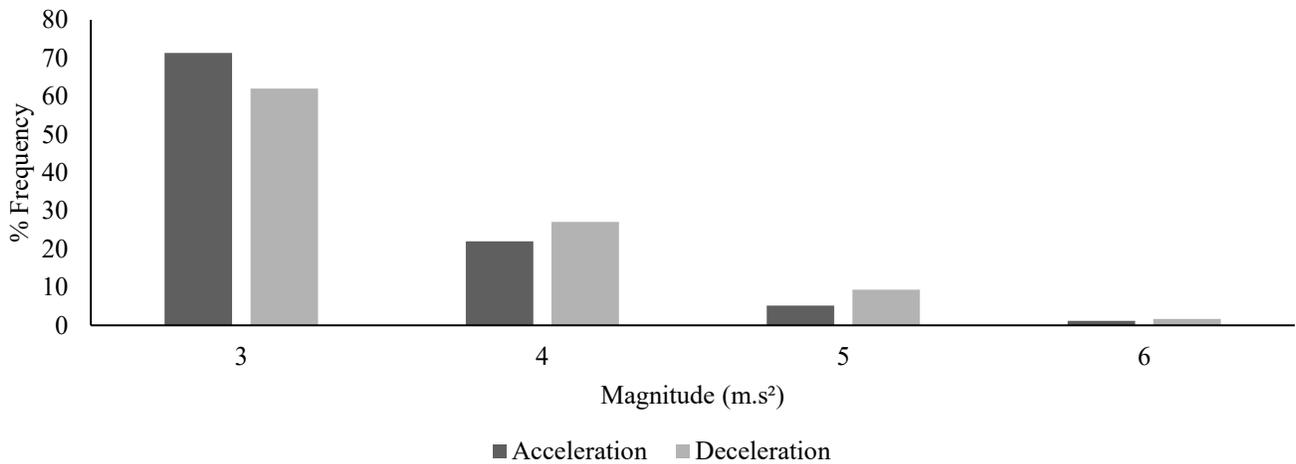


Figure 3: Percentage frequency of acceleration and decelerations by magnitude (m.s⁻²).

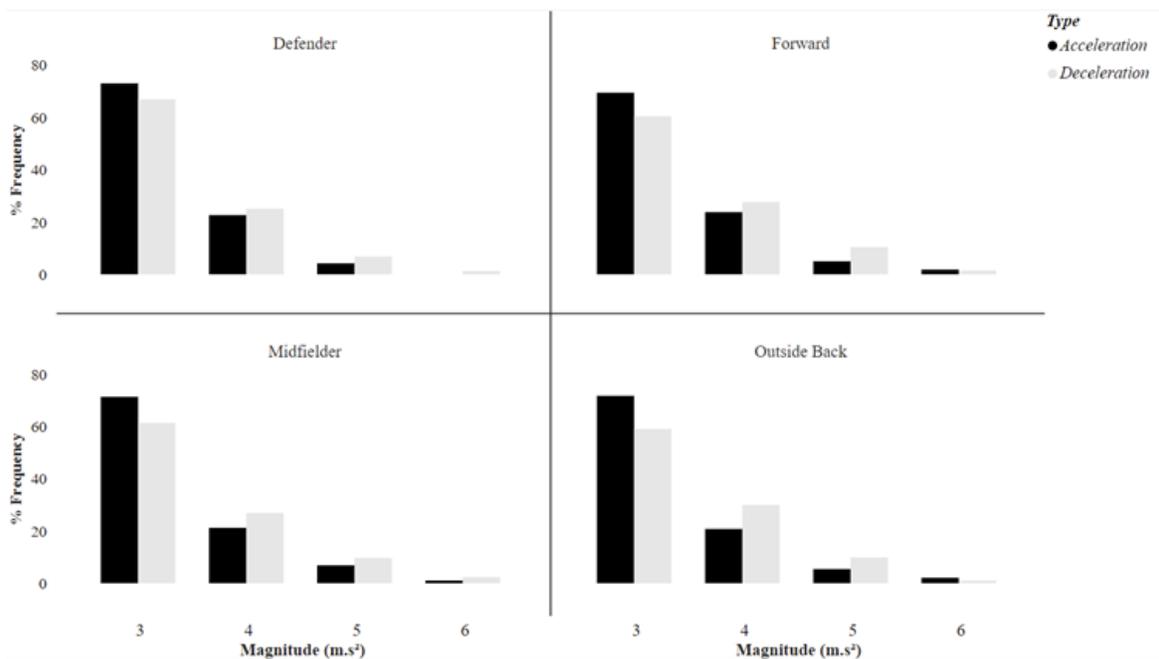


Figure 4: Percentage frequency of acceleration and decelerations by magnitude (m.s⁻²) categorised by position.

players movement or change of direction (Cunniffe, Connor, et al., 2021). Unplanned changes of velocity or direction have been shown to have altered kinetic and kinematic patterns relative to planned movements which may be a contributory factor to the greater magnitude displayed (Brown et al., 2014). Further investigation is required to ascertain the phase of play that field hockey players accumulate the majority of deceleration efforts in. As such, this may provide further context for drill prescription regarding elements such as body orientation, angle of approach, and whether this is an on-ball or off-ball evasion event. Previous investigations (Morencos et al., 2018) have reported that forwards typically exhibit greater magnitudes when accelerating compared to decelerating, however, in this investigation this finding was not confirmed. This may highlight that forwards are starting to have a larger role in the defensive aspect of match play as it is assumed that deceleration events are linked to defensive actions when attempting to track the movements of opposition players. This requires further investigation with greater context added to the physical output data of field hockey players.

The mean deceleration magnitude in this paper is lower than the mean magnitude detected in the study of Chesher et al. (2019) for defenders, midfielders, and forwards. The average deceleration magnitudes across positions, in the investigation, can be categorised as low-intensity according to Chesher et al. (2019) however, they can be classified into the very high-intensity category suggested by Harper et al. (2019). 99% of the decelerations captured in this investigation can be placed in the low intensity bracket (-3--5.99m.s²) range recommended by Chesher and colleagues (2019). At least 38% of deceleration efforts and 28% of acceleration efforts fall into the high-intensity categories recommended by Harper et al. for team sports (Harper

et al., 2019; Harper & Kiely, 2018). Accordingly, the high volume of actions completed in high intensity categories may explain the cause of the decrement identified in output across match play in hockey (Haro et al., 2021; James et al., 2021; Morencos et al., 2018). Strategies should be put in place in order to prevent this fatigue while enhancing the players' capabilities, as it may provide a performance advantage particularly as the ability to deceleration has been identified as a key factor in change of direction performance in team sport (Lakomy & Haydon, 2004).

The maximal magnitude of deceleration is much lower in this investigation (-8.30m.s²) compared to the only other hockey investigation (-13.6m.s²) that provides a maximal value (Chesher et al., 2019). Additionally, a lower volume of deceleration activities was also found in the current investigation when compared to Chesher et al. (2019). This is potentially due to GPS units from different manufacturers utilised in each study. Thornton et al. have established substantial between differences between manufacturers for both accelerations and decelerations, within the same task, due to data processing approaches such as the filtering algorithms applied (Thornton et al., 2019). This is further substantiated by the findings of Crang et al. (2021) who highlighted, in particular, the variance between unit manufacturers for counts of acceleration and deceleration events during the same task. Both studies utilised GPS (10Hz) derived values and a similar minimum threshold of 3m.s², however, the match format (halves compared to quarters), differences in squad size (15 compared to 16) and differences between manufacturers data processing approaches make comparisons difficult.

Defenders complete less distance per acceleration effort than both midfielders and forwards, with close to 1m less reported per effort (small ES). This may reflect the different tactical roles

demanded from each position with defenders playing closer to their own goal and exploring less of the pitch. Given that deceleration events frequently follow acceleration events, and that the magnitude of accelerations are similar for each position despite defenders achieving this magnitude in a shorter distance, defenders may require greater eccentric strength to ensure they have the capacity to repeatedly produce and sustain these efforts. In this cohort, as reported in the methods section, defenders have a higher 1 repetition max back squat, relative to their bodyweight, compared to other positions. Additionally, as deceleration events have been shown to reach a greater magnitude than acceleration events across positions field hockey players require a greater focus on their eccentric strength capacity (Harper & Kiely, 2018; Jones et al., 2017; Lakomy & Haydon, 2004; Sabido et al., 2017).

An increase in eccentric strength can have a dual impact on acceleration and deceleration performance as athletes with greater levels of eccentric strength are able to approach change of direction tasks/scenarios at higher velocities as they are better able to tolerate the greater ground reaction forces generated by a faster approach. This has been suggested by Jones and colleagues as a “‘self-regulation’ effect (i.e., a player approaches faster based on the deceleration load they know/feel they can tolerate)” (Jones et al., 2017). This may offer performance benefits due to the importance of change of direction in field hockey.

Over 90% of deceleration efforts are less than 5m in distance. This must be considered when prescribing training drills and drills targeted towards improving hockey specific deceleration capabilities. This is important as a field hockey athlete with high deceleration capabilities may have a performance advantage. For both activities, typical distance per effort can be deemed as short, however, events that fall outside the typical pattern must also be considered to ensure that players have been exposed to what can be considered “maximal” or greater than typical demands. Particularly, as longer distance acceleration efforts may be linked to sprint efforts and given the importance of acceleration to obtaining maximal velocity. Preparing players for the average demands of the sport may lead to injury and underperformance, while safely exposing players to demands beyond average values in a progressive manner may lower injury levels “likely through higher performance ability rendering typical match demands as being relatively lower for any given individual” (Gabbett, 2016). Thus, players should be afforded the opportunity to train acceleration over longer distances despite the abundance of shorter acceleration efforts within match play using the maximal values displayed in this investigation. Upton et al has reported that different strategies should be employed for training acceleration efforts over greater distance (>14m) with resisted efforts proving beneficial whereas assisted efforts were more beneficial for shorter distance efforts (<5m) (Upton, 2011). However, Spinks et al. (2007) reported that longer distance efforts, without resistance, were just as effective at improving acceleration velocity.

Completing high intensity acceleration and deceleration events have been linked with an increase in creatine kinase (Gastin et al., 2019). An increase in creatine kinase (+1 Z score) has been reported to decrease accelerations, decelerations, distance completed while completing these actions and maximal velocity by $-4.3 \pm 2.9\%$, $-4.1 \pm 2.9\%$, $-3.1 \pm 2.9\%$, and $-4.6 \pm 1.9\%$

respectively (Malone et al., 2018). Thus, monitoring the frequency, magnitude and duration of acceleration and deceleration events could provide coaches with the useful information as to the physical status of their athletes for performance within a hockey tournament or the training environment. This is particularly important in field hockey as peak creatine kinase levels have been found at forty-eight hours post activity and typical hockey scheduling means that a second match occurs within this time period. Furthermore, Beato et al found meaningful differences in internal load variables between protocols which compared high magnitude accelerations versus lower magnitude acceleration during repeat sprint training (Beato & Drust, 2021). Higher peak heart rate and time spent at > 85% heart rate peak were noted alongside moderate differences were found in the muscular and cardiovascular rate of perceived exertion values reported (Beato & Drust, 2021). This highlights the higher perceived cardiovascular and muscular load required during maximal accelerations and the value in tracking and preparing for them in elite sport.

This investigation provides normative data for acceleration and deceleration efforts during international hockey matches. The typical magnitude, duration of and distance of each effort type (Table 2), have been established providing markers for the monitoring of hockey players. Training drill data can be compared to the data provided in this investigation to ensure players are exposed to acceleration and deceleration efforts similar to match exposure. Further investigation relating to the contextual environment in which these events are accumulated is warranted.

Conflict of Interest

The authors declare no conflict of interests.

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Supplementary Materials

Supplementary Table 1: Accelerations and decelerations categorised into velocity bands.

Type	Velocity (m.s ²)	Percentage	Type	Velocity (m.s ²)	Percentage
Deceleration	-3 – 3.99	62%	Acceleration	3 – 3.99	71%
Deceleration	-4-4.99	27%	Acceleration	4-4.99	22%
Deceleration	-5-5.99	9%	Acceleration	5-5.99	5%
Deceleration	-6-6.99	2%	Acceleration	6-6.99	1%

Supplementary Table 2: Accelerations and decelerations categorised into velocity bands by position.

Type	Velocity (m.s ²)	Defender	Outside Back	Midfielder	Forward
Accelerations	3-3.99	73%	71.65%	71.28%	69.41%
Accelerations	4-4.99	23%	20.74%	21.16%	23.75%
Accelerations	5-5.99	4%	5.41%	6.85%	4.93%
Accelerations	6-6.99	0%	2.%	1.%	2%
Deceleration	-3-3.99	67%	59%	62%	60%
Deceleration	-4-4.99	25%	30%	27%	28%
Deceleration	-5-5.99	7%	10%	10%	10%
Deceleration	-6-6.99	1%	1.%	2%	1%
Deceleration	-7-7.99	0%	<0%	0%	1%

Physiological and subjective responses to a novel military specific load carriage treadmill protocol

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ABSTRACT

Treadmill-based load carriage protocols typically use a single fixed speed; however, these are not representative of occupational load carriage tasks. This study aimed to quantify the metabolic, cardiovascular, thermal, neuromuscular, and perceptual responses to a treadmill-based, military-specific, fast load carriage protocol (FLCP). This protocol comprised of carrying 25 kg, for 20 minutes at 5.1 km·h⁻¹; 40 minutes, at 6.5 km·h⁻¹; and 8 x 9 s shuttles, at 11 km·h⁻¹ with 11 s recovery. Twelve men (age, 27 ± 6 y; stature, 1.83 ± 0.05 m; body mass, 80.6 ± 8.0 kg; maximal oxygen uptake, 52.7 ± 5.5 mL·kg⁻¹·min⁻¹), completed a FLCP during which oxygen consumption ($\dot{V}O_2$), heart rate, core body temperature, and perceptual ratings were recorded. Performance assessments (weighted counter-movement jump [wCMJ], maximal isometric voluntary contraction [MIVC] of the quadriceps, seated medicine ball throw [SMBT]) were completed pre-FLCP, immediately post and, 30, 60, 120 minutes' post. $\dot{V}O_2$ was similar for 5.1 km·h⁻¹, but increased by 7.4% during the 40 minutes at 6.5 km·h⁻¹ ($p = 0.013$). Core temperature increased by 0.92 ± 0.22 °C in response to the FLCP. Post-FLCP, SMBT was not dissimilar across measurement points, ($p = 0.315$), however, MIVC peak force reduced by 12.6 ± 10.9% 60 minutes post-FLCP ($p = 0.031$), and wCMJ height decreased by 8.7 ± 5.9% 120 minutes post-FLCP ($p = 0.011$). The completion of the FLCP does not affect upper body power (SMBT), but appears to modestly decrease lower body explosiveness (wCMJ and MIVC) up to two hours' post. Future investigations can use the FLCP protocol to investigate occupationally relevant scenarios, such as the interaction between physical and cognitive performance during load carriage, or the implications of multiple repeated load carriage bouts.

1. Introduction

Load carriage is a strategically important facet of military training and operations; which can often be mission-critical (Knapik et al., 2004). Specifically, load carriage refers to the action of moving from one location to another, by way of walking or running, whilst carrying an external load of mission-specific equipment. As a consequence of its criticality, factors influencing load carriage performance have generally been well researched (see review by Knapik et al., 2012). In particular, the influence of external load mass has received considerable attention; with studies detailing an upward trend over time in loads carried during military operations (Knapik et al., 2004, 2012; Orr, 2010). However, scenarios exist, where the combination of faster load carriage

speeds (> 4.8 km·h⁻¹) and lighter load masses (< 30 kg), to facilitate these movement speeds, are undertaken; termed herein a 'fast march'. For example, soldiers will be required to move at speed with lighter loads as when coming under fire or whilst assaulting an enemy position. This necessity to complete load carriage tasks at different speeds and with different loads is reflected in the new British Army annual fitness tests (British Army, 2020). Despite its relevance to military populations, the implications of this alternative speed-load combination have received considerably little attention. Notably, those studies investigating this combination have typically utilized purely rucksack borne loads at fixed speeds (e.g., Blacker et al., 2009, 2010), which does not reflect the external load distribution of soldiers during these aforementioned scenarios. Instead, the

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lighter load mass carried during a fast march would typically consist of a belt webbing system, body armor, a personal weapon, and in some instances a small rucksack; totaling ~25 kg. This ensemble is carried in situations where enemy contact is anticipated (Knapik et al., 2004), and represents a typical minimum load carried by dismounted infantry soldiers whilst patrolling. It is important to assess this load distribution given the known metabolic cost implications of different load mass carrying locations (e.g., Soule & Goldman, 1969; Browning et al., 2007; Taylor et al., 2012).

Military load carriage and other arduous military tasks are rarely completed in isolation. As such, it is important to consider the impact of load carriage on subsequent military and physical performance (Knapik et al., 2012; van Dijk, 2007). For example, following a fast march, soldiers may be likely to undertake a fire and maneuver task in response to enemy contact. In turn, this may be followed by other tasks such as a casualty evacuation, replenishment of stores or even subsequent assaults on enemy positions. However, due to factors such as high task complexity, the multitude of sequential task permutations, and the difficulty in accurately replicating military scenarios, investigating subsequent military task performance can be problematic. As a result, field-expedient tests are frequently used to assess changes in key physical competencies (Hauschild et al., 2017). These physical performance assessments can therefore act as an indicator of task-induced fatigue as well as indicators of role-specific physical readiness. Broadly, these physical assessments can be categorized into those assessing cardiorespiratory endurance (e.g., multi-stage fitness test), muscular strength (e.g., back squat), muscular endurance (e.g., repeated shuttles), and flexibility (e.g., sit-and-reach) (Hauschild et al., 2017). Of these assessment domains, cardiorespiratory endurance, lower body strength and upper body muscular endurance are among the most effective predictors of occupational performance (Hauschild et al., 2017; Knapik et al., 2006). These assessments, therefore, provide a time and space-efficient method for quantifying soldier physical readiness.

A number of studies have utilized physical performance assessments as indicators of fatigue following load carriage tasks. For example, Fallowfield et al., (2012) demonstrated a reduction in vertical jump height ($8 \pm 9\%$) following a 19.3 km march at $4.3 \text{ km}\cdot\text{h}^{-1}$ (including breaks), carrying 31 kg. Conversely, Knapik et al. (1991) reported no decrement in soldiers vertical jump height following a 20 km march (mean completion speed $3.82 \text{ km}\cdot\text{h}^{-1}$), carrying 46 kg; however, grenade throw distance decreased by 9%. It was noted that this latter observation was likely due to nerve entrapment or pain in the shoulder region caused by the strenuous march (Knapik et al., 1991). Critically, these studies investigated load carriage tasks conducted at relatively modest paces ($<4.8 \text{ km}\cdot\text{h}^{-1}$), using moderate to heavy loads ($>30 \text{ kg}$), carried predominantly in a rucksack. As such, the implications of a fast march with load distributed on the torso and waist on indicators of soldier physical readiness are not well known.

The current study designed and employed a novel treadmill protocol to replicate the physical demands of a military specific fast march, and fire and maneuver task. Physical performance assessments were included to evaluate the effect of load carriage on subsequent indicators of soldier physical readiness in the 2 hours' post-task. Therefore, this study aimed to; 1) quantify the metabolic, cardiovascular, thermal, neuromuscular, and perceptual responses to a treadmill-based, military-specific, fast

load carriage protocol (FLCP); and 2) identify the effects of the FLCP on subsequent indicators of soldier physical readiness.

2. Methods

2.1. Experimental Overview

Participants completed a familiarization session followed by an experimental session, separated by a minimum of five days. For the familiarization session participants had baseline measures of body composition recorded, after which they completed an unloaded treadmill walking assessment, followed by a maximal rate of oxygen consumption ($\dot{V}O_{2\text{max}}$) test. Participants were also familiarized with the physical performance assessments (4 kg seated medicine ball throw [SMBT], weighted countermovement jump [wCMJ], quadriceps maximal isometric voluntary contraction [MIVC]), and an abridged version of the FLCP. For the experimental session, participants completed these performance assessments before completing the FLCP, immediately afterwards and at 30-, 60-, and 120-minutes' post. During the FLCP, oxygen consumption ($\dot{V}O_2$), heart rate (HR), core temperature, and perceptual ratings were recorded. All testing was conducted in an air-conditioned laboratory.

2.2. Fast Load Carriage Protocol Design

This occupationally relevant load carriage task was developed from prior literature and current military load carriage assessments. The FLCP (Figure 1), consisted of walking at $5.1 \text{ km}\cdot\text{h}^{-1}$ and $6.5 \text{ km}\cdot\text{h}^{-1}$ for 20 and 40 minutes respectively (1% gradient). At 60 minutes, participants walked for one minute at $2.5 \text{ km}\cdot\text{h}^{-1}$ (1% gradient) before completing eight, nine-second shuttles at $11 \text{ km}\cdot\text{h}^{-1}$ and 3% gradient. Shuttles were interspersed by an 11 second recovery period at $2.5 \text{ km}\cdot\text{h}^{-1}$ and 3% gradient. The first part of the FLCP mimicked the load carriage speeds typical of fast marches undertaken by the British Army, and are speeds and distances that have been utilized effectively in both prior load carriage literature (Blacker et al., 2010; Blacker, Fallowfield, Bilzon, et al., 2013; Vine et al., 2020), and the new British Army physical employment standards (British Army, 2020). The subsequent shuttle speed, distance, and work-to-rest ratio are in line with offence or defensive fire and maneuver based tasks, undertaken by militaries worldwide (Myers et al., 2016; Silk & Billing, 2013; Treloar & Billing, 2011), and again are in line with the new British Army physical employment standards (British Army, 2020).

2.3. Participants

Twelve recreationally active men, with no military experience volunteered to participate (age, 27 ± 6 years; stature, $1.83 \pm 0.05 \text{ m}$; body mass $80.6 \pm 8.0 \text{ kg}$; body fat percentage, $13.3 \pm 2.8\%$; $\dot{V}O_{2\text{max}}$, $52.7 \pm 5.5 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$). Ethical approval was granted by the Institutional Research Ethics Committee and data collection was conducted in accordance with the Declaration of Helsinki. Participants provided full written consent, having received both a written and verbal brief.

For both sessions, participants were instructed to attend the laboratory in a hydrated state, having avoided caffeine and

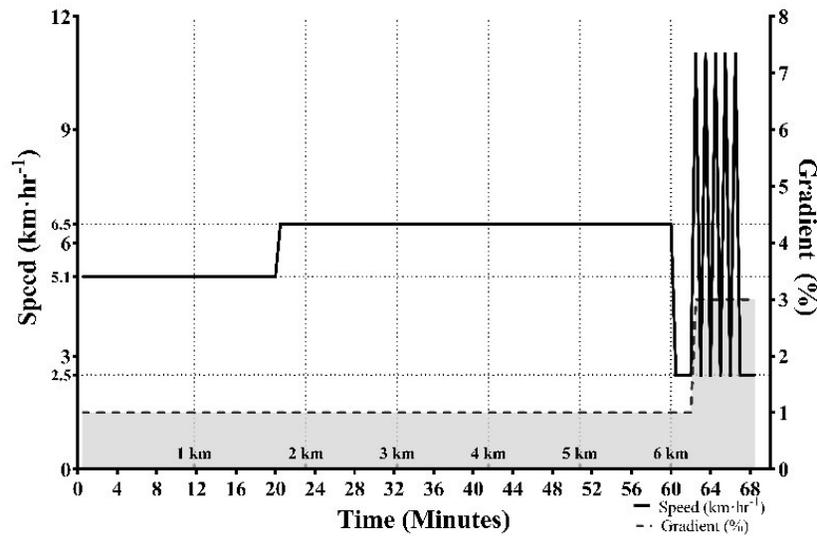


Figure 1: The fast load carriage protocol, detailing the changes in treadmill speed (solid black line) and gradient (dashed grey line and light grey fill). *Note:* Number of shuttles are for diagrammatic clarity, as per the manuscript there are a total of eight, the time duration of the shuttle period is however correct. Vertical dashed lines denote cumulative distance covered.

strenuous exercise for a minimum of three hours and 24 hours preceding respectively. In addition, participants were instructed to maintain a habitual diet in the lead up to, and between sessions, along with abstaining from nutritional supplements for the entirety of the data collection period, and two weeks preceding. For both sessions, participants wore a sports t-shirt, shorts, and training shoes.

2.4. Familiarization Session

Upon arrival at the laboratory, participants provided a urine sample to determine hydration status (urine specific gravity [ATAGO Uricon-Ne 2722, Fisher Scientific, UK]) (Sawka et al., 2007). Stature and body mass (Seca 837 digital scales & 213 portable stadiometer, Seca Ltd, UK) were then recorded to the nearest 0.01 m and 0.01 kg respectively, prior to body composition being assessed using the bioelectrical impedance method (Tanita BC-418MA, Tanita EU, Netherlands). Participants then rested for 10 minutes before undertaking two six-minute periods of unloaded walking on a motorized treadmill (HP Cosmos Saturn, HP Cosmos, Germany) at 5.1 and 6.5 km·h⁻¹ with gradient fixed at 1% (replicating speeds and gradient of the full FLCP, described subsequently). In the final two minutes of each six-minute period $\dot{V}O_2$ was assessed using the Douglas bag technique; allowing the calculation of load carriage economy utilizing the external load index (described subsequently).

Upon completion of the unloaded walking periods, participants were familiarized with the three performance assessments (SMBT, wCMJ, MIVC). These were selected due to either their known correlations to military performance (Pihlainen et al., 2018; Spiering et al., 2019) or demonstrated sensitivity to load carriage tasks (Blacker et al., 2010; Blacker, Fallowfield, Bilzon, et al., 2013; Fallowfield et al., 2012; Knapik et al., 1991). For all performance assessments, three maximal attempts were

conducted at each assessment interval, with peak performance reported.

Seated Medicine Ball Throw. Performance was assessed by measuring the maximum distance (to the nearest 0.01 m) an individual could throw a 4 kg medicine ball, using a chest pass technique. Participants conducted the SMBT whilst in a seated position, on the floor, with legs extended out in front of them and back upright against a wall (Cronin & Owen, 2004).

Weighted Counter Movement Jump. Force data were collected using two force plates with a sampling rate of 1000 Hz, calibrated prior to use, in accordance with the manufacturer's guidelines (Pasport Force Platform, PASCO, USA). During the wCMJ, participants wore military webbing and a weighted vest (20 kg). To negate the influence of the upper body, participants were instructed to place their arms across their chest and maintain this position throughout the jump (Lake & McMahon, 2018). Prior to jumping, a three-second quiet standing period was enforced, before the command "jump", where participants were instructed to jump as high and as fast as possible (Lake & McMahon, 2018).

Quadriceps Maximal Isometric Voluntary Contraction. Force data were collected using an adjustable custom-built chair (University of Chichester, UK) and an s-beam load cell (250kg Tedeo-Huntleigh, RS Components, UK). Data were recorded at 1000 Hz, using a PowerLab data acquisition device (AD Instruments, UK), and a computer running Chart 4 software (V4.1.2, AD Instruments, UK). Using the adjustable backrest, participants were positioned so that hip and knee angles were at 90° of flexion, whilst their right leg was attached to the base of the chair via the load cell and ankle cuff (Blacker et al., 2010). Chest and waist Velcro straps were used to restrict participant's upper body movement. Before the maximal contraction, participants were instructed to 'take up the slack' and remain still (three seconds), before the command 'go' at which time participants were instructed to contract as hard and fast as possible.

Maximal Aerobic Capacity Assessment. Following familiarization to the physical performance assessment, participants completed a $\dot{V}O_{2\max}$ assessment (Part 1) and subsequent verification (Part 2) (Draper et al., 2006; Midgley et al., 2009). For Part 1 participants commenced running at $9 \text{ km}\cdot\text{h}^{-1}$, with a gradient increase of $1 \text{ \%}\cdot\text{min}^{-1}$ until minute five, thereafter speed only was increased by $0.4 \text{ km}\cdot\text{h}^{-1}$ every 20 s ($1.2 \text{ km}\cdot\text{h}^{-1}\cdot\text{min}^{-1}$), until they reached volitional exhaustion. Participants were given verbal encouragement throughout. On completion, they rested for five minutes, before commencing Part 2. Here, participants initially ran for three minutes at $9 \text{ km}\cdot\text{h}^{-1}$, 5% gradient, after which the speed increased to $1 \text{ km}\cdot\text{h}^{-1}$ above their peak treadmill speed from Part 1. Again, participants were instructed to run to volitional exhaustion.

Heart rate was recorded continuously throughout the assessment using short-range telemetry (RS800, Polar Electro, Finland), with HR averaged across 5 s epochs. Expired gas samples were collected via a mouthpiece, Salford type valve, and low resistance tubing into 150 L Douglas bags (Cranlea Human Performance Limited, UK). Collections of ~60 seconds were taken with a minimum final sample of 75 L. Gas fractions were quantified using an offline gas analyzer (Servomex 5200, Servomex, UK), volumes using a dry gas meter (Harvard Apparatus, USA), and temperature measured using a digital thermometer (Fisher Scientific, UK). The gas analyzer was calibrated using a two-point calibration, following the manufacturer's instructions.

After the participant was sufficiently rested, they were familiarized with an abridged version of the FLCP comprising two, eight-minute bouts of walking at 5.1 and $6.5 \text{ km}\cdot\text{h}^{-1}$ (1% gradient), followed by three, nine-second shuttles at $11 \text{ km}\cdot\text{h}^{-1}$ (shuttles were separated by 11 seconds at $2.5 \text{ km}\cdot\text{h}^{-1}$). Throughout this protocol, participants wore a military-specific load mass ensemble ($25.0 \pm 0.3 \text{ kg}$) consisting of a belt webbing system (10 kg), a weighted vest mimicking body armor (10 kg), and a replica assault rifle with sling (5 kg). Participants were instructed to carry the replica rifle in the 'ready position' with the weapon slung across their chest and supported by both hands.

2.5. Experimental Session

Participants arrived at the laboratory, between 07:30-08:00, in a euhydrated and fed state. A standardized breakfast was provided (carbohydrate - 34 g; fat - 5.8 g; protein - 9.6, 0.95 MJ) 1.5 hours before the start of the trial with participants having fasted for the preceding 11 hours. Hydration status was assessed in the manner previously described.

Before commencing the baseline performance assessments, participants completed a standardized cycle ergometer (Wattbike Pro, Wattbike, UK) warm-up comprising of five minutes at ~100 W at a rating of perceived exertion (RPE) (Borg, 1970) ~10 (Lake et al., 2014). This warm-up was then repeated prior to all post-performance assessments, apart from immediately post-FLCP. Participants completed the three performance assessments to best effort, to obtain baseline performance data. Subsequently, nude, and clothed (base layer minus shoes) body masses were collected. Participants then inserted a rectal thermistor (Grant Instruments, UK), for the measurement of core body temperature, fitted their

HR monitor and donned the load ensemble. Participants then commenced the FLCP (Figure 1).

During the FLCP, participants RPE, load discomfort (Comfort Affective Labelled Magnitude, CALM) (Cardello et al., 2003), thermal comfort (Bedford, 1936), and thermal sensation (ASHRAE Standard, 1992) were collected at five-minute intervals (Table 1). A 90 second expired gas collection was taken at the end of the first 5 minutes, and then every 10 minutes subsequently, to assess $\dot{V}O_2$. Environmental conditions (QT-34 WBGT Monitor, 3M, USA), HR, and core temperature were recorded continuously (Squirrel 1000 series, Eltek, UK). To ensure euhydration, 150 mL of water was provided to participants every 15 minutes (Sawka et al., 2007). All measures taken throughout the protocol are detailed in Table 1. After completion of the treadmill protocol, clothed, and nude body mass were measured to determine sweat loss, euhydration was deemed to have been maintained if <1% reduction in nude body mass had occurred (Sawka et al., 2007). Additionally, a post-exercise urine sample was collected and assessed for urine specific gravity. Following completion of load carriage protocol, removal of the rectal thermistor, and assessment of body mass (seven minutes' post), participants then completed the three physical performance assessments (SMBT, wCMJ, MIVC). Participants then rested in a seated position until they repeated the performance assessments at 30-, 60-, and 120-minutes' post.

2.6. Data Analysis

Physiological Variables Measured $\dot{V}O_2$, HR, environmental data, and perceptual scales were time aligned; with HR data averaged over the final minute of each five-minute block. The highest $\dot{V}O_2$ and HR values obtained during both assessments were taken as $\dot{V}O_{2\max}$ and HR maximum (HR_{max}) respectively. For secondary analysis purposes, $\dot{V}O_2$ and HR data were expressed relative to $\dot{V}O_{2\max}$, HR_{max}, and HR reserve (HRR; calculated using HR_{max} and lowest resting value from the familiarization session). Furthermore, using unloaded $\dot{V}O_2$ (familiarization session) and loaded $\dot{V}O_2$ (experimental session), External Load Index was calculated to describe load carriage economy (Lloyd et al., 2010). It has been suggested that this approach has a distinct advantage over other economy metrics (such as % $\dot{V}O_{2\max}$), as it factors in individual walking gait (Lloyd et al., 2010).

Performance Assessments For the wCMJ, the performance variable of jump height was calculated using the flight time method described by Moir (2008). Take-off and landing were the first instances where resultant vertical force fell below and increased above 10 N, respectively. Flight time was the time between these instances. In addition, Reactive Strength Index Modified (RSI_{Mod}) was calculated for each jump (McMahon et al., 2018). The onset of the wCMJ was identified as the instance where resultant force fell below the threshold of body mass minus five standard deviations of the 'quiet standing' period. These variables were identified using visual inspection in combination with Dplot Jr software (version, 2.3.5.7; HydeSoft Computing, USA).

For the MIVC, contractions lasted approximately five seconds and were separated by 45 seconds (Blacker et al., 2009). The onset of the contraction was identified as the instance where force exceeded mean 'slack' force plus three times standard deviations

Table 1: Overview of experimental measures and their timings during the fast load carriage protocol.

	Time (minutes)														
	0	5	10	15	20	25	30	35	40	45	50	55	60	65*	
Speed (km·h ⁻¹)	0	5.1	5.1	5.1	5.1	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	FM
Gradient (%)	0	1	1	1	1	1	1	1	1	1	1	1	1	1	3
Perceptual Scales	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
$\dot{V}O_2$		✓		✓		✓		✓		✓		✓			
HR	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Environmental	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Water Provision				✓			✓			✓			✓		

Note: Speeds – see methodology for detailed description of the treadmill speed in this section of the protocol. *Note this block is not 5 minutes in duration – see methodology for detailed description of duration of this section of the protocol.

of this period. The variables of peak force, peak 250 ms, and 500 ms force epochs were calculated as these have been identified as reliable performance outcomes (Blacker, Fallowfield, & Willems, 2013).

2.7. Statistical Approach

Data are presented as mean \pm standard deviation unless otherwise stated. Statistical analysis was conducted using JASP (version 0.11.1, University Amsterdam, Netherlands). The *P*-values were converted to base-2 log-transformed *S*-values (*S*) (Shannon, 1948) to aid interpretation and clarity of statistical estimation (Cole et al., 2021). Data were assessed for normality, using skewness and kurtosis ratios, and sphericity; with the Greenhouse-Geisser correction applied if assumptions of sphericity were violated. For normally distributed data a one-way repeated measures Analysis of Variance (ANOVA) was conducted to identify whether a main effect of time was present for both the physiological measures across the FLCP task and for the performance measures. Effect sizes are presented as Omega squared (G^2) (Levine & Hullett, 2002), where 0.01, 0.06, 0.14 are classed as small, medium and large effect sizes, respectively (Field, 2013). Where the combination of *F*-statistics, *p*-values / *S*-values, and effect sizes, indicate a likely incompatibility with the null model, *post-hoc* pairwise comparisons were made with a Holm-Bonferroni adjustment (denoted by subscript H). Mean differences and 95% compatibility (confidence) intervals, with Bonferroni adjustment, were calculated for pairwise comparisons. In addition, effect sizes were calculated as Cohen's standardized means and converted to Hedges g_z (Lakens, 2013), to account for the overestimation of effect sizes from small sample sizes. From these *post-hoc* effect sizes, common language effect sizes (CLES) were also calculated (Lakens, 2013). In some instances, where many differences are observed ranges of *p*-values / *S*-values, and effect sizes are presented. For non-parametric data, a Friedman's test was employed with effect sizes presented using Kendall's *W*. Where the combination of χ^2 -statistics, *p*-values / *S*-values, and effect sizes, indicate a likely incompatibility with the null model, *post hoc* pairwise comparisons were made using Conover's test.

3. Results

The environmental conditions in the laboratory were 12.3 ± 1.5 °C Wet Bulb Globe Temperature indoors, 64.9 ± 9.9 % relative humidity with a mean change across the trials of 0.9 ± 0.5 °C and 6.3 ± 4.3 % respectively. Pre- and post-FLCP urine specific gravity values were 1.010 ± 0.006 and 1.007 ± 0.003 respectively.

3.1. Physiological and Subjective Responses

Relative $\dot{V}O_2$ increased throughout the FLCP ($F_{(1.207, 12.07)} = 189.423$, $p < 0.001$, $S > 9.97$, $G^2 = 0.743$) (Figure 2a). *Post-hoc* comparisons did not provide evidence that $\dot{V}O_2$ values differed between both measurement points at $5.1 \text{ km}\cdot\text{h}^{-1}$ ($t_{(11)} = -0.696$, $p_H = 0.503$, $S_H = 0.99$, $g_z = -0.187$, 95% CI_H [0.396, -0.572]). However, compared with the first measurement point, at $6.5 \text{ km}\cdot\text{h}^{-1}$ (25 minutes) mean $\dot{V}O_2$ increased by 2.5%, 5.9%, and 7.4% at 35, 45 and 55 minutes respectively (35 minutes: $t_{(11)} = -2.473$, $p_H = 0.105$, $S_H = 3.25$, $g_z = -0.654$, 95% CI_H [0.423, -1.905]; 45 minutes: $t_{(11)} = 3.608$, $p_H = 0.024$, $S_H = 5.38$, $g_z = -0.969$, 95% CI_H [0.078, -2.655]; 55 minutes: $t_{(11)} = 4.177$, $p_H = 0.013$, $S_H = 6.27$, $g_z = -1.122$, 95% CI_H [-0.139, -3.174]). As such, controlling for individual differences, the likelihood that an individual had a greater relative $\dot{V}O_2$ at 35, 45, and 55 minutes, compared with 25 minutes was 76%, 85%, and 89% respectively, as indicated by the CLES. External Load Index also increased across measurement points ($F_{(1.186, 11.859)} = 24.581$, $p_H < 0.001$, $S_H > 9.97$, $G^2 = 0.435$). Compared with External Load Index values at 25 minutes there was an increase of 3.6%, 5.9%, and 7.4% at measurement points 35, 45 and 55 minutes respectively (35 minutes: $t_{(11)} = -2.322$, $p_H = 0.128$, $S_H = 2.97$, $g_z = -0.624$, 95% CI_H [0.02, -0.081]; 45 minutes: $t_{(11)} = -3.521$, $p_H = 0.028$, $S_H = 5.16$, $g_z = -1.100$, 95% CI_H [0.005, -1.111]; 55 minutes: $t_{(11)} = -4.097$, $p_H = 0.015$, $S_H = 6.06$, $g_z = -1.122$, 95% CI_H [-0.005, -0.133]). Thus, the likelihood that an individual had a greater External Load Index at 35, 45, and 55, compared with 25 minutes, when controlling for individual differences was 75%, 85%, and 88% respectively, as indicated by the CLES. Conversely, External Load Index values at $5.1 \text{ km}\cdot\text{h}^{-1}$ did not appear to differ according to *post-hoc* comparisons ($t_{(11)} = -0.611$, $p_H = 0.555$, $S_H = 0.85$, $g_z = -0.164$, 95% CI_H [0.023, -0.032]).

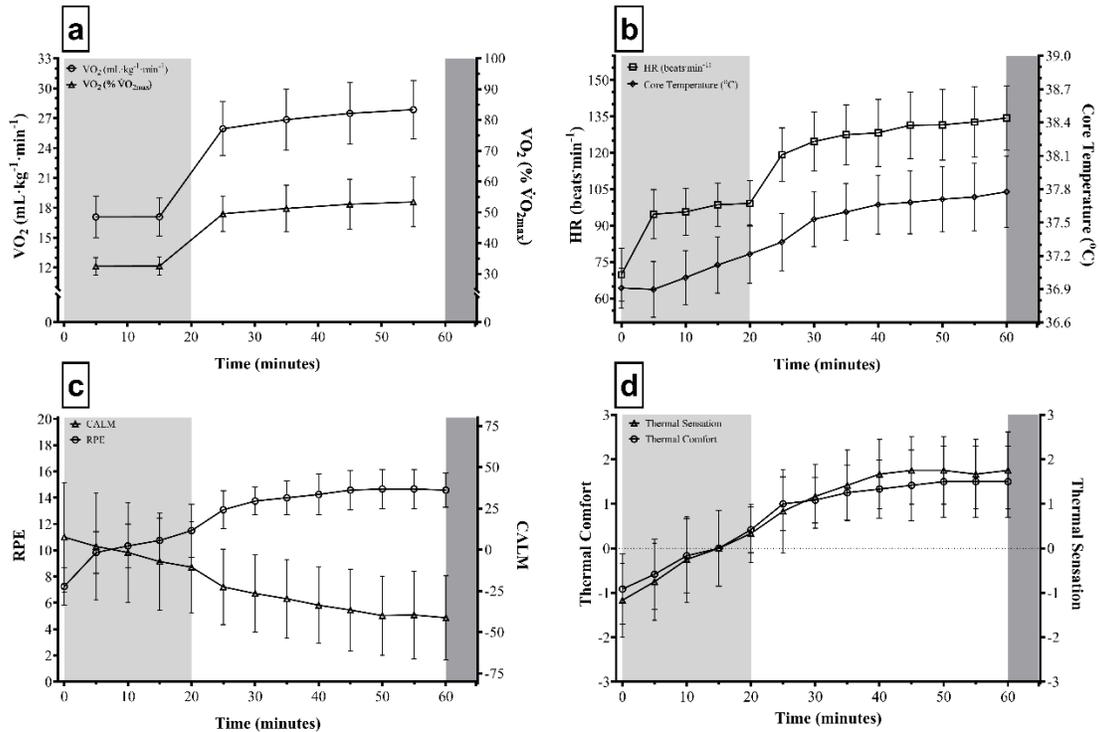


Figure 2: The relative $\dot{V}O_2$ (a), heart rate and core temperature (b), comfort affective labelled magnitude (CALM) and ratings of perceived exertion (RPE) (c), and thermal sensation and thermal comfort (d) during the fast load carriage protocol. *Note:* Data are presented as mean \pm SD. The light grey, white, and dark grey areas denote the 5.1 km·h⁻¹, 6.5 km·h⁻¹, and simulated fire and maneuver portions of the protocol respectively. Note core temperature values were only obtained for 10 participants.

A large effect for measurement point was also evident in HR responses ($F_{(1,599, 17,594)} = 116.344, p < 0.001, S > 9.97, \mathcal{G}^2 = 0.616$) (Figure 2b). At 5.1 km·h⁻¹, measurements at 5 and 10 minutes, did not appear to be different according to *post-hoc* comparisons ($t_{(11)} = 1.168, p_H = 1.000, S_H = 0.00, g_z = 0.314, 95\% CI_H [4.808, -2.863]$); however, mean HR increased from minutes 5 to 15 ($t_{(11)} = 3.963, p_H = 0.033, S_H = 4.92, g_z = 1.064, 95\% CI_H [8.499, -0.638]$). When compared with the first measurement point at 6.5 km·h⁻¹ (25 minutes), there was an increase in HR across all subsequent measurement points ($p_H = 0.033 - <0.001, S_H = 4.92 - >9.97, g_z = -1.056 - -1.941$). During the shuttles phase of the FLCP, peak HR corresponded to $81.9 \pm 5.9\%$ and $73.5 \pm 8.7\%$ HR_{max} and HRR, respectively.

Core body temperature also displayed a large effect for measurement point ($F_{(12, 108)} = 50.153, p < 0.001, S > 9.97, \mathcal{G}^2 = 0.584$); with a mean increase of 0.92 ± 0.22 °C in response to the FLCP (Figure 2b; $n=10$ participants only). *Post-hoc* comparisons did not provide an indication that core body temperature differed from baseline to measurements at 5 and 10 minutes but did at all following measurement points ($p_H = 0.031 - <0.001, S_H = 5.01 - >9.97, g_z = -1.383 - -3.748$). Pre- to post-FLCP nude body mass remained similar, with a change in body mass of $0.0 \pm 0.4\%$ ($n=11$; one participant's data was removed due to a transcriptional error leading to an implausible post-FLCP body mass).

Perceived exertion increased across the protocol ($F_{(12, 132)} = 85.153, p < 0.001, S > 9.97, \mathcal{G}^2 = 0.693$) with a mean change of

7 ± 1 points (Figure 2c). This change reflected a transition from a median response of 'extremely light' to a median response of 'hard' at 60 minutes. Conversely, CALM, had a mean reduction of 49 ± 32 points ($\chi^2_{(12)} = 132.427, p < 0.001, S > 9.97, Kendall's W = 0.637$); indicating participants were finding the load carried during the protocol progressively more uncomfortable (Figure 2c). Median ratings decline from around 'neither comfortable nor uncomfortable' pre-FLCP to around 'moderately uncomfortable'. Ratings of thermal comfort ($F_{(12, 132)} = 31.771, p < 0.001, S > 9.97, \mathcal{G}^2 = 0.556$) and thermal sensation ($F_{(12, 132)} = 35.195, p < 0.001, S > 9.97, \mathcal{G}^2 = 0.593$) both increased across measurement points, with a mean change of 2 ± 1 , and 3 ± 1 for thermal comfort and sensation respectively. Thus, indicating participants perceived they were getting hotter and becoming less comfortable throughout the FLCP, transitioning from 'comfortably cool' and 'slightly cool' to 'too warm' and 'warm'.

3.2. Performance and Neuromuscular Responses

Table 2 lists physical performance assessments outcomes, whilst Figure 3 displays the percentage change in performance compared with pre-FLCP values. Statistical analysis did not provide evidence that SMBT distance differed across measurement points ($F_{(4, 44)} = 1.223, p = 0.315, S = 1.67, \mathcal{G}^2 = 0.001$). Conversely, for wCMJ, both jump height and RSI_{Mod} displayed a moderate main

Table 2: Change in performance for each performance metric across assessment time points post-fast load carriage protocol (Mean \pm SD).

Performance Measure		Pre-FLCP Performance	Effect Size for Assessment Time Point (G^2)	Post-Load Carriage Protocol Mean Difference [95% Compatibility Intervals]			
				Post	30 min post	60 min post	120 min post
SMBT	Distance (m)	4.48 \pm 0.40	0.001	-0.03 [-0.10, 0.05]	0.00 [-0.08, 0.07]	-0.03 [-0.11, 0.05]	-0.06 [-0.15, 0.03]
	Jump Height (m)	0.26 \pm 0.06	0.013	-0.01 [0.03, 0.02]	-0.01 [-0.04, 0.01]	-0.02 [-0.04, 0.01]	-0.02 [-0.04, -0.01]*
wCMJ	RSI _{Mod} (ratio)	0.27 \pm 0.08	0.024	-0.02 [-0.06, 0.02]	-0.03 [-0.05, 0.00]	-0.03 [-0.07, 0.00]	-0.04 [-0.06, -0.01]*
MIVC	Peak Force (N)	816.0 \pm 108.6	0.092	-72.1 [-150.4, 6.2]	-85.6 [-198.8, 27.7]	-105.7 [-203.5, -7.8]*	-99.0 [-229.2, 31.3]
	250 s Force Epoch (N)	808.4 \pm 108.4	0.097	-78.5 [-165.3, 8.4]	-91.6 [-217.3, 34.1]	-109.3 [-209.2, -9.5]*	-102.4 [-234.7, 30.0]
	500 s Force Epoch (N)	570 \pm 149.6	0.071	-67.0 [-163.2, 29.2]	-86.7 [-201.9, 28.4]	-90.9 [-184.1, 2.3]	-86.2 [-207.7, 35.3]

Note: SMBT, seated medicine ball throw; wCMJ, weighted counter movement jump; MIVC, maximal isometric voluntary contraction of the quadriceps; RSI_{Mod}, reactive strength index modified. * $p < 0.05$ compared to pre-fast load carriage protocol performance. Note, where post hoc comparisons have occurred (wCMJ & MIVC) compatibility intervals are Bonferroni adjusted.

effect for measurement point (jump height: $F_{(4,44)} = 3.441$, $p = 0.016$, $S = 5.97$, $G^2 = 0.013$, RSI_{Mod}: $F_{(4,44)} = 5.145$, $p = 0.002$, $S = 8.97$, $G^2 = 0.024$). *Post-hoc* comparisons identified a mean reduction in jump height of $13.6 \pm 7.2\%$ at 120 minutes post-FLCP ($t_{(11)} = -4.386$, $p_H = 0.011$, $S_H = 6.51$, $g_z = -1.178$, 95% CI_H [-0.005, -0.041]). Thus, as indicated by the CLES, the likelihood that an individual had a reduced jump height at 120 minutes post-FLCP compared with pre-FLCP was 90%, when controlling for individual differences. Compared with pre-FLCP values, a reduction in RSI_{Mod} were observed for 30, 60, and 120 minutes post-FLCP (30 minutes: $t_{(11)} = -3.44$, $p_H = 0.05$, $S_H = 4.32$, $g_z = -0.924$, 95% CI_H [0.000, -0.053]; 60 minutes: $t_{(11)} = -3.154$, $p_H = 0.073$, $S_H = 3.78$, $g_z = -0.847$, 95% CI_H [0.003, -0.066]; 120 minutes: $t_{(11)} = -5.154$, $p_H = 0.003$, $S_H = 6.51$, $g_z = -1.178$, 95% CI_H [-0.005, -0.041]). Correspondingly, CLES indicated that the likelihood that an individual had a reduction in RSI_{Mod} at 30, 60, and 120-minutes post-FLCP was 84%, 82%, and 93% respectively, when controlling for individual differences.

For all MIVC variables a moderate main effect of measurement point was evident (peak force: $F_{(1,480,16,281)} = 7.192$, $p = 0.009$, $S = 6.80$, $G^2 = 0.092$; peak 250 ms epoch: $F_{(1,510,16,607)} = 7.061$, $p = 0.010$, $S = 6.64$, $G^2 = 0.097$; and peak 500 ms epoch: $F_{(1,860,20,461)} = 5.539$, $p = 0.013$, $S = 6.27$, $G^2 = 0.071$). Compared with pre-FLCP values, peak force reduced by $8.4 \pm 8.2\%$ immediately post-FLCP ($t_{(11)} = -3.219$, $p_H = 0.074$, $S_H = 3.76$, $g_z = -0.864$, 95% CI_H [6.208, -150.36]), and by $12.6 \pm 10.9\%$ 60 minutes' post FLCP ($t_{(11)} = -3.776$, $p_H = 0.031$, $S_H = 5.01$, $g_z = -1.014$, 95% CI_H [-7.83, -203.49]). Similarly, 250 ms peak force epochs reduced at these two measurement points by $9.1 \pm 9.1\%$ and $13.2 \pm 11.2\%$ respectively (post: $t_{(11)} = -3.16$, $p_H = 0.082$, $S_H = 3.61$, $g_z = -0.849$, 95% CI_H [-8.361, -165.305]; 60 minutes: $t_{(11)}$

$= -3.828$, $p_H = 0.028$, $S_H = 5.16$, $g_z = -1.024$, 95% CI_H [-9.464, -209.209]). 500 ms peak force epochs also reduced at 60 minutes post-FLCP by $14.0 \pm 13.9\%$ ($t_{(11)} = -3.412$, $p_H = 0.058$, $S_H = 4.11$, $g_z = -0.916$, 95% CI_H [2.265, -184.061]). According to all other *post-hoc* comparisons for the MIVC variables post-FLCP performance did not differ compared with pre-FLCP values.

4. Discussion

This is the first study to collectively measure the metabolic cardiovascular, thermoregulatory, neuromuscular, and perceptual responses to a military-specific and occupationally relevant treadmill-based load carriage protocol. The $\dot{V}O_2$ remained similar during the $5.1 \text{ km} \cdot \text{h}^{-1}$ portion of the protocol and an upwards drift was apparent during the $6.5 \text{ km} \cdot \text{h}^{-1}$ portion. A similar observation was apparent for HR; collectively indicating an increased metabolic cost as the protocol ensued. With respect to the FLCP's effect on subsequent physical performance, it appeared not to affect the upper body, as indicated by no change in SMBT performance but did affect the lower body, demonstrated by reduced wCMJ peak height, RSI_{Mod}, MIVC peak force, peak 250 ms force epoch, and peak 500 ms force epoch at measurement points up to two hours' post.

The slowest portion of the FLCP ($5.1 \text{ km} \cdot \text{h}^{-1}$) resulted in no discernible difference between $\dot{V}O_2$ values from 5 to 15 minutes ($\sim 32\% \dot{V}O_{2\text{max}}$) indicative of individuals achieving a steady-state. Conversely, when the treadmill speed was increased to $6.5 \text{ km} \cdot \text{h}^{-1}$, there was a notable increase in $\dot{V}O_2$ at the final two assessment points (45 and 55 minutes; $50\text{-}53\% \dot{V}O_{2\text{max}}$) compared to the first assessment point (25 minutes); indicative of $\dot{V}O_2$ drift. Previously

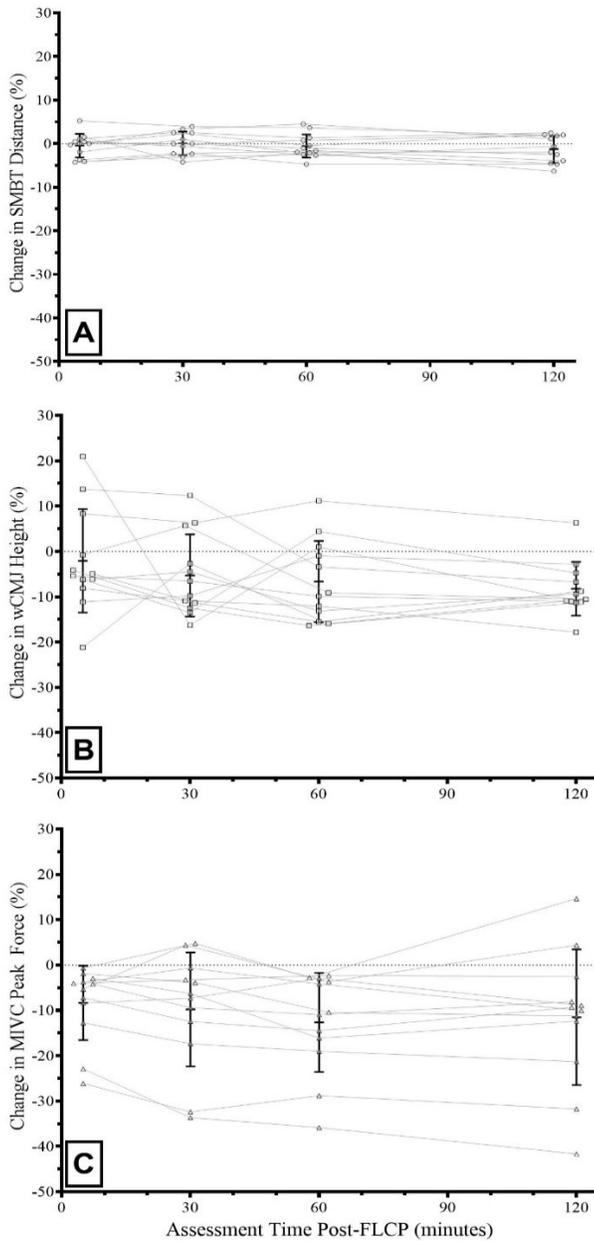


Figure 3: Percentage change in seated medicine ball throw (SMBT) distance (a), weighted countermovement jump (wCMJ) height (b), and maximal isometric voluntary contraction of the quadriceps (MIVC) force (c) post-fast load carriage protocol. *Note:* Data are presented as mean \pm SD.

a $\dot{V}O_2$ drift has been demonstrated in prolonged load carriage exercise, at intensities generally above 50% $\dot{V}O_{2max}$ (Blacker et al., 2009; Epstein et al., 1988; Patton et al., 1991).

The observed 7.4% increase in $\dot{V}O_2$ over the faster portion of the FLCP, is broadly in line with the magnitudes of change observed in other investigations. For example, an 8.8% increase was observed for a 2-hour march at 4.5 km·h⁻¹, 5% gradient, carrying 40 kg (Epstein et al., 1988). With $\dot{V}O_2$ drift evident,

participant’s movement efficiency worsened throughout the FLCP; evidenced by the rising External Load Index values. Specifically, the rising External Load Index scores suggest a reduction in efficiency compared with unloaded walking at the same speed, when corrected for the additional load mass carried. External Load Index values are, broadly comparable to those previously published in non-military personnel (6 km·h⁻¹ and 20 kg) (Hudson et al., 2017). However, the progressive inefficiency, resulting from a $\dot{V}O_2$ drift, has not previously been demonstrated using External Load Index.

Similar to $\dot{V}O_2$, a HR drift was evident across the 6.5 km·h⁻¹ element of the protocol, with a ~15 beat mean change between minutes 25 and 60. This cardiovascular drift, the magnitude of change in HR, and average HR values are comparable to previously reported data during similar load carriage conditions, despite the difference in load mass distributions walking at a fixed pace (Blacker et al., 2009; Quesada et al., 2000). Moreover, mean changes in RPE across the time course of the current study are similar to those reported previously (+5 vs +4) (Blacker et al., 2009); when calculated in the same manner. However, the task duration in the current study was half that of Blacker and colleagues (2009). This difference could therefore be attributed to the way the load mass was distributed in the current study (belt webbing, weighted vest, and weapon vs. rucksack), and the perceived additional effort associated with the increased thermal discomfort of the weighted vest.

The thermal implications of the load carriage protocol in the present study resulted in an average core temperature increase of approximately 1°C. This response is similar to that observed during a field-based load carriage study, where 60 soldiers undertook the load carriage element of the British Army’s new physical employment standards (Waldock et al., 2021). Moreover, the thermal load of the current study resulted in thermal comfort and sensation increases of approximately 2.5 and 3 points respectively; indicating participants perceived they were getting hotter and becoming less comfortable across the time course of the FLCP. As well as participants perceiving they were getting hotter their ratings of comfort associated with the load also reduced with a mean change of -50 points; indicating participants were finding the load carried progressively more uncomfortable. Initial CALM values were similar to those reported previously for heavier load masses (44.45 kg) in combatants (Kobus et al., 2010); which is likely a result of the participant’s familiarity with the load. A decline in comfort ratings has also been reported by Mullins et al. (2015), who reported progressive increases in shoulder/upper-back pain and discomfort scores over 2 hours of walking at 5.5 km·h⁻¹, carrying 22 kg. The current study demonstrated no discernible effect of the FLCP on upper body neuromuscular performance, as measured through the SMBT. Previously grenade throw distance has reduced following a load carriage task (Knapik et al., 1991), however, the authors suggested this decrement may be the result of brachial plexus nerve entrapment in the shoulder region. Plausibly, this difference between studies is a result of the differences in load (20 versus 46 kg), load distribution (hands, hips, torso, vs. back, hands, and head), and task duration (~65 minutes vs. 314 \pm 70 minutes). Load carriage has also previously been shown to reduce shoulder peak torque at slow velocities immediately post a load carriage task (Blacker et al., 2010). Whilst a similar additional load mass was carried in this investigation, a duration two-fold greater, and a

load purely supported by the shoulders is likely to contribute to the differences in findings. Moreover, with load carriage increasing trapezius activity (Holewijn, 1990), and subsequently reducing muscle function, it is likely that the overhead shoulder flexion and extension protocol employed by Blacker et al. (2010) to assess shoulder function would be attenuated to a greater extent than the SMBT by a reduction in trapezius function. The current results, therefore, suggest operationally relevant upper body 'push' capabilities, for tasks such climbing through a window or overhead lifts are unlikely to be impacted. Moreover, with upper body strength, which contributes to power, being demonstrated to correlate well with load carriage performance (e.g., Orr et al., 2021; Robinson et al., 2018), it is unlikely that subsequent load carriage tasks are going to be influenced by changes in upper body performance.

In contrast, lower body neuromuscular performance was likely affected by the FLCP. A decrease in wCMJ performance was apparent at 120 minutes' post-FLCP, with an approximately 9% reduction in jump height evident. This modest decrement in performance corresponds to a mean jump height reduction of 2.2 cm. There was a large degree of variation in performance change from the pre-performance scores, particularly across the first two assessment points as evidenced by a standard deviation of 11.4 and 9.6% respectively. This variability in performance immediately post-task perhaps, partially explains the opposing outcomes of Knapik et al. (1991) and Fallowfield et al. (2012); where following their respective load carriage tasks no change (0.46 ± 0.07 m vs 0.45 ± 0.07 m) and a reduction (0.37 ± 0.05 m vs. 0.34 ± 0.06 m) in jump height was observed. Differences between studies could be attributed to the study populations employed and their load carriage experience (e.g., serving soldiers (Knapik et al., 1991); Royal Marines recruits (Fallowfield et al., 2012); vs. a civilian population, in the current study. A progressive decline in RSI_{Mod} values was also observed. The RSI_{Mod} has been suggested to be indicative of an individual's slow stretch-shortening capabilities (Suchomel et al., 2015), with data indicating that individuals are prolonging their impulse generation period; a change considered to be less desirable for performance (McMahon et al., 2018). However, to date, the RSI_{Mod} literature is limited to sporting contexts, with no data linking decrements to occupational or military tasks. With a lower RSI_{Mod} being suggestive of a reduced force and power capacity, it could be purported that explosive and/or anaerobic-based military tasks such as a fire and maneuver or casualty drag task could be negatively impacted post-load carriage task. Further research within this area is therefore warranted to ascertain whether this is a meaningful metric for occupational and military testing.

The MIVC values in the present study are similar to those previously reported (Blacker, Fallowfield, Bilzon, et al., 2013), although differences in magnitudes of change do exist. As with the SMBT performance, differences could be principally attributed to the longer load carriage duration (~65 min vs 120 min for Blacker et al. 2013a). However, the inclusion of the repeated shuttles, in the current study, may somewhat attenuate these differences observed, due to the rapid accelerations and decelerations of the fire and maneuver aspect of the FLCP. Previously a similar magnitude (~5%) of knee flexor strength reduction has been observed following a 12.1 km march ($4.8 \text{ km} \cdot \text{h}^{-1}$) carrying between 13.2-18.6 kg (Clarke et al., 1955), although as noted by Blacker et al. (2010) caution should be used

when interpreting these data due to the rudimentary data collection techniques. Collectively, these investigations support those data presented in the current study. In addition, the current study demonstrates this neuromuscular impairment and performance reduction may last upwards of two hours. This is despite carrying a relatively 'light' load compared with load masses commonly carried during operations (Dean, 2003; Knapik et al., 2012). Previously, neuromuscular function has been investigated over successive days post load carriage task (Blacker et al., 2010), but not within the hours preceding the task. The study by Blacker et al. (2010) demonstrated that peak torque values remained suppressed for up to 48 hours post a load carriage task. From an applied perspective, a decrement in muscle function may increase musculoskeletal injury risk whilst also degrading military physical and skilled task performance (Blacker et al., 2010); an outcome likely compounded by the frequent operational requirement for multiple military tasks to be completed successively.

A key focus of the present study was to maximize the external validity of the load carriage task, the external load mass, and how it was distributed. The protocol was designed to replicate the demands of a fast approach march or an advance to contact, and the subsequent fire and maneuver task, a highly probable pairing during military operations. As such, all parameters of the load carriage protocol were derived from the literature (Myers et al., 2016; Silk & Billing, 2013; Treloar & Billing, 2011). Critically, due to the protocol being undertaken on a motorized treadmill, participants were unable to safely undergo the prone to standing and standing to prone transitions typical in a fire and maneuver task. To mitigate this limitation, shuttle speed was increased along with shuttle duration. These alterations resulted in the attainment of work rates corresponding to $81.9 \pm 5.9\%$ and $73.5 \pm 8.7\%$ of HR_{max} and HRR respectively, which match well to previous data [$\sim 80\% HR_{max}$ (Myers et al., 2016); $\sim 80\% HRR$, (Silk & Billing, 2013)]. The external validity of the FLCP's design therefore makes it suitable for future intervention studies which wish to use a laboratory-based treadmill protocol. An additional limitation of the present study was the use of non-military male participants. However, markers of both aerobic fitness ($\dot{V}O_{2max}$) and strength (wCMJ) match those previously reported for military populations (Pihlainen et al., 2018; Vine et al., 2020). However, differences pertaining to load carriage efficiency between trained and untrained populations may exist. As such, changes in performance measures may be different for populations more accustomed to load carriage. Moreover, differences in load carriage kinematics between sexes have also been reported, with females working at a higher relative intensity for a fixed load carried, and having a higher cadence and shorter stance time; although this may in fact be a repercussion of differences in body mass and stature (Vickery-Howe et al., 2020). To extend this applied focus, future investigations should look beyond discrete bouts of load carriage and characterize the physiological responses and military performance repercussions of repeated bouts. Despite the high relevance of sequential military taskings, only two studies have investigated this previously, with both having alternative primary focuses (Giles et al., 2019; Scales et al., 2021).

In conclusion, the present study has developed a treadmill-based FLCP that combines the individual aspects of an approach march and a fire and maneuver task. The demands of this protocol resulted in an increased metabolic and cardiovascular requirement

when moving at a faster pace. These data also demonstrate that the completion of a single FLCP does not affect neuromuscular performance in the upper body power (SMBT) but appears to modestly decrease neuromuscular performance in the lower body (wCMJ and MIVC) up to two hours' post. Moreover, those RSI_{Mod} data demonstrate that individuals may be prolonging their impulse generation period, which is suggested to be less favorable, although a greater understanding of these implications within the military context is required. Future investigations can use the FLCP protocol to investigate externally relevant scenarios, such as the interaction between physical and cognitive performance during load carriage, or the implications of multiple repeated load carriage bouts.

Conflict of Interest

The authors declare no conflict of interests.

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Bilateral lower limb asymmetry characteristics of female amateur high school football players

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ABSTRACT

The measurement of bilateral asymmetry is common practice in many sporting environments and is often measured via left/right comparisons, or differences between dominant and/or preferred limbs. Despite each approach having their merits, these measures are fundamentally different and must be used with caution. This study aimed to identify limb asymmetries contextually relevant to sidedness, preference and dominance and compare the likeliness of asymmetries for jumping and change of direction performance tasks. Nine female high-school footballers volunteered for this study and performed various acyclic and cyclic performance tasks to capture asymmetry characteristics. No significant group differences ($p > 0.05$) were calculated between right and left limbs for the jumping or change of direction tasks. However, participants jumped significantly higher in the vertical jump ($p = 0.017$), and further in the horizontal jump ($p = 0.006$) on their preferred limb compared to non-preferred limb. All jump and change of direction performance tasks were performed significantly ($p < 0.05$) better on the dominant limb compared to the non-dominant limb. Three participants demonstrated imbalances greater than asymmetry thresholds, and a like for like identification of asymmetry had low agreement (56%) when comparing vertical and horizontal jump tasks and poor agreement (22 to 33%) when comparing change of direction to jump tasks. This research extends the importance of testing asymmetry characteristics in sports teams, especially in younger female populations who may be at an increased predisposition of associated injuries. The use of a unilateral acyclic measure of asymmetry is deemed to be the most effective measure of capturing asymmetry in this population and sporting context.

1. Introduction

Bilateral imbalance, or asymmetry, refers to the discrepancies between sides of the body regarding muscular performance or function (Jones & Bampouras, 2010). These imbalances may be influenced by gender, training age, pre-existing injuries, sporting demands and/or anthropometric variables (Cane, Maffulli, & Caine, 2008; Fousekis, Tsepis, & Vagenas, 2010; Häggglund & Waldén, 2016; Hewit, Cronin, & Hume, 2012). Measurement of an individual's asymmetry can aid in identifying prospective injury markers (De Britto, Franco, Pappas, & Carpes, 2015; Xaverova et al., 2015), individual strength imbalances (Hewit et al., 2012), limb dominance (Dos'Santos, Thomas, Jones, & Comfort, 2017) and/or motor skill synchronicity (Vieira et al., 2016).

Bilateral strength imbalances are commonly assessed via comparisons of sidedness (Dos'Santos et al., 2017; Newton et al., 2006), limb preference (Capranica, Cama, Fanton, Tessitore, & Figura, 1992; Samadi, Rajabi, Minoonejad, & Aghaiari, 2009; Valdez, 2003), and/or limb dominance (Daneshjoo, Rahnama, Mokhtar, & Yusof, 2013; Dos'Santos et al., 2017; Dos'Santos, Thomas, Jones, & Comfort, 2018; Sugiyama et al., 2014), through both cyclic and acyclic measures including unilateral jump performance (De Britto et al., 2015; Lockie et al., 2014), isokinetic dynamometry (Daneshjoo et al., 2013; Jones & Bampouras, 2010; Petschnig, Baron, & Albrecht, 1998) and change of direction tasks (Dos'Santos et al., 2017, 2018). These tests utilise a range of metrics including force, time and velocity to measure asymmetry, ultimately comparing percentage difference between limbs. Literature has shown discrepancies

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when comparing sidedness, preference and dominance between limbs (Dos'Santos et al., 2017; Newton et al., 2006); and although each method is commonly used to measure imbalances, these terms are fundamentally different (Sadeghi, Allard, Prince, & Labelle, 2000), and therefore, the need to perform a like for like comparison between methods is required.

Traditionally, an asymmetry index of >10-15% has been considered potentially problematic and highlights an area of concern for an athlete. Various team sports (Hart, Nimphius, Spiteri, & Newton, 2014; Menzel et al., 2013) and rehabilitation literature (Clark, 2001; Petschnig et al., 1998) have adopted this 15% asymmetry index as an indicator of potential injury and rehabilitation protocol success. By doing so, it provides an objective measure of imbalance and guides consequent practise with the hope of keeping players on the field for longer and prevent a premature return to sport. Despite this range being partially accepted by injury and performance literature, this has been refuted in some instances (Bennell, 1998; Beukeboom, Birmingham, Forwell, & Ohrling, 2000). More recently, studies by Dos'Santos et al. (2017) and Lockie et al. (2014), have adopted the use of banded asymmetry thresholds based upon Hopkins (2006) approaches. This strategy acknowledges that asymmetry is commonplace and provides a more sensitive framework than a percentage comparison, which may be conceptually problematic if aiming to discern meaningful change or identify potentially injurious discrepancies.

When investigating sport specific asymmetries such as those observed in footballers, it is important to understand the nature of the motor skills performed in the sport, the movements' performance velocities and the population under investigation. Current research has identified that football is a sport that has an increased risk of lower limb injuries because players often utilise one side over another, potentially creating an environment conducive to generating sport specific imbalances (Cowley, Ford, Myer, Kernozek, & Hewett, 2006; Sannicandro, Rosa, De Pascalis, & Piccinno, 2012). Furthermore, females and those with a lower professional training age are also more likely to display problematic asymmetry characteristics (Bailey, Sato, Burnett, & Stone, 2015; Fousekis et al., 2010; Pappas & Carpes, 2012). This is suggested to be due to factors including inconsistent movement patterns, hip valgus and muscular strength deficits (Bailey et al., 2015; Fousekis et al., 2010). It is suggested that through early identification of asymmetries, corrective training interventions can be administered to facilitate long-term performance and participation. Consequently, it stands to reason that an amateur female football team may be a population that has an increased predisposition to lower limb asymmetries.

This study aims to identify limb asymmetries contextually relevant to sidedness, preference and dominance and compare the nature of asymmetries for jumping and change of direction performance tasks. These tasks mimic the demands of football and may extend to other field-based invasion sports. The purpose of this study is to compare various methods of asymmetry measurement to aid practitioners working with this population in the development of targeted training programmes and coaching strategies aimed at the long-term development and participation of these athletes. Previous literature has informed the hypothesis that significant imbalances will be seen in preferred and dominant

limbs, particularly within acyclic jump tasks. Secondly, limb preference and dominance will display greater asymmetries when compared to sidedness within this sporting context.

2. Methods

2.1. Experimental approach

A cross-sectional design was utilised to compare between variables. This testing design was performed to capture and compare the current asymmetry status of the participants in their pre-season condition. All participants wore their own personal active-wear for the singular testing session which was executed on a wooden floor in a school-gym facility. The participants underwent a standardised warm-up and familiarisation process prior to testing commencement. Ethical approval for this study was provided by the Waikato Institute of Technology's Human Ethics Research Group.

2.2. Participants

Nine high school female footballers (mean \pm standard deviation; age, 17 ± 1 years; height, 161 ± 1 cm; body mass, 61 ± 12 kg) playing at a 3rd XI level or lower volunteered for this study. All participants provided written informed consent and completed health questionnaires prior to their participation. All were injury free, and not aware of any contraindications that may interfere with data collection.

2.3. Procedures

Height was measured via a free-standing stadiometer (Seca 213; Seca, Hamburg, Germany), with the participant's feet shoulder width apart and participant's head positioned so that their tragus and line of sight were parallel. The headpiece was lowered firmly on the centre of the participant's head whilst standing with erect posture. Weight was taken on electronic scales (Seca 899; Seca, Hamburg, Germany) which were zeroed prior to each participants measurement. The participant's preferred leg was determined via questioning about their habitual kicking preference (Bjelica et al., 2013).

A dual-beam-modulated SWIFT timing light system (Wacol, Queensland, Australia) was used to measure 505 change-of-direction test performance times. Participants were required to sprint from the start line (0m) through the timing lights set at a 10m distance, before turning at the 15m line, and returning through the timing lights as fast as possible (Abdullah et al., 2017). The participants were free to begin each trial after the researcher said the verbal command "when you're ready". Athletes were advised not to overstep the line to avoid adding to their change of direction time (Abdullah et al., 2017).

The single leg horizontal jump (HJ) required participants to perform three maximal unilateral horizontal jumps and land bilaterally. Participants were required to maintain hand placement on the hips throughout the procedure and jump as far as possible in a forwards direction (Hewitt et al., 2012). A measuring tape extending from the starting point in the direction of the jump was

used to measure the jump to the nearest mm with a ruler placed from the rear-most heel perpendicular to the measuring tape.

Single leg vertical jump (VJ) height was measured via a pre-set Vertec jump system (Power Systems, Knoxville, Tennessee), which required participants to perform a maximal unilateral vertical jump using the ipsilateral hand to swipe the Vertec at the jump apex. Prior to the jump occurring participants were required to stand directly under the Vertec and reach as high as they could while keeping their shoulders square to determine their standing reach height. This value was later subtracted from their recorded jump height (Best et al., 2020). Intersession reliability of the Vertec has previously been reported as ICC: 0.80 for females and ICC: 0.90 for males (Nuzzo et al., 2011).

For each performance test, three trials were performed per leg with approximately two minutes passive recovery between efforts.

2.4. Statistical analysis

The following metrics were calculated for each performance test: Asymmetry index (imbalance between right and left limbs) in the form of a percentage difference was calculated by the following formula (Newton et al., 2006):

$$\% \text{ Difference} = ((\text{Right limb} - \text{Left Limb}) \div \text{Right Limb}) \times 100$$

Limb preference was determined via asking the participants their habitual kicking leg preference (Bjelica et al., 2013). Asymmetry index (imbalance between preferred and non-preferred limbs) was calculated by the following formula:

$$\% \text{ Difference} = ((\text{Preferred limb} - \text{Non-preferred Limb}) \div \text{Preferred Limb}) \times 100$$

Limb dominance was defined as the limb that performed the highest vertical jump, furthest horizontal jump, or fastest CODS performance (Jones & Bampouras, 2010) and calculated as per:

$$\% \text{ Difference} = ((\text{Dominant limb} - \text{Non-dominant Limb}) \div \text{Dominant Limb}) \times 100$$

Descriptive statistics were calculated for all performance tasks and statistical analyses were performed using SPSS (version 24, IBM, Seattle, USA). The assessment of data uniformity (normal distribution) was carried out as per previous literature (Maulder, 2013; Standing & Best, 2019). Specifically, a critical appraisal approach according to the following criteria was utilised. If the difference between the mean and the median was within 10% of the mean, then normality was assumed. However, if the initial criterion was breached, an additional 2 of 4 criteria would also have to be breached for the data to be described as exhibiting non-normal characteristics. These criteria were: (1) mean and standard deviation test ($2 \times \text{SD} > \text{mean}$); (2) Shapiro-Wilks statistics ($p < 0.05$); (3) skewness and kurtosis statistics (within 1); and (4) skewness or kurtosis \div standard error (within 1.96). All performance task data collected in this study were normally distributed thus the following parametric procedures were utilised.

Differences between limbs for all performance tasks were assessed with paired sample t-tests. A p value of < 0.05 was considered significant. Furthermore, effect sizes (Cohen's d) were calculated and interpreted as: $0 - 0.2$ *trivial*; $0.2 - 0.6$ *small*; $0.6 -$

1.2 *moderate*; $1.2 - 2.0$ *large*; $2.0 - 4.0$ *very large* (Hopkins, Marshall, Batterham, & Hanin, 2009).

Agreement between the dominant limb for performance tasks involved calculating the asymmetry threshold as mean imbalance $+ (0.2 \text{ SD of the mean})$ for jumps and mean imbalance $- (0.2 \text{ SD of the mean})$ for CODS (Lockie et al., 2014). Participants with imbalances exceeding the asymmetry threshold were classified as asymmetrical whereas imbalances below the threshold were classified as balanced (Dos'Santos et al., 2017). The level of agreement between like for like outcomes of asymmetry calculation methods (asymmetrical or balanced) were calculated by the following formula, with percentage agreements $\geq 80\%$ considered 'good' (Dos'Santos et al., 2017).

$$\% \text{ agreement} = (\text{frequency of like for like diagnoses} \div \text{number of participants}) \times 100$$

Correction for multiple comparisons has not taken place, due to the small sample size of the present investigation. Application of a correction for multiple comparisons, would likely reduce the corrected alpha level to a level considered too conservative, and thus increase the risk of committing a type 2 error (accepting the null, when it should be rejected), thus given the preliminary nature of this work we present uncorrected values (Havenith et al., 2008; Ouzzahara et al., 2012). We encourage the reader to interpret the p -values presented alongside effect statistics, and consider the percentages alongside their experiences of smallest worthwhile enhancement in applied practice (Datson et al., 2021).

3. Results

No significant differences ($p > 0.05$) were calculated between right and left limbs for the jumping and change of direction performance tasks (see Table 1). Participants were able to jump significantly ($p < 0.05$) higher in the vertical jump, and further in the horizontal on the preferred limb compared to non-preferred limb (see Table 2). All jump and change of direction performance tasks were performed significantly ($p < 0.05$) better on the dominant limb compared to the non-dominant limb (see Table 3). Irrespective of sidedness, preference or dominance, the vertical jump had the largest imbalance (6.8% - 14.3%) or asymmetry threshold (10.5% - 16.4%).

Three participants (3 out of 9; 33.3%) demonstrated like for like dominance in all performance tasks, on the same limb identified as their preferred limb (see Table 4). Participants' limb preference typically matched their vertical jump and horizontal jump dominant limb(s) (6 out of 9; remainder reported even and dominant limb preference).

Figure 1 shows imbalances between right and left limbs for the jumping and change of direction performance tasks. Four, six, and seven total participants demonstrated imbalances greater than asymmetry thresholds of 10.5, 5.3 and -0.5% for vertical jump, horizontal jump, and change of direction speed, respectively. Two participants had sidedness imbalances that exceeded asymmetry thresholds for all performance tasks. A like for like identification of asymmetry had low agreement (56%) when comparing the jump tasks, and poor agreement (22 to 33%) when comparing change of direction to jump tasks (see Table 5).

Table 1: Sidedness comparisons for jumping and change of direction performance tasks.

Metric	Right		Left		Imbalance (%)		<i>p</i> value	Cohen's <i>d</i>	Asymmetry Threshold (%)
	Mean	SD	Mean	SD	Mean	SD			
Vertical Jump (cm)	27.3	4.8	25.0	4.1	6.8	18.2	0.181	0.52	10.5
Horizontal Jump (cm)	125.6	16.7	120.1	15.4	4.2	5.9	0.055	0.34	5.3
CODS (s)	2.89	0.15	2.89	0.14	-0.1	2.1	0.979	0.00	-0.5

Note: CODS = Change of direction speed.

Table 2: Preference comparisons for jumping and change of direction performance tasks.

Metric	Preferred		Non-Preferred		Imbalance (%)		<i>p</i> value	Cohen's <i>d</i>	Asymmetry Threshold (%)
	Mean	SD	Mean	SD	Mean	SD			
Vertical Jump (cm)	28.1	4.2	24.3	4.3	12.7	12.6	0.017*	0.88	15.3
Horizontal Jump (cm)	126.4	15.7	119.3	16.1	5.6	4.2	0.006*	0.44	6.5
CODS (s)	2.89	0.14	2.89	0.14	-0.1	2.1	0.937	-0.01	-0.5

Note: CODS = Change of direction speed; * = Significant difference ($p < 0.05$).

Table 3: Dominance comparisons for jumping and change of direction performance tasks.

Metric	Dominant		Non-Dominant		Imbalance (%)		<i>p</i> value	Cohen's <i>d</i>	Asymmetry Threshold (%)
	Mean	SD	Mean	SD	Mean	SD			
Vertical Jump (cm)	28.3	4.2	24.1	4.0	14.3	10.5	0.004*	1.01	16.4
Horizontal Jump (cm)	126.4	15.7	119.3	16.1	5.6	4.2	0.006*	0.44	6.5
CODS (s)	2.87	0.15	2.92	0.13	-1.7	1.3	0.004*	-0.34	-1.9

Note: CODS = Change of direction speed; ES = effect size; * = Significant difference ($p < 0.05$).

Table 4: Matches between preferred limb and dominant limb during jumping and change of direction performance tasks.

Participant	Preferred Limb	VJ Dominant Limb	HJ Dominant Limb	CODS Dominant Limb
1	R	R	R	R
2	L	L	L	L
3	R	R	R	R
4	R	L	E	R
5	R	R	R	L
6	R	R	E	L
7	R	E	R	R
8	R	R	R	L
9	R	R	R	L
Preference Match (#, %)		7, 78	7, 78	5, 56

Note: VJ = Vertical jump; HJ = Horizontal jump; CODS = Change of direction speed; R = Right; L = Left; E = Equal.

Table 5: Percentage agreements between like for like identifications of asymmetry classification.

Frequency (#)	B	Vertical Jump	Horizontal Jump	CODS
		L	5	3
	R	1	1	4
		3	5	3
<hr/>				
% agreement with VJ performance like for like identification (#, %)			5, 56	2, 22
<hr/>				
% agreement with HJ performance like for like identification (#, %)		5, 56		3, 33
<hr/>				
% agreement with CODS performance like for like identification (#, %)		2, 22	3, 33	

Note: CODS = Change of direction speed; B = Balanced; L = Left Asymmetrical; R = Right Asymmetrical.

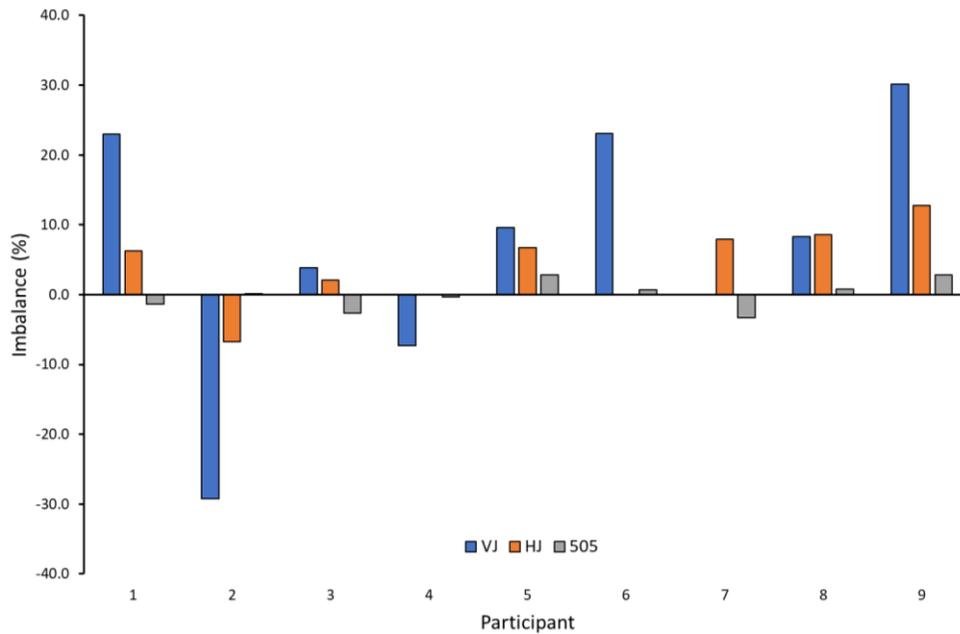


Figure 1: Left and right imbalances for vertical jump, horizontal jump and 505 performance tasks.

4. Discussion

This study aimed to identify limb asymmetries of amateur female footballers contextually relevant to sidedness, preference and dominance and compare the likeliness of asymmetries for jumping and change of direction performance tasks. Levels of asymmetry were considered potentially problematic in the vertical (n = 4) and horizontal jump (n = 4) and COD (n = 4) tasks for this cohort. Preferred vs non-preferred imbalances were significant (*p*

< 0.05) in jump tests (Table 2), with dominant vs non-dominant statistics displaying significant asymmetries in both jump and COD tasks (Table 3), therefore supporting the hypotheses. Interestingly, 78% of jump tasks displayed a performance match between preferred and dominant limbs, whilst COD tasks presented with a 56% match, suggesting preference and dominance may vary in description and application between various movement tasks. Finally, there was poor agreement when comparing like for like asymmetries between jump and COD

tasks (VJ = 22%, HJ = 33%), which highlights that asymmetries in acyclic jump tasks may not correspond with asymmetries in cyclic COD tasks.

The development of asymmetry is often attributed to the repetitive and at times asymmetric nature of sporting movements (Hadzic, Sattler, Markovic, Veselko, & Dervisevic, 2010). In the present cohort, there are several individuals displaying potentially problematic asymmetry measures (Table 5), with dominance values exceeding the established asymmetry thresholds for VJ ($n = 4$), HJ ($n = 4$) and COD ($n = 4$). It is important to note, that only one individual presented as problematically asymmetric for all tests. Based on these findings and support from previous literature, these individuals may have a greater likelihood of strength, stability and skill performance imbalances (Sadeghi et al., 2000), possibly fostering an increased likelihood of asymmetry-related lower limb injuries (Brophy, Silvers, Gonzales, & Mandelbaum, 2010; De Britto et al., 2015). This is not unreasonable due to the elevated injury statistics associated with football players (Bjelica et al., 2013; Sannicandro et al., 2012) and female non-contact ACL injuries (Cowley et al., 2006). It is recommended that trainers, coaches and athletes attempt to re-align the imbalance through strength and movement tasks requiring both multi-limb coordination and segment sequencing (Fousekis et al., 2010; Hewit et al., 2012; Lockie et al., 2014; Wright & Laas, 2019). These training elements will help to decrease the imbalance and in turn decrease the potential for future injuries and performance decrements – a worked example of this in a return to play programme following recurrent knee injuries can be found in Wright and Weston (2014).

As advised by Schlumberger et al. (2006) and Jones and Bampouras (2010), strength differences in the lower limb cannot truly be estimated in group settings by left-right comparisons or limb preference. The results of the current study support this statement, and have highlighted that by establishing multiple measures of asymmetry via limb dominance specific to the individual test, clearer imbalances may be identified in a comparative strength context, as per the findings of Dos'Santos et al. (2017). Furthermore, some of the observed asymmetry may be accounted for by intra-individual variability in performance and variability within the test. For example, we have previously established the importance of providing proper familiarisation for vertical jump performance (Best et al., 2020), despite being shown to possess acceptable levels of reliability (Nuzzo et al., 2011). Likewise, horizontal jump performance (Standing et al., 2019) and change of direction performance (Wright & Atkinson, 2019) may improve as a result of maturation, thus if one were to perform these tests as part of an annual or repeated testing battery, biological maturity also warrants consideration, especially if used to inform strength and conditioning approaches (e.g., Wright & Laas, 2019) or when used as part of a larger testing battery due to potential collinearity due to neurological transfer (Wright et al., 2014).

Comparisons of left and right limb performances showed no significant differences ($p < 0.05$) at the group level (Table 1). Similar to the results seen by Jones and Bampouras (2010), this finding suggests that left and right comparisons are limited in application when looking at strength-based performance measures. This statement is further supported by Schlumberger et

al. (2006), who suggests the need to evaluate strong-weak-leg-differences rather than sidedness, as the assumption that these two measures are the same lacks adequate validity. This is likely due to the multitude of individual factors that influence performance such as limb preference, previous injury, sport-specific demands, movement tasks and training experience (Jones & Bampouras, 2010; Sadeghi et al., 2000; Schlumberger et al., 2006). It is therefore noted as un-wise to use left and right comparisons for athletes without first identifying individual performance characteristics and demands of the movement task.

Conversely, when comparing preferred and non-preferred kicking limb (Table 2), significant differences in performance were identified for jump tasks only (VJ $p = 0.017$, HJ $p = 0.006$). This suggests that individual limb preference identifies clearer asymmetry characteristics than sidedness comparisons and may be used to differentiate performance for jump tasks, but not for COD tasks. It is important to note that limb preference does not necessarily match the dominant limb within this population, especially in the 505 tasks. Using the 505 total completion time as an indirect measure of bilateral asymmetry means the non-tested limb is utilised in the acceleration and linear speed components of the test. Dos'Santos et al. (2018), states this involvement may in fact hide the imbalance and dilute the input of the tested limb during this particular style of test. This theory has been further supported by literature (Nimphius, Callaghan, Bezodis, & Lockie, 2018), where it was found that athletes changed their technique in the 505 test to load the preferred leg when changing direction on the non-preferred leg; therefore concluding that this test has limited practical utility in some populations (Taylor et al., 2019).

The above supports the notion that change of direction tasks are multifactorial and include elements of foot placement, adjustment of strides, posture, body lean, and several other acceleration/deceleration variables (Dos'Santos et al., 2017; Sheppard & Young, 2006; Young, James, & Montgomery, 2002). It is recommended that acyclic tasks be utilised where possible to test for asymmetries to clearly define the roles of each limb, remove multifactorial variables associated with cyclic tasks and therefore improve the validity of the tests utilised. This interpretation clearly supports Schlumberger et al. (2006) and Jones and Bampouras (2010), who also state that strength differences in the lower limb cannot truly be estimated by left-right comparisons or limb preference.

Limb preference matched limb dominance in 78% of both jumps tasks, but only 56% of COD performances. In alignment with Dos'Santos et al. (2017) agreement levels $>80\%$ were considered 'good'. Table 4 begins to highlight a potential justification for this finding; the dominant limb for COD and jump tasks varies for all but three participants. This may be attributed to the cyclic nature of the COD test, which requires input from both limbs in a repetitive and non-specific manner. It is also suggested that the jump and COD tasks required varying force application characteristics across multiple planes (Dos'Santos et al., 2017). Previous literature that has utilised the dominant vs non-dominant approach of measuring asymmetry have identified significant differences in single leg vertical jumps (Meylan, Nosaka, Green, & Cronin, 2010; Miyaguchi & Demura, 2010), drop jumps (Schiltz et al., 2009), and COD tasks (Dos'Santos et

al., 2017; Hart et al., 2014), supporting the findings of the current study. It was identified that limb dominance displayed significant differences between vertical ($p = 0.004$), horizontal jump ($p = 0.006$) and COD ($p = 0.004$). Interestingly, the term 'dominant limb' has been described as being the limb responsible for mobilisation (Sadeghi et al., 2000), preferred leg for kicking a ball (Fagenbaum & Darling, 2003), strongest limb (Jones & Bampouras, 2010) and/or a combination of these terms (Maulder, 2013) in previous literature. This study adopted the strategy of 'best vs worst' in alignment with other research (Dos Santos et al., 2018; Jones & Bampouras, 2010; Petschnig et al., 1998), in order to measure a raw performance difference, replicable of those witnessed during competitive and real-world environments in a worst case scenario. The findings of this method of asymmetry characterisation suggest that dominance-based comparisons of force and velocity through unilateral jump and COD tasks are the best strategy to highlight both strength and potential performance imbalances within this population.

4.1. Practical applications

This research extends the importance of testing asymmetry characteristics in both team and individual sports, especially in younger female populations who may be at an increased predisposition of associated injuries. Sidedness and limb preference have been shown to be less effective at highlighting performance asymmetries when compared with limb dominance. The use of unilateral acyclic testing of asymmetry is further recommended over cyclic tasks that require input from both limbs, as this may hide the imbalances in the recorded performance measure. Coaches, trainers and strength and conditioning practitioners should adopt a thorough multi-test approach to identifying asymmetry and aim to minimise asymmetries that exceed the 15% threshold, if deemed non-functionally relevant. This may be achieved through incorporating purposeful and sport specific movements to ensure the longevity of athletes and help reduce the likelihood of asymmetry-related injuries. As limb preference does not necessarily match the dominant limb within this population, especially in the 505 tasks; it is recommended that testing and monitoring practices should be implemented to capture this information, rather than reliance on individual feedback.

Conflict of Interest

The authors declare no conflict of interests.

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Analysis of cortisol response and load in collegiate female lacrosse athletes: A pilot study

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ABSTRACT

Currently, it is unknown how cortisol fluctuates across a season in female athletes and how it is related to other measures of training load. The purpose of this study was to 1) evaluate changes in salivary cortisol in Division I female collegiate lacrosse athletes ($n = 26$) and 2) assess the relationship between cortisol and athlete wellness and training load. Saliva samples were collected biweekly on Monday mornings during the first six weeks of the competitive season. Subjective athlete total wellness scores and sub-scores (muscle soreness, sleep quality, fatigue, and stress) were collected on the same days. Objective total weekly workload for distance, high-intensity distance (HID), sprints, accelerations, and decelerations were tabulated from the previous week. A repeated measures analysis of variance assessed weekly changes in cortisol, wellness, and training load across the season. Pearson correlations were used to determine relationships among cortisol, wellness, and training load. There was an upward trend in cortisol (wk 0: $0.637 \pm 0.296 \mu\text{g/dL}$, wk 2: $0.611 \pm 0.450 \mu\text{g/dL}$, wk 4: $0.767 \pm 0.495 \mu\text{g/dL}$), but no difference in time points. HID and sprints were lower in week 2 than weeks 0 and 4 ($p < 0.05$). Although cortisol did not correlate with wellness scores or objective workload, the upward trend from week 0 to week 4 suggested that as the season progressed, the athletes had increasing levels of stress, possibly resulting from performance or game settings. These findings provide coaches with a better understanding of competition-related stress throughout the season and allow for the implementation of pre- and post-game strategies for stress management among their athletes.

1. Introduction

Cortisol is a glucocorticoid hormone that fluctuates with sympathetic response to stress and is associated with neuromuscular performance (Balsalobre-Fernández et al., 2014a). This plays an important role in metabolic activities including blood pressure regulation, cardiovascular function, regulation of metabolic substrate selection, and immune system function (Sapolsky et al., 2000). Depending on the stressors present, cortisol levels can fluctuate throughout the day, but typically cortisol is secreted in the highest concentrations in the morning, also known as diurnal variation (Lippi et al., 2009). Cortisol is traditionally assessed using blood serum assay; however salivary cortisol tests have shown to be a simple and less invasive method

to achieve reliable results (Haneishi et al., 2007). In addition, salivary cortisol levels have high correlations with serum cortisol levels (Dorn et al., 2007).

In sport, cortisol levels have been shown to negatively correlate with several markers of athlete readiness and recovery (e.g., countermovement jump and subjective wellness), as well as fluctuate throughout a competitive season with performance and workload demands (Balsalobre-Fernández et al., 2014b; Drew & Finch, 2016; Mason et al., 2020; Skoluda et al., 2012). Training can be affected by the fluctuation of cortisol levels within the athletic body and can hinder physical and mental wellbeing (Duclos et al., 2007). Salivary cortisol can be used to determine the effects of high and low intensity exercises during immediate and prolonged periods of time after training. This is important

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because cortisol levels can show how the body is truly responding to stress and how training can be improved by adapting the protocol to the individual. Cortisol has been assessed in male collegiate and professional athletes across a variety of high-intensity and endurance sports. Results from these studies show an acute increase in cortisol with workload (Balsalobre-Fernández et al., 2014a, 2014b; Filaire et al., 2001; McGuigan et al., 2004); however, cortisol did not appear to impact athlete performance. Weekly assessments of cortisol had low correlations with workload ($r = -.366-0.171$) but showed no differences between an athlete's best performance and their worst performance (Balsalobre-Fernández et al., 2014a). The measurement of cortisol can provide evidence to coaches in an effort to fine tune or alter their training schedule to better serve and improve the effectiveness of the current training regimen and reduce the risk of injury and overtraining.

Stressors from sport can be physical (illness, trauma, surgery, fever, physical exercise and extreme temperatures) or psychological (clinical depression, anxiety, strain, fear and pain) (Sapolsky et al., 2000). Self-reported wellness scores and ratings of perceived exertion (RPE) are subjective measurements that evaluate athlete stress levels in various aspects of training (Gallo et al., 2016; op de Beéck et al., 2019). Pre-training wellness scores have been shown to be correlated with external load output, which suggests that wellness scores may be used to help coaches determine training intensity (Gallo et al., 2016). While previous literature has addressed athlete stressors and cortisol response, few studies have examined this relationship in high level female athletes. The present study will only be the second to delve into cortisol responses in female lacrosse athletes (Fields et al., 2020). It is important to evaluate the cortisol response in various athlete populations because it cannot be assumed that all athletes respond the same to the physical and emotional stressors they undergo in-season.

Lacrosse is a sport quickly growing in popularity within the United States and across the globe (Burton & O'Reilly, 2010; Hayhurst, 2005). However, there is little research regarding optimal training load and recovery in female collegiate lacrosse athletes. Current literature provides concepts of game profiles by position (Devine et al., 2022), the relationship between wellness scores and external load output (Crouch et al., 2021), analysis of drill intensities (Alphin et al., 2020), evaluation of important training metrics by training mode (Bunn et al., 2021), and an assessment of the relationship between objective and subjective markers of athlete fatigue (Frick et al., 2021). The first study evaluating cortisol levels in female collegiate lacrosse athletes showed weak relationships between physiological, hormonal, and psychological markers of load and no change in cortisol across a competitive season (Fields et al., 2020). Because this was the first study to evaluate cortisol in this population, it is unknown if these results hold true outside of the sample athletes assessed.

Evaluating athlete wellness may serve as a surrogate of objectively measuring stress through salivary cortisol, but this has not yet been supported with data from collegiate female athletes (Haneishi et al., 2007; op de Beéck et al., 2019). The primary purpose of this study was to evaluate changes in salivary cortisol in Division I female collegiate lacrosse athletes during the

competitive season. A secondary purpose of this study was to assess the relationship between cortisol and athlete wellness and training load using RPE.

2. Methods

2.1. Study design and ethical approval

This was a non-experimental observational study design that took place during the first six weeks of the competitive season. On average, the team completed 4.4 ± 0.5 practices per week and 1.6 ± 0.5 games per week. During the week of baseline assessments and week 3, athletes participated in five practices and one game, and weeks 1, 2 and 4 each consisted of four practices and two games. Salivary cortisol was measured bi-weekly in the morning. Athlete wellness was assessed each morning prior to any practice or physical activity. Workload measures were obtained through microtechnology during each training and game day.

This study was approved by the institutional review board and conducted in accordance with the Declaration of Helsinki. All participants had the opportunity to ask questions prior to participation, and all participants completed a written informed consent. All elements of the study coincided with FERPA guidelines.

2.2. Participants

In this study, cortisol samples were collected from 26 female athletes (aged 18-22) who were recruited by association with the women's lacrosse team at Campbell University. Participants were included in this study if they were members of the varsity women's lacrosse team and eligible for play. Participants were excluded if they were deemed ineligible for play by an athletic trainer or team physician.

2.3. Measurements

Salivary Cortisol Assessment. Saliva samples were collected biweekly on Monday mornings during the first six weeks of the competitive season, for a total of three samples per athlete. Athletes provided saliva samples into the provided tubes via passive drool shortly after waking and prior to eating or drinking. Athletes provided the sample in compliance with previously validated collection methods provided by Salimetrics (Salimetrics, 2021a). Samples were stored in -80°C per collection and storage protocol until analysis. Saliva samples were analyzed for cortisol using the Salivary Cortisol ELISA Kit (Salimetrics, State College, PA). These analyses have been shown to provide low coefficients of variation (3-5%) between samples and labs (Salimetrics, 2021b). Samples were thawed, vortexed and centrifuged at $1500 \times g$ for 15 minutes before adding to the ELISA plate. Cortisol levels were determined using the manufacturer's instructions. The absorbance of the wells at 450 nm was measured using a BioTek plate reader (Winooski, VT). To calculate the concentration of cortisol, a standard curve was generated for the B/Bo from known standards provided in the Saliva ELISA kit ranging from 300 $\mu\text{g/dL}$ to 0.012 $\mu\text{g/dL}$ (Salimetrics, State College, PA).

Athlete Wellness. Subjective athlete total wellness scores and sub-scores (muscle soreness, sleep quality, fatigue, and stress) were taken each morning prior to training. This was done using a smart device linked to VX Sport Cloud (Wellington, New Zealand). A five-point Likert scale (0/25/50/75/100) was used with the following questions to determine athlete wellness:

1. How are your muscles feeling today?
2. How did you sleep last night?
3. How are your energy levels feeling for your training today?
4. How stressed are you?

Athlete Training Load. Athletes wore VX Sport (Wellington, New Zealand) units in order to track objective training load for distance, HID, sprints, accelerations, and decelerations. The units included a global positioning system (GPS; collecting at 10 Hz), 3-axis accelerometer (104 Hz per channel), 3-axis magnetometer (18 Hz), 3-axis gyroscope (18 Hz) and heart rate monitor (2.4 GHz) and have been shown to provide valid and reliable measures (Alphin et al., 2020; Malone et al., 2014). GPS units were inspected to ensure proper working order and satellite connection prior to each training session. Athletes used only their assigned unit in conjunction with their corresponding vest equipped by VX Sport. The unit was placed in the designated pocket on the vest located between the shoulder blades. After training each day, all data were uploaded to the VX Sport Training software. Data were trimmed to remove inactive time periods and split to supply data specific to the training plan provided by the coaches. Objective total weekly training load for distance, high-intensity distance (HID), sprints, accelerations, and decelerations were tabulated from the previous training week. HID represents the distance run at greater than 60% of maximum sprint speed (MSS). Sprints repetitions were counted when sprint efforts exceeded 80% of MSS. Accelerations and decelerations were determined by a change of $\pm 3 \text{ m/s}^2$. MSS was determined using the methods previously described by Alphin et al. (2020).

2.4. Statistical analysis

All analyses were conducted in SPSS (IBM, Chicago, IL), and an alpha level of $p < 0.05$ was used to determine significance. Data were first analyzed for normality using a Shapiro-Wilks test. Data were determined to be normally distributed, so parametric analyses were utilized. Changes over time in cortisol, wellness, and training load were evaluated using a repeated measures analysis of variance (RM-ANOVA). Partial eta squared (η^2) effect sizes were calculated in conjunction with the RM-ANOVA. Effect sizes were interpreted as small (.01), medium (.06), and large (.14). An LSD post-hoc analysis was used to determine specific differences if the RM-MANOVA indicated a main effect for time. Due to the ordinal nature of the wellness data, a Friedman test was used to analyze differences over time for these data. The second aim of this study—relationships between cortisol, wellness, and training load—was assessed using repeated measures Pearson correlation (Bland & Altman, 1995). This analysis incorporates the dependence of multiple measures taken

over time. Correlation values (r) were interpreted as low (.29), moderate (.49), and large (.50), (Bland & Altman, 1995).

3. Results

The RM-ANOVA indicated a main effect for time (Lambda(12,14) = 8.212, $p < 0.001$, partial $\eta^2 = .876$, large). Univariate analyses showed no difference over time for cortisol ($p = 0.241$, partial $\eta^2 = .056$, medium; wk 0: $0.574 \pm 0.297 \text{ }\mu\text{g/dL}$, wk 2: $0.701 \pm 0.481 \text{ }\mu\text{g/dL}$, wk 4: $0.772 \pm 0.603 \text{ }\mu\text{g/dL}$) as shown in Figure 1. Workload metrics across the three time points are shown in Table 1. There was a difference in HID ($p = 0.001$, partial $\eta^2 = .283$, large) and sprints ($p = 0.028$, partial $\eta^2 = .148$, large). Post-hoc analyses showed that HID was lower in week 2 ($2660.4 \pm 770.3 \text{ m}$) compared to baseline ($3593.4 \pm 917.4 \text{ m}$, $p < 0.001$) and week 4 ($3238.7 \pm 1560.3 \text{ m}$, $p = 0.008$). The same was shown in sprints with lower repetitions in week 2 (22.9 ± 10.2 efforts) compared to baseline (27.4 ± 12.5 efforts, $p = 0.013$) and week 4 (29.5 ± 18.3 efforts, $p = 0.006$). There was no difference over time for total distance ($p = 0.836$, partial $\eta^2 = .006$), accelerations ($p = 0.152$, partial $\eta^2 = .073$, medium) or decelerations ($p = 0.087$, partial $\eta^2 = .093$, medium).

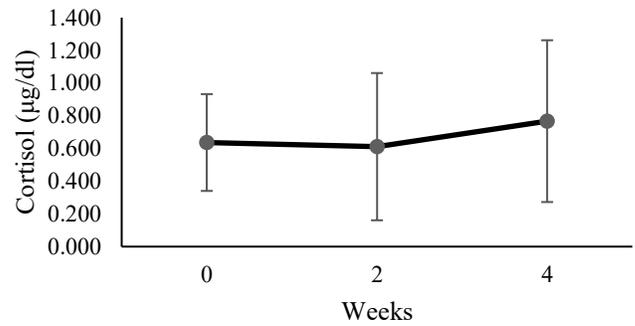


Figure 1: Mean ± standard deviation for changes in cortisol from baseline (week 0) to week 4 of the study.

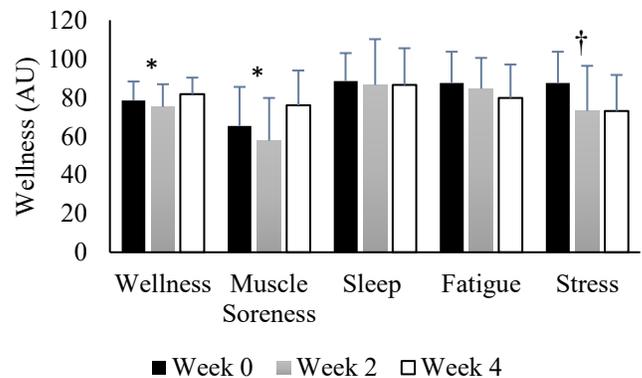


Figure 2: Subjective wellness scores across the assessment period. Note: *Indicates a difference between week 4 and week 2 for wellness and muscle soreness, $p < 0.05$. †Indicates a difference between week 0 and weeks 2 and 4 for stress, $p < 0.05$.

Table 1: Training load values (mean \pm SD) over three time periods demonstrating the trends within each training load measure.

	Week 0	Week 2	Week 4
Distance (m)	27483.9 \pm 4162.6	27402.5 \pm 7593.1	26807.5 \pm 6688.4
HID (m)	3593.4 \pm 917.4	2660.4 \pm 770.3*	3238.7 \pm 1560.3
Sprint (efforts)	27.4 \pm 12.5	22.9 \pm 10.2*	29.5 \pm 18.3
Acceleration (efforts)	542.2 \pm 142.2	588.9 \pm 203.6	536.5 \pm 164.5
Deceleration (efforts)	151.6 \pm 48.5	153.7 \pm 61.8	134.9 \pm 53.0

Note: HID, high-intensity distance. *Indicates a significant difference from week 0 and week 4, $p < 0.05$.

The subjective wellness scores are shown in Figure 2. Higher values indicate better wellness, less soreness, improved sleep, less fatigue, and less stress. Analyses indicated time differences for wellness ($p < 0.001$), muscle soreness ($p = 0.001$), and stress ($p < 0.001$). Pairwise comparisons showed week 4 scores were higher than week 2 for wellness ($p = 0.001$) and muscle soreness ($p = 0.011$). These data indicate that athletes felt better and had less muscle soreness in week 4. Athletes indicated lower feelings of stress at baseline compared to week 2 ($p = 0.031$) and week 4 ($p = 0.046$). There were no time differences for sleep quality ($p = 0.917$) or fatigue ($p = 0.109$).

Correlational analyses were all low and not statistically significant. For objective workload, cortisol had low correlations with HID ($r = .158$, $p = 0.168$) and sprints ($r = .205$, $p = 0.071$), and negligible correlations with distance ($r = .043$, $p = 0.708$), accelerations ($r = .083$, $p = 0.469$), and decelerations ($r = .017$, $p = 0.884$). For the subjective wellness measures, cortisol had low correlations with fatigue ($r = .160$, $p = 0.162$) and sleep ($r = 1.53$, $p = 0.181$) and correlations with wellness ($r = .062$, $p = 0.589$), muscle soreness ($r = .801$, $p = 0.485$), and stress ($r = .100$, $p = 0.385$).

4. Discussion

The purposes of this study were to 1) evaluate changes in salivary cortisol in Division I female collegiate lacrosse athletes ($n = 26$) and 2) assess the relationship between cortisol and athlete wellness and training load. There was a small non-significant upward trend in cortisol as the season progressed, and the athletes experienced increasing levels of stress within the body. This stress could be a result of stress induced from performance or game settings. However, cortisol did not correlate with wellness scores or objective load measures. The present study was conducted during the 2020 season which was halted early due to the COVID-19 pandemic. If carried out to completeness, this trend could be analyzed more thoroughly across the competitive season.

Previous literature showed no change in cortisol between in season and out of season training, but an upward trend was observed throughout the 13-week competitive season (Fields et al., 2020). A similar trend was also observed among collegiate female soccer players (Haneishi et al., 2007) and judo athletes (Filaire et

al., 2001). This trend is analogous to the slight trend present in our study. Previous literature in female swimmers and volleyball players showed a decline in cortisol throughout the competitive seasons (Roli et al., 2018; Santhiago et al., 2011). The conflicting evidence of cortisol response in female athletes provide evidence for more research and for a more consistent assessment in cortisol response. Studies are not consistent in the time parameters employed in measuring cortisol (e.g., weekly, bi-weekly, monthly), nor are they comparable in the timing of assessment as it relates to workload (e.g., beginning of the training week, end of the training week, before/after a recovery day). In the present study, salivary cortisol was collected biweekly at the beginning of the training week after a recovery day. The sample collection after a recovery day may have resulted in a reduced cortisol response. Moreover, the athletes represented in this study are also college students who engaged in a full academic workload. Stress from schoolwork was not evaluated in this study, or parsed out from the general stress question utilized in the daily wellness survey. Because college athletes also carry a role as a student, it may be useful to differentiate school-based stress versus physical stress.

According to Fields et al. (2020) weak relationships were established between physiological, hormonal, and psychological markers of load. Similarly, none of the workload variables evaluated within the current study correlated strongly with the cortisol levels. Additionally, no correlations were found between muscle soreness, sleep quality, or stress. Collectively, these studies indicate that cortisol levels do not follow the same trend as subjective ratings of stress. In a systematic review, Saw et al. (2016) concluded that subjective assessments of wellness were more sensitive to athletes' physical demands, recovery, and fatigue, than that of common objective measures. Utilizing daily and weekly subjective assessments are also a more cost-effective method to measure stress response and—with the right questions—may provide more specific data about the type of stress the athlete is experiencing (e.g., physical, personal, school-based). Similarly, data from subjective wellness surveys have been shown to predict the daily workload response in female lacrosse athletes, male American football players, male Australian football players, and elite male football athletes (Crouch et al., 2021; Gallo et al., 2017; Gastin et al., 2013; Govus et al., 2018; Malone et al., 2018). Cortisol assessment provides concept of

general physiological stress, but because it cannot be measured and evaluated at the same frequency and speed as subjective assessments, it may have less value for athlete workload management. Nevertheless, it is valuable to know the changes in physiological stress athletes experience throughout a competitive season, especially with some of the evidence suggesting that athletes' stress levels do return to baseline or near baseline levels with each training week (Fields et al., 2020; Roli et al., 2018; Santhiago et al., 2011).

A number of limitations may have affected the outcomes of our study. Due to the COVID-19 pandemic in the United States, the NCAA terminated the collegiate lacrosse competitive season after six weeks of competition. This provided this study with only three collection points worth of data. In addition, saliva samples were only collected on a biweekly basis. This could limit the validity of the trend by allowing too much time to pass between each collection time, therefore altering the results of this study. Other limitations that could have affected the outcome of this study was the small sample size and the reliance on the participants to strictly adhere to protocol.

5. Conclusion

This study sought to evaluate changes in salivary cortisol in Division I female collegiate lacrosse athletes and assess the relationship between cortisol and athlete wellness and training load. There was an upward trend for cortisol as the season progressed, but only small relationships with subjective assessments of workload and athlete wellness. There was also increased variation in cortisol in subsequent weeks from baseline, which warrants further analysis. These data agree with the one previously published finding indicating that cortisol did not have significant changes throughout the competitive season in collegiate female lacrosse athletes. Future research should examine these variables across a full-length competitive season with data collection occurring on a weekly basis. Analyses may also want to consider the occurrences on the student component for collegiate athletes and how that affects their cortisol and wellness. Coaches and support staff can then use this knowledge to help manage workload during practices in conjunction with their course load. These data may also be used to help educate and improve self-awareness of athletes and their stress.

Conflict of Interest

The authors declare no conflict of interests.

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