

Countermovement Jump Assessment for Athlete Neuromuscular Fatigue Monitoring

by

Robert Gathercole

BSc., Leeds Metropolitan University, 2007

MSc., Leeds Metropolitan University, 2008

A Dissertation Submitted in Partial Fulfillment
of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY

in the School of Exercise Science, Physical and Health Education

© Robert Gathercole, 2014

University of Victoria

All rights reserved. This dissertation may not be reproduced in whole or in part, by
photocopy or other means, without the permission of the author.

Supervisory Committee

Countermovement Jump Assessment for Athlete Neuromuscular Fatigue Monitoring

by

Robert Gathercole

BSc., Leeds Metropolitan University, 2007

MSc., Leeds Metropolitan University, 2008

Supervisory Committee

Dr. Lynne Stuart-Hill, **Supervisor**

(School of Exercise Science, Physical and Health Education)

Dr. Ben Sporer, **Co-Supervisor**

(School of Exercise Science, Physical and Health Education)

Dr. Trent Stellingwerff, **Outside Member**

(School of Exercise Science, Physical and Health Education; Canadian Sport Institute Pacific)

Abstract

Supervisory Committee

Dr. Lynne Stuart-Hill, **Supervisor**

(School of Exercise Science, Physical and Health Education)

Dr. Ben Sporer, **Co-Supervisor or Departmental Member**

(School of Exercise Science, Physical and Health Education)

Dr. Trent Stellingwerff, **Outside Member**

(School of Exercise Science, Physical and Health Education; Canadian Sport Institute Pacific)

Neuromuscular (NM) fatigue can be defined as an exercise-induced decrease in skill-based performance and/or capacity that originates within the NM system (i.e. between activation of the primary motor cortex to the performance of the contractile apparatus (Bigland-Ritchie, 1981)) (Boyas & Guével, 2011). NM fatigue is a fundamental component of athlete training and competition, required for both optimal adaptation and performance. However, in the short-term, NM fatigue can decrease performance and increase injury risk, whilst its accumulation can produce long-term deleterious performance and health consequences. Consequently, athlete fatigue monitoring is recommended for precise management of athlete training adaptation and recovery

practices. Regular NM function measurement is a key component of athlete fatigue monitoring; still the best means of assessing fatigue-induced effects on NM function is presently unclear. A broader understanding of the most suitable NM testing methods, and associated NM constructs, would therefore be of value to sport practitioners. As elaborated below, this dissertation aimed to first identify the most suitable NM function test, and then develop the testing technique to better determine the NM responses associated with acute fatigue, an accumulation of exercise stress (i.e. accumulated fatigue), and post-exercise recovery. A secondary aim was to provide a greater understanding of the NM responses elicited by fatiguing exercise.

First, the suitability of four NM function tests (e.g. countermovement jump (CMJ), squat jump (SJ), drop jump (DJ), 20-m sprint (SPRINT)) for the regular measurement of NM fatigue was examined. Assessment of test repeatability (mean coefficient of variation for various measures of force, velocity, power, impulse and flight time; SPRINT: 1.2%; CMJ: 3.0%; SJ: 3.5%; DJ: 4.8%) and sensitivity to NM fatigue (substantial post-exercise changes observed up to; SPRINT: 0-hr post; SJ: 24-hr post; CMJ & DJ: 72-hr post) revealed the CMJ test to be the most suitable, with it highly repeatable and sensitive to fatigue-induced changes immediately following fatiguing exercise and during post-exercise recovery. Subsequent investigations further explored the use of CMJ testing for NM fatigue detection.

Second, CMJ responses to acute NM fatigue and during post-exercise recovery were examined in recreational athletes. As part of this process, two analytic approaches,

anticipated to decrease measurement error and improve test sensitivity through the examination of CMJ mechanics, were utilised. Fatiguing exercise resulted in a biphasic recovery profile. Immediate decreases were evident in most CMJ variables (i.e. small-to-moderate changes), followed by mechanical changes indicative of NM fatigue (i.e. small changes in CMJ time- and rate-based variables) at 72-hour. Observation of mechanical changes at 72-hour, supported the use of the two adopted CMJ analytic approaches.

Third, the developed methodology was used with elite snowboard-cross athletes to examine fatigue- and training-induced changes in NM function. Compared to concentric CMJ variables (i.e. peak/mean power/force/velocity), mechanical CMJ changes were more marked following both the fatiguing protocol (ES: moderate-to-large vs. small-to-moderate) and the 19-week training block (large-to-extremely large vs. small-to-very large). The more apparent mechanical changes observed in this highly-trained population (vs. the recreational athletes in Chapter 3) indicated that CMJ mechanical analysis may be of particular value in athlete populations.

Fourth, the CMJ testing techniques were used to examine NM changes associated with accumulated fatigue (i.e. an accumulation of exercise and/or non-exercise stress) in a highly-trained population. Alongside increased training loads and decreased wellness, substantial changes in CMJ mechanics (e.g. time to peak force, force at zero velocity) and jump outcome (e.g. flight time, peak displacement) were observed, thereby supporting the inclusion of mechanical CMJ assessment for the monitoring of accumulated NM fatigue effects.

This series of investigations support the use of CMJ testing for athlete NM fatigue monitoring, and highlight that NM fatigue can manifest as alterations in the mechanical strategies used to accomplish a task. These changes appear evident in response to acute fatigue (Chapters 3 and 4), alongside increases in training load (Chapters 4 and 5) and during post-exercise recovery (Chapter 3). Practitioners should therefore incorporate analyses of CMJ mechanics to provide a more comprehensive assessment of fatigue- and training-induced changes in NM function.

Table of Contents

Supervisory Committee	ii
Abstract	iii
Table of Contents	vii
List of Tables	xi
List of Figures	xiii
Acknowledgments.....	xv
1 General Introduction	1
1.1 Fatigue.....	4
1.1.1 .Central Fatigue.....	6
1.1.2 .Peripheral Fatigue	9
1.1.3 .Recovery from Fatigue	13
1.1.4 .Summary	16
1.2 Athlete Fatigue Monitoring.....	18
1.2.1 .Neuromuscular Function Testing.....	19
1.2.2 .Summary of Neuromuscular Function Testing.....	41
1.3 Dissertation objectives	43
2 Comparison of three vertical jump tests and 20-m sprint testing for neuromuscular fatigue detection.....	45
2.1 Abstract	45
2.2 Introduction.....	46
2.3 Methods.....	48
2.3.1 .Experimental design.....	48
2.3.2 .Participants and familiarization	49
2.3.3 .Testing sessions	49
2.3.4 .Fatiguing protocol.....	51

2.3.5 . Vertical jump test variables	52
2.3.6 . Statistical analysis	52
2.4 Results.....	54
2.4.1 . Test Repeatability	54
2.4.2 . Fatigue sensitivity	57
2.5 Discussion	60
2.5.1 . Repeatability of varying NM testing approaches.....	60
2.5.2 . Fatigue sensitivity	62
2.5.3 . Conclusions.....	69
3 Alternative countermovement jump analysis to quantify acute neuromuscular fatigue	71
3.1 Abstract	71
3.2 Introduction.....	72
3.3 Methods.....	75
3.3.1 . Experimental design.....	75
3.3.2 . Participants and Familiarization	75
3.3.3 . Countermovement Jump Testing Session	76
3.3.4 . Fatiguing Protocol.....	77
3.3.5 . CMJ Variables	78
3.3.6 . Statistical analysis.....	81
3.4 Results.....	83
3.4.1 . Repeatability	83
3.4.2 . Fatigue Sensitivity	85
3.5 Discussion	91
3.5.1 . Repeatability	91
3.5.2 . Fatigue Sensitivity	93
3.5.3 . Altered Movement Strategy in Response to Stretch-Shortening Cycle Fatigue.	96
3.5.4 . Alternative Analysis Methodology	98

3.5.5 .Practical Applications	99
3.5.6 .Conclusions.....	99
4 Effect of acute fatigue and training adaptation on countermovement jump performance in elite snowboard cross athletes	100
4.1 Abstract	100
4.2 Introduction.....	101
4.3 Methods.....	104
4.3.1 .Experimental Approach to the Problem.....	104
4.3.2 .Subjects	104
4.3.3 .Procedures	105
4.4 Statistical Analyses	108
4.5 Results.....	109
4.5.1 .Study I.....	109
4.5.2 .Study II.....	114
4.6 Discussion	118
4.6.1 .Effect of Acute Fatigue on CMJ Performance.....	118
4.6.2 .Effect of Chronic Training on CMJ Performance.....	122
4.6.3 .Practical Applications	125
5 Longitudinal countermovement jump performance with increased training loads in elite female rugby players.....	127
5.1 Abstract	127
5.2 Introduction.....	128
5.3 Methods.....	130
5.3.1 .Participants and Familiarization	130
5.3.2 .Countermovement Jump Testing Session	131
5.3.3 .CMJ variables	132
5.3.4 .Training Load and Wellness	133
5.3.5 .Statistical analysis	133

5.4 Results.....	137
5.4.1 . Participants.....	137
5.4.2 . Training loads and wellness.....	137
5.4.3 . CMJ variables	138
5.4.4 . CMJ performance during monitoring period	138
5.4.5 . OR and Non-OR groups during monitoring period	139
5.5 Discussion	145
5.5.1 . TRIMP and Wellness.....	145
5.5.2 . CMJ performance changes over the monitoring period.....	146
5.5.3 . CMJ Monitoring Considerations	151
5.5.4 . Conclusions.....	152
6 Conclusions.....	153
6.1 Dissertation: Summary.....	153
6.2 Dissertation: Practical Applications.....	158
6.3 Dissertation: Recommendations for Future Research.....	160
Bibliography	163

List of Tables

Table 1-1: Summary of previously reported coefficient of variation (CV) for CMJ test variables.....	37
Table 1-2: Summary of previously reported acute post-exercise fatigue responses in CMJ variables	39
Table 2-1: Mean \pm SD intra- and inter-session coefficient of variation for the SPRINT variables	55
Table 3-1: Description of A) typical (CMJ-TYP) and B) alternative (CMJ-ALT) CMJ variables	80
Table 3-2: Mean and SD of the intra-day and inter-day coefficient of variation (CV) for A) CMJ-TYP and B) CMJ-ALT variables.....	84
Table 3-3: CMJ-TYP Variables: Mean and SD, effect size (ES) & inferences for baseline (day 3) and 0-hour, 24-hour and 72-hour post-exercise (n=9; 24 CMJ per participant). .	88
Table 3-4. CMJ-ALT Variables: Mean and SD, effect size (ES) & inferences for baseline (day 3) and 0-hour, 24-hour and 72-hour post-exercise (n=9; 24 CMJ per participant). .	89
Table 4-1: Acute fatigue effect (Study I): Group mean and SD, effect size (ES) and interpretation between pre- and post-exercise	112
Table 4-2: Chronic training effect (Study II): Group mean and SD, effect size (ES) and interpretation between pre- and post-exercise	116
Table 5-1: Mean and SD for the intra-session coefficient of variation (CV) and the smallest worthwhile change (SWC). A) Typical and B) Alternative variables.....	141

Table 5-2: Qualitative inferences and mean effect size for the differences over time compared to baseline within OR and Non-OR groups and OR versus Non-OR groups (Vs. line) for the CMJ variables.....	142
---	-----

List of Figures

Figure 1-1: The effect of training on fatigue, recovery and performance	3
Figure 2-1: Mean and 90% confidence intervals for the intra- (white markers) and inter-session (black markers) coefficient of variation (CV) for CMJ (squares), SJ (triangles) and DJ (circles) testing.....	56
Figure 2-2: Fatigue Sensitivity) 90% confidence intervals (CI) of the effect sizes (ES) for the group changes in CMJ, DJ, SJ and 20m sprint test variables at 0-, 24- and 72-hour post-exercise.	59
Figure 3-1 (A) Schematic Representation of the study timeline including familiarization, repeatability (i.e. ‘Reliability’), and fatigue sensitivity portions; (B) The fatigue protocol	78
Figure 3-2: Description of (A) alternative start time and (B) outlier removal techniques	82
Figure 3-3: (A) Force-velocity and (B) power-time trace at baseline, 0-hour, 24-hour and 72-hour post-exercise (n=8; 16 CMJ trials from each participant).....	87
Figure 3-4: Mean and 90% confidence level (CL) for the percent change between baseline, 0-hour, 24-hour & 72-hour (select variables only), and the inter-day CV.	90
Figure 4-1: The 19-week training program, the number, type and total hours of conditioning sessions, and the period of pre-and post-testing for study I and II.	107
Figure 4-2: Acute fatigue (Study I): (A) Force-velocity and (B) power-time trace at pre-and post-exercise.....	111

Figure 4-3: Acute fatigue (Study I): Effect sizes (ES) (mean \pm 90% confidence limits (CL)) for the change between pre- and post-exercise.....	113
Figure 4-4: Chronic training (Study II): (A) Force-velocity and (B) power-time trace at pre- and post-training.....	115
Figure 4-5: Chronic training (Study II): Effect sizes (ES) (mean \pm 90% confidence limits (CL)) for the change between pre- and post-training.....	117
Figure 5-1: The mean force-velocity trace for A) all group, B) OR and C) Non-OR groups at baseline (black line) and week 6 (dotted line).	135
Figure 5-2: The mean power-time trace for A) all group, B) OR and C) Non-OR groups at week 1 (black line) and week 6 (dotted line).	136
Figure 5-3: Mean and 90% CL for time to peak force, peak displacement (peak disp.), flight time, relative force at zero velocity (Rel.F@0V), wellness and TRIMP for the whole group at each time point.	143
Figure 5-4: Mean and 90% CL for peak power, time to peak force, relative area under the eccentric phase of the force-velocity trace (Rel.F-V AUC), wellness and TRIMP for OR and Non-OR groups at each time point.....	144

Acknowledgments

There are a number of individuals I wish to acknowledge that have provided great support to me during this doctoral program. Firstly, my heartfelt thanks to Dr. Tim Walzak. When I first set out on my ‘Canadian adventure’ I could not have envisaged where I am today. I will forever be indebted to you for the huge gamble you took and the opportunities that await as a result.

Thanks to my supervisors, Dr. Ben Sporer, Dr. Trent Stellingwerff, Dr. Lynneth Stuart-Hill and the late great Dr. Gord Sleivert. Ben, for your excellent mentorship, encouragement and enthusiasm throughout this journey. I have never once left a meeting with you without feeling a little bit wiser and a lot more energised. Trent, for always being available for ‘quick little questions’ that were rarely that, and for all the invaluable guidance you have provided. To both Ben and Trent, I am particularly grateful for the thousands of conjunctive adverbs removed from my papers; *however*, I do feel that on occasion your criticism has been somewhat unjust. Thanks Lynneth, for the advice you gave when I needed it most (Christmas ’11). To Gord, though you are not able to witness the end of this journey, you are an inspiration and I am honoured to have had the time I did with you.

I also wish to acknowledge my many friends and colleagues at the Canadian Sport Institute Pacific, the Sport Innovation Centre, and the University of Victoria. Particular

thanks go to Joe Misius, for all the chats, advice and confidence you've shown in me; to my closest CSI confidant, Megan Kidston, for all the times we muddled through things together; to Ryan Brodie for saving me from many additional months of jump data analysis, and to Rebecca Zammit for all her help with everything 'UVic'.

Thanks also to the athletes and coaches of Canada Snowboard and Rugby Canada, and to all the other participants (particularly, Graham 'Pilot Subject-Extraordinaire') for making my research a reality. To all my friends and family outside of work and academia, thank you for being my truly supportive support network!

Finally, I would like to acknowledge those dearest to me. Megan, thank you for all your love, encouragement and never-ending patience, I know it's been difficult at times. To my wonderful parents, Anne and Brain, thank you for the perfect upbringing, for your tremendous unwavering support, and for instilling in me all the tools that I have needed to complete this PhD.

1 General Introduction

The basic purpose of training is to induce acute homeostatic disruptions in order to stimulate chronic improvements in physiological capacity (Bishop, Jones, & Woods, 2008). For these adaptations to be realised, and the negative consequences of excessive exercise stress accumulation (e.g. decreased performance, increased injury and illness risk (Twist & Highton, 2013)) avoided, the demands placed on athletes must be balanced with sufficient recovery (Kellmann, 2010). However, discriminating between favourable and unfavourable adaptive responses remains challenging (Borresen & Lambert, 2009). Furthermore, increased training loads are assumed to lead to greater performance improvements (Bishop et al., 2008; Borresen & Lambert, 2009), contributing to the continued rise in athlete demands, whereas optimising the balance between training stress and recovery would perhaps instead be a more fruitful endeavour. Consequently, continual monitoring of athlete physiological state (such as fatigue-, fitness- and performance-based metrics) is considered an essential component of athlete fatigue management (Halsen et al., 2002; Kellmann, 2010; Robson-Ansley, Gleeson, & Ansley, 2009; Twist & Highton, 2013).

Consequences of fatigue and its accumulation are thought to exist on a continuum, ranging from acute fatigue to overtraining syndrome (Fig.1.1) (Halsen & Jeukendrup, 2004; Meeusen et al., 2013; Urhausen & Kindermann, 2002). Based on previous definitions (Meeusen et al., 2013), these consequences will be described here as:

- Acute fatigue: Exercise and/or non-exercise stress from a single exercise session resulting in **very short-term** performance decrements. Performance restoration is quick, requiring **several days at most**. Repeated generation leads to improved performance following sufficient recovery.
- Functional Overreaching Training and/or non-training stress accumulation resulting in **short-term** performance decrement. This can occur with (or without) related physiological and psychological signs and symptoms of maladaptation. Performance restoration may require **several days to several weeks** but **improved performance follows sufficient recovery**.
- Non-Functional Overreaching Training and/or non-training stress accumulation resulting in **short-term** performance decrement. This can occur with (or without) related physiological and psychological signs and symptoms of maladaptation. Performance restoration may require **several days to several weeks** but improved **performance does not follow sufficient recovery**.
- Overtraining syndrome Training and/or non-training stress accumulation resulting in **long-term** performance decrement. This can occur with (or without) related physiological and psychological signs and symptoms of maladaptation. Performance restoration may require **several weeks or months**.

Acute fatigue results from a single exercise bout (i.e. day(s)) and is considered the ‘normal’ training response (Halsen & Jeukendrup, 2004), and essential to the adaptation process (Bishop et al., 2008). If the partial to complete-restoration of fatigue is prevented, and begins to accumulate, then this accumulation of exercise and/or non-exercise stress can result in a state of overreaching. Both forms of overreaching (i.e. functional and non-functional) are associated with diminished performance. However, following adequate recovery, a ‘super-compensatory’ effect is observed in functional overreaching, whereby subsequent performance is improved (Halsen & Jeukendrup, 2004). In contrast, no performance enhancement is observed following non-functional overreaching. For this reason, intensive training phases are often incorporated into training plans with the intention of inducing functional overreaching (Urhausen & Kindermann, 2002). Non-

functional overreaching, by contrast, is considered a transitory phase between overreaching and overtraining syndrome (Schmikli, de Vries, Brink, & Backx, 2012), and differs only to overtraining syndrome in its duration (Meeusen et al., 2013). Given the prolonged decreases in performance and health, both non-functional overreaching and overtraining states are of utmost concern (Meeusen et al., 2013).

PROCESS	TRAINING (overload)	INTENSIFIED TRAINING →		
		OUTCOME	ACUTE FATIGUE	FUNCTIONAL OR (short-term OR)
RECOVERY	Day(s)	Days – weeks	Weeks – months	Months - ...
PERFORMANCE	INCREASE	Temporary decrement (e.g., training camp)	STAGNATION DECREASE	DECREASE

Figure 1-1: The effect of training on fatigue, recovery and performance (Meeusen et al., 2013). OR: Overreaching; OTS: Overtraining syndrome.

Many definitions of fatigue exist (Enoka, 1995), but for the purposes of this dissertation we adopt an applied description, referring to fatigue as an exercise-induced decline in skill-based performance and/or capacity (Knicker, Renshaw, Oldham, & Cairns, 2011). Neuromuscular (NM) fatigue can therefore be considered an exercise-induced decrease that originates within the NM system (i.e. between activation of the primary motor cortex to the performance of the contractile apparatus (Bigland-Ritchie, 1981)) (Boyas & Guével, 2011). Despite the seeming simplicity of these definitions, no single marker has been identified that can detect athlete fatigue in all circumstances

(Borresen & Lambert, 2009). Although it is clear that multiple factors contribute to fatigue symptoms (Cairns, Knicker, Thompson, & Sjøgaard, 2005), identifying the specific underlying mechanisms remains elusive (Abbiss & Laursen, 2005; Ament & Verkerke, 2009; Enoka, 2012). Efforts to identify the processes involved are complicated by the task dependent nature of fatigue, with causative mechanisms influenced by the sporting task (i.e. type, intensity and duration), the individual (e.g. age, genetics, training history) (Borresen & Lambert, 2009), and the environment (e.g. heat, hypoxia) (Knicker et al., 2011). Meanwhile, these considerations relate not only to the mechanisms inducing the fatigue, but also to the recovery kinetics that follow the fatiguing exercise bout, where a fatigue marker would likely be utilised. Consequently, given the complexity of fatigue its detection can be challenging.

1.1 Fatigue

The reductionist approach (i.e. the assumption that fatigue can be explained by a single dominant cause, and measured by a single approach/tool/metric) traditionally used to examine fatigue is considered to have contributed to uncertainty regarding underlying fatigue processes and, in particular, their influence on performance (Abbiss & Laursen, 2005; Cairns et al., 2005; Knicker et al., 2011). As outlined by Abbiss & Laursen (2005), a notable discipline bias is evident in the various models of fatigue: cardiovascular/anaerobic, energy supply/depletion, NM fatigue, muscle trauma, biomechanical, thermoregulatory, psychological/motivational, and central governor (i.e.

regulation of exercise performance by the central nervous system (CNS) to prevent catastrophic failure). Rather than acting in isolation, more recent suggestions have promoted the notion that fatigue symptoms manifest through complex interaction of numerous physiological inputs, with the brain acting as the coordinator of such signals (Abbiss & Laursen, 2005; Amann, 2011; Ament & Verkerke, 2009; Knicker et al., 2011; Marcora & Staiano, 2010; Millet, 2011; Minett & Duffield, 2014; St Gibson et al., 2006). Although these models are not in complete agreement (Minett & Duffield, 2014), each considers exercise fatigue the result of both central and peripheral changes that culminate in decreased exercise performance.

NM fatigue is broadly categorised into central and peripheral components depending on whether the mechanisms originate proximally or distally to the neuromuscular junction (Gandevia, 2001). Although recent evidence suggests that such mechanisms are mutually dependent (Jubeau et al., 2014), central fatigue is associated with a decreased CNS drive to the muscle, whereas peripheral fatigue reflects a decreased response by the muscle to neural excitation (Amann, 2011; Minett & Duffield, 2014). NM fatigue can originate from several potential 'central' and 'peripheral' sites (Ament & Verkerke, 2009), with this determined by the form of muscular contraction performed (Millet & Lepers, 2004). Recognition of the demands of an exercise task is therefore essential before underlying fatigue processes can be understood (Cairns et al., 2005).

Traditionally, researchers have favoured the use of isometric contractions when studying fatigue mechanisms. However this type of contraction is uncharacteristic of typical human movement (Cairns et al., 2005), while whole-body movement is likely to

result in different fatigue mechanisms than isolated muscle contractions (Sidhu, Bentley, & Carroll, 2009). In contrast, dynamic human movement is typified by the utilisation of both eccentric and concentric contractions in a form of muscle function referred to as the stretch-shortening cycle (SSC) (Komi, 2000; Nicol, Avela, & Komi, 2006). SSC muscle function during running is characterised by pre-activation to resist ground impact, followed by braking (the stretch/eccentric phase) and subsequent push-off (the shortening/concentric phase) (Komi, 2000). These actions cause a complex loading of the NM system (Nicol et al., 2006), stressing metabolic, mechanical and neural components (Komi, 2000). Accordingly, SSC exercise is likely associated with numerous central and peripheral fatigue-induced changes in NM function. As specific contributory mechanisms depend upon the task performed (Borresen & Lambert, 2009; Sidhu, Cresswell, & Carroll, 2013), the following discussion will be limited to fatigue-induced changes resulting from whole-body SSC exercise.

1.1.1 Central Fatigue

The CNS is speculated to involuntarily decrease motor drive to prevent potentially catastrophic changes in homeostasis (Amann, 2012; Ament & Verkerke, 2009; Gandevia, 2001; Sidhu, Cresswell, et al., 2013). Decreased CNS drive (i.e. central fatigue) is classified as either spinal or supraspinal fatigue, according to where the mechanism originates (Gandevia, 2001). Spinal fatigue mechanisms concern the

inhibition of motor neuron excitability via spinal reflex circuitry, whereas supraspinal processes are associated with reduced motor cortex output (Gandevia, 2001).

Group III and IV muscle afferents are implicated in both spinal and supraspinal processes (Avela, Kyrolainen, Komi, & Rama, 1999; Sidhu, Cresswell, et al., 2013). These afferents, terminating within skeletal muscle, project through the lumbar dorsal horn of the spinal cord to various sites within the CNS, and are activated by contraction-induced changes within the internal muscle environment (e.g. metabolic disturbances, muscle damage) (Amann, 2011, 2012; Amann et al., 2011; Taylor, Butler, & Gandevia, 2000). Through neural feedback these afferents appear to link intramuscular changes with spinal and supraspinal fatigue mechanisms (Amann, 2011, 2012; Amann et al., 2011).

While spinal fatigue mechanisms appear primarily the result of these muscle afferents, systemic physiological changes (e.g. temperature, oxygenation, energy state) may influence motor cortex output (i.e. originating from supraspinal fatigue mechanisms) (Jubeau et al., 2014; Sidhu, Cresswell, et al., 2013). For example, voluntary activation decreases more so during prolonged multi-joint exercise than single-joint exercise (Sidhu, Cresswell, & Carroll, 2012), and when exercise is performed in hypoxic versus normoxic conditions (Billaut et al., 2013; Goodall, Ross, & Romer, 2010). Although specific mechanisms have yet to be elucidated, these changes are considered the result of direct effects on supraspinal sites (e.g. cerebral deoxygenation/temperature) (Goodall et al., 2010; Sidhu et al., 2009; Sidhu, Lauber, Cresswell, & Carroll, 2013).

Systemic changes may modulate supraspinal fatigue mechanisms through disturbances in cerebral neurotransmitter concentrations (Gandevia, 2001; Meeusen,

Watson, Hasegawa, Roelands, & Piacentini, 2006, 2007; Watson et al., 2005). Despite the recognition that many brain neurotransmitters are likely involved, the majority of focus has been placed on the serotonergic system (Ament & Verkerke, 2009; Gandevia, 2001; Meeusen et al., 2006). For example, in addition to physiological and behavioural processes, such as mood state (Meeusen et al., 2007) and exercise effort perception (Ament & Verkerke, 2009), cerebral serotonin has been linked to the regulation of motor cortex output (Sidhu, Lauber, et al., 2013), exercise-induced hyperthermia responses (Watson et al., 2005), and overtraining syndrome (Meeusen et al., 2007).

Still, despite mounting evidence, identification of the specific spinal and supraspinal changes remains largely speculative (Millet, Martin, Martin, & Verges, 2011). Although agreement is not total (Billaut, Basset, & Falgairette, 2005; Duffield, Murphy, Snape, Minett, & Skein, 2012), central fatigue has frequently been reported following SSC-type exercise. For example, decreased voluntary activation has been observed following acute resistance exercise (Ruotsalainen, Ahtiainen, Kidgell, & Avela, 2014), and various running (Place, Lepers, Deley, & Millet, 2004; Rampinini et al., 2011; Ross, Middleton, Shave, George, & Nowicky, 2007), jumping (Kuitunen, Avela, Kyrolainen, Nicol, & Komi, 2002), and cycling protocols (Billaut et al., 2013; Girard, Bishop, & Racinais, 2013; Jubeau et al., 2014; Perrey, Racinais, Saimouaa, & Girard, 2010). While decreased muscle activity (i.e. EMG) has also been reported following running- (Avela & Komi, 1998; Avela et al., 1999; Oliver, Armstrong, & Williams, 2008; Place et al., 2004; Rampinini et al., 2011) and cycling-based (Lepers, Hausswirth, Maffiuletti, Brisswalter, & van Hoecke, 2000; Mendez-Villanueva, Hamer, & Bishop,

2008; St Clair Gibson, Schabert, & Noakes, 2001) protocols, suggesting changes in neural drive.

Although decreased muscle function is considered indicative of fatigue, NM fatigue may also manifest through qualitative changes in movement control (Ament & Verkerke, 2009). It has been suggested that neural changes may limit the influence of fatigue-induced decreases in muscle function by altering intra- and inter-limb strategies (e.g. synergistic muscle activation, division of load between motor units) (Knicker et al., 2011). For example, EMG analysis has revealed fatigue-induced changes in cycling (Billaut et al., 2005) and jump (Cone et al., 2012; Morio et al., 2011; Oliver et al., 2008) strategies, while biomechanical analysis has repeatedly demonstrated fatigue-induced changes in running mechanics (Girard, Micallef, & Millet, 2011; Millet, 2011; Millet et al., 2009; Morin, Jeannin, Chevallier, & Belli, 2006; Place et al., 2004). Although these coordinative changes may permit the maintenance of performance output, indirect performance effects may result (Knicker et al., 2011) such as increased injury risk (Morio et al., 2011), decreased NM efficiency, as demonstrated through decreases in the force-to-integrated EMG activity ratio (Deschenes et al., 2000), or increased energy cost (Millet et al., 2009).

1.1.2 Peripheral Fatigue

In addition to influencing CNS behaviour (as described in the previous section), homeostatic and muscle damage-related disturbances within the periphery also elicit direct effects on muscle function. Peripheral fatigue has been defined as a decrease in the

force-generating capacity of skeletal muscle as a result of changes distal to the NM junction (Ross et al., 2007). Peripheral factors responsible for this decreased force capacity relate to metabolic changes (e.g. altered intracellular milieu, substrate depletion) and muscle damage. Altered intracellular milieu accompanying muscular contraction include increases in P_i , ADP, AMP, Mg^{2+} and reactive oxygen species (ROS), and decreases in ATP, pH (through increased H^+ accumulation) and the transmembrane K^+ gradient (Allen, Lamb, & Westerblad, 2008; Cairns & Lindinger, 2008; Fitts, 2008). Substrate depletion (e.g. PCr, muscle glycogen) accompanying muscular contraction can also directly (e.g. decreased ATP availability) and/or indirectly (e.g. decreased sarcoplasmic reticulum (SR) Ca^{2+} release) decrease force production (Gejl et al., 2014; Hargreaves, 2008). Exercise-induced muscle damage meanwhile results from mechanical stress and the intracellular factors that contribute to the damaging process, resulting in a disruption of excitation-contraction (E-C) coupling (Byrne, Twist, & Eston, 2004). Although the impact of each parameter remains speculative (Fitts, 2008; Jones, 2010), each is ultimately considered to influence muscle function through impaired Ca^{2+} kinetics (Jones, 2010), via decreases in maximum Ca^{2+} activated force, Ca^{2+} sensitivity, and/or SR Ca^{2+} release (Allen et al., 2008).

The NM effect of altered intracellular milieu, substrate depletion, and muscle damage on muscle contractile properties has been characterised as disrupting either NM propagation, E-C coupling, and/or the intrinsic capacity of the muscle to produce force (Millet & Lepers, 2004; Millet et al., 2011). Reduced NM propagation, via decreased sarcolemmal excitability, lowers SR Ca^{2+} release and is generally attributed to

extracellular K^+ accumulation and a decreased trans-sarcolemmal K^+ gradient (Abbiss & Laursen, 2005; Ament & Verkerke, 2009; Jones, 1996; Millet et al., 2011). Substrate depletion may also play a role in sarcolemmal excitability (Nielsen, Schröder, Rix, & Ørtenblad, 2009), with low muscle glycogen associated with a reduction in SR Ca^{2+} release (Gejl et al., 2014). Results of previous investigations indicate that while NM propagation can decrease following SSC-type exercise (Avela et al., 1999; Lepers et al., 2000; Perrey et al., 2010; Place et al., 2004), such changes are not always evident (Billaut et al., 2013; Rampinini et al., 2011; Ruotsalainen et al., 2014), with training status (higher being more resistant) suggested to contribute to the divergent responses (Millet & Lepers, 2004). Restoration of NM propagation is nevertheless fairly rapid (Jones, 1996), with recovery reported within 2 hours of exercise cessation (Avela et al., 1999; Perrey et al., 2010). Substrate depletion may however elicit a more enduring effect, with reductions in SR Ca^{2+} release rate reported 4-hours following prolonged cycling when glycogen resynthesis was prevented (Gejl et al., 2014).

E-C coupling refers to the process linking NM propagation to Ca^{2+} release (Girard, Mendez-Villanueva, & Bishop, 2011), and is thought to occur via sarcomeric disruption and/or increases in P_i , H^+ and ROS (Abbiss & Laursen, 2005; Allen et al., 2008; Byrne et al., 2004; Fitts, 2008; Jones, 1996). These perturbations decrease SR Ca^{2+} release and myofibrillar Ca^{2+} sensitivity (Jones, 1996; Millet et al., 2011), which, in addition to the direct structural damage, decreases the number of strongly bound cross-bridges and so the maximum Ca^{2+} activated force (Fitts, 2008). Impaired E-C coupling has been reported following both fatiguing running- (Avela et al., 1999; Girard, Lattier,

Maffiuletti, Micallef, & Millet, 2008; Perrey et al., 2010; Rampinini et al., 2011; Ross et al., 2007) and cycling-based protocols (Girard et al., 2013; Lepers et al., 2000). Furthermore, E-C coupling failure is associated with a slow restoration, with several days recovery potentially required (Jones, 1996).

Reductions in the intrinsic capacity of the muscle to produce force can develop through decreases in joint and muscle stiffness (Komi, 2000; Nicol et al., 2006). Altered stiffness is considered the result of interaction between metabolic, structural (i.e. muscle damage) and neural (i.e. group III/IV afferent inhibition) responses associated with SSC exercise, with these changes reducing the number of active cross-bridges and stretch-reflex sensitivity (Avela et al., 1999; Horita, Komi, Nicol, & Kyrolainen, 1996; Nicol, Komi, & Marconnet, 1991). Decreased stiffness has been observed following repeated running sprints (Girard, Micallef, et al., 2011; Morin, Tomazin, Samozino, Edouard, & Millet, 2012), marathon running (Avela et al., 1999; Nicol et al., 1991), and repeated cycling bouts (Ditroilo et al., 2011). Disturbed stiffness regulation is speculated to reduce the efficiency of elastic energy utilisation (Nicol et al., 2006; Nicol et al., 1991), immediately decreasing force capacity and also accelerating fatigue development via an increased work demand to maintain output (Komi, 2000). Moreover, altered stiffness may heighten injury risk through decreased joint stability and movement control (Cone et al., 2012; Pruyn et al., 2012; Watsford et al., 2010).

1.1.3 Recovery from Fatigue

Above we have detailed central and peripheral mechanisms that can contribute to the deterioration in sport performance during fatiguing exercise. Although restoration of these processes is required for the recovery of muscle function, like fatigue, the processes governing exercise recovery are also not completely understood (Barnett, 2006; Bishop et al., 2008).

Recovery has traditionally focused on the restoration of peripheral mechanisms (e.g. metabolic disturbances, glycogen resynthesis, rehydration, muscle damage) (Barnett, 2006; Minett & Duffield, 2014; Nedelec et al., 2012), but central factors may also be important (Bishop et al., 2008; Minett & Duffield, 2014). For example, fatiguing SSC exercise is associated with prolonged post-exercise reductions in voluntary activation (e.g. (Dousset et al., 2007; Prasartwuth, Taylor, & Gandevia, 2005; Rampinini et al., 2011; Sidhu et al., 2009), with systemic disturbances following exercise (e.g. cerebral temperature/neurotransmitters) proposed as possible factors (Sidhu et al., 2009). Similarly, recovery of performance can require multiple days, with this rarely mirroring changes in muscle damage markers (Minett & Duffield, 2014), while metabolic disturbances, such as decreased ATP and PCr, are generally restored within ~60 minutes (Allen et al., 2008). Thus, a lack of correspondence has been suggested to exist between the restoration of peripheral processes and performance (Minett & Duffield, 2014). Furthermore, it has been observed that the perceived effectiveness of a recovery intervention strongly correlates with the extent of recovery, indicating that central factors (possibly centrally-mediated analgesic effects) may alter recovery profile (Cook &

Beaven, 2013). Consequently, recovery of performance following exercise would not appear entirely a peripheral event.

As fatigue responses depend on the task performed, it seems probable that recovery kinetics and the associated mechanisms are similarly task dependent (Allen et al., 2008; Bishop et al., 2008). NM fatigue following with SSC activity is associated with a bimodal recovery trend (Dousset et al., 2007; Komi, 2000; Nicol et al., 2006), with reduced E-C coupling strongly implicated in the secondary phase (Avela et al., 1999). Specifically, an initial decrease in function is followed by a temporary restoration (within ~2-hours), and then a secondary decrease, potentially requiring multiple days recovery (Komi, 2000; Nicol et al., 2006). The initial temporary recovery is typically attributed to the quick restoration of the internal environment (e.g. metabolic by-products, temperature) (Minett & Duffield, 2014), while the secondary decline is less clear but associated with exercise-induced muscle damage (Dousset et al., 2007; Kuitunen et al., 2002) and glycogen and muscle protein resynthesis (Howatson & van Someren, 2008).

Exercise-induced muscle damage is associated with initial structural disruption, followed by a secondary regenerative phase mediated through inflammatory processes (Byrne et al., 2004; Howatson & Milak, 2009; Howatson & van Someren, 2008). In addition to the initial direct impairment of contractile function (i.e. E-C coupling failure), muscle damage may alter glycogen re-synthesis rates (Asp, Rohde, & Richter, 1997; Tee, Bosch, & Lambert, 2007), which may in turn limit NM propagation, given the effect of low glycogen on sarcolemmal excitability (Gejl et al., 2014). Secondary changes following muscle damage may also activate group III and IV muscle afferents through

increases in pressure, temperature, and inflammatory parameters (Avela et al., 1999; Dousset et al., 2007). As with fatigue responses, these afferents may serve a protective role during the recovery phase, triggering pre-synaptic inhibition and decreasing reflex sensitivity (Avela et al., 1999; Nicol et al., 2006). Moreover, as is the case during fatiguing exercise (Amann, 2012; Amann et al., 2011), these afferents may link peripheral changes with the modulation of central drive during recovery.

NM mechanisms associated with the accumulation of fatigue (i.e. functional and non-functional overreaching) appear to have been examined less frequently than acute post-exercise fatigue responses. It has even been suggested that the lack of NM assessment during demanding training phases may have hindered the understanding of such conditions (Halsen & Jeukendrup, 2004). This is particularly interesting given that decreased performance is a key criterion for the detection of conditions resulting from an accumulation of training stress/fatigue (i.e. overreaching) (Meeusen et al., 2013). In contrast, these conditions are typically examined through indirect measures of physiological status such as psychological assessment and/or the use of immunological, hormonal and biochemical markers (Barnett, 2006; Halsen & Jeukendrup, 2004; Meeusen et al., 2013; Urhausen & Kindermann, 2002). Consequently, the possible NM mechanisms underlying the associated decreased performance are unclear, while the capacity to detect and monitor such changes warrants further investigation.

1.1.4 Summary

Despite the huge amount of research that has been undertaken to elucidate NM fatigue responses following whole-body SSC exercise, many unknowns remain. Nevertheless, more evidence is coming to light highlighting the interaction of peripheral and central mechanisms (e.g. Group III/IV afferents) (Amann, 2012; Amann et al., 2011). Consequently, despite traditionally being viewed as isolated entities, the complex integration of these fatigue factors is becoming more apparent.

It has been suggested that the primary concern of the CNS during fatiguing exercise is the prevention of catastrophic changes in homeostasis. This is achieved via the regulation of the central input to the muscle, through spinal and/or supraspinal mechanisms. Altered afferent inputs (i.e. spinal fatigue) have been linked to the chemical and/or mechanical stimulation of group III/IV afferents within the muscle, while changes in both peripheral and systemic homeostasis have been implicated in supraspinal mechanisms (i.e. decreased motor cortex output). Altered cerebral neurotransmitter concentrations may also have a direct and/or indirect role in supraspinal fatigue processes. Centrally-originating diminished NM function has been repeatedly observed following fatiguing SSC exercise, with the induced changes associated with both direct (e.g. decreased muscle function) and indirect (e.g. less efficient neural strategies) performance effects. Thus central factors appear an important component of athlete fatigue responses following most activities.

Peripheral fatigue concerns altered NM propagation, E-C coupling failure, and decreases in the intrinsic force producing capacity of the muscle. These changes are

primarily associated with cellular homeostatic disturbances, exercise-induced muscle damage, and substrate depletion. Effects of altered NM propagation are generally considered more short-lived and of lower significance in highly trained individuals, and so E-C coupling and changes in muscle and joint stiffness appears of greatest concern in athlete recovery.

Like fatigue, the focus of recovery has typically taken a peripherally-oriented approach (e.g. metabolic disturbances, glycogen resynthesis, muscle damage), although the restoration of central factors may also be important. Demanding SSC exercise is associated with prolonged E-C coupling failure and a common biphasic recovery profile; considered the result of transient metabolic, structural and neural effects, highlighting both central and peripheral mechanisms. These more enduring NM responses appear largely related to exercise-induced muscle damage and the associated recovery processes, although substrate depletion may also contribute. Investigative work into the NM effects of accumulated fatigue nevertheless appear largely under-represented; with both the potential contributory NM mechanisms and the most suitable means of detection warranting further investigation.

1.2 Athlete Fatigue Monitoring

The previous section illustrates the complexity of mechanisms that govern fatigue-induced changes in NM function following whole-body SSC exercise. Although these changes can manifest as a direct deterioration in muscle function (e.g. decreased muscle force), it is apparent that performance can also be influenced indirectly (e.g. coordinative changes, decreases in NM efficiency, increased injury risk). Accordingly, the detection of fatigue-induced changes in NM function can be challenging.

Accurately identifying the presence of NM fatigue requires regular monitoring of athlete performance (Twist & Highton, 2013). Performance in the event or sport itself is considered the most valid fatigue indicator (Bishop et al., 2008); however this approach is often inconvenient, may further impede the recovery process, or is unavailable (i.e. sport/event competitions occurring only periodically). Consequently, to ensure a thorough assessment of athlete fatigue state, the use of a battery of potential measurement tools (e.g. subjective questionnaires, heart rate variability, physiology monitoring, biomarkers, NM function testing) has been investigated and utilized by athletes to varying degrees (Twist & Highton, 2013). In reality, the selection of fatigue monitoring tools depends on the sport demands, availability of tools (cost and professional deployment) and the “buy-in” from the coach, athlete and sport.

Assessment of NM function comprises a key component of this recommended test battery, permitting the interpretation of performance in a controlled scientific manner (Currell & Jeukendrup, 2008), and, in contrast to the other fatigue markers, providing a

direct assessment of NM state (Twist & Highton, 2013). As a result, depending on the sport demands, NM function testing can be considered an important fatigue assessment tool (Hubal, Rubinstein, & Clarkson, 2007). The following discussion will focus specifically on the use of NM function testing for the detection and monitoring of NM fatigue.

1.2.1 Neuromuscular Function Testing

The features of a test that determine its suitability are its validity, reliability and sensitivity (Currell & Jeukendrup, 2008; Reilly, Morris, & Whyte, 2009), while the ‘real-world’ practicality of a test is also essential when it is to be used regularly in the training environment (Twist & Highton, 2013). A valid NM function test permits the prediction of subsequent performance (i.e. predictive criterion validity) through examination of NM constructs and/or movements characteristic of performance itself (i.e. face validity) (Currell & Jeukendrup, 2008). For example, both the specificity of movement pattern and contraction type influence the validity of the measurement performed, and so require careful consideration by practitioners (McMaster, Gill, Cronin, & McGuigan, 2014). This between-test relationship is typically examined through a correlational approach (Cronin & Hansen, 2005). For a test to demonstrate both reliability and sensitivity, the measures collected must exhibit consistency when performance status is unchanged (reliability; herein referred to as ‘repeatability’) and clear changes when fatigue changes (sensitivity) (Currell & Jeukendrup, 2008; Hopkins, 2000). Although the most repeatable test is not

always the most suitable (e.g. too much stability can obscure important changes) (Hopkins, Schabert, & Hawley, 2001), it is important that the test-retest repeatability (measured through the coefficient of variation; CV) is sufficiently low for the smallest worthwhile change to be detected (i.e. the magnitude of change associated with a meaningful performance effect) (Currell & Jeukendrup, 2008; Hopkins, 2004). Finally, the practicality of a test is determined by the constraints of the testing environment. In the training setting, testing can involve a large number of athletes in a short amount of time, thus a highly practical test is essential. Specifically, a practical test of NM function for athlete fatigue monitoring must be cost-effective and convenient enough to be used quickly and regularly (Meylan, McMaster, Cronin, Mohammad, & Rogers, 2009; Twist & Highton, 2013). Accordingly, a test associated with superior repeatability and validity may in fact be less appropriate if it is less practical, time-consuming, and/or costly (McMaster et al., 2014).

NM testing can be broadly classified into voluntary (e.g. isometric and isokinetic dynamometry, isoinertial/'functional' testing) and involuntary (e.g. electrical and magnetic stimulation) measurement techniques. Additionally, EMG can be utilised alongside both techniques to analyse the neural drive to the muscle (Farina, Holobar, Merletti, & Enoka, 2010). The most appropriate NM function test to use in a given situation is determined by the specific research question and the needs/demands of the sport environment (Currell & Jeukendrup, 2008). A large proportion of NM function tests examine mechanisms underlying fatigue rather than their resultant influence on performance, and so many are unsuitable for the purposes of athlete fatigue monitoring

(Cairns et al., 2005; Knicker et al., 2011). Furthermore, the practicality of a test is critical to its usefulness in the training environment. Accordingly, voluntary techniques are the generally preferred method, as the comparative impracticality and mechanistic-focus of EMG and involuntary NM assessment preclude their use in regular athlete monitoring.

1.2.1.1 Voluntary Neuromuscular Function Testing

NM function is typically examined through voluntary methods (Abernethy, Wilson, & Logan, 1995), and classified according to the muscular contraction involved: specifically, isometric, isokinetic or isoinertial testing. In isometric testing, NM function is assessed during the application of force to an immovable resistance (Wilson & Murphy, 1996), whereas isokinetic testing examines movement performed at a constant contractile velocity through a set range of motion (e.g. 60°s^{-1}) (Abernethy et al., 1995; Cronin & Hansen, 2005). In contrast, isoinertial testing examines NM function during the movement of a constant gravitational load, where there are changes in muscle tension, length and velocity (Abernethy et al., 1995; Murphy & Wilson, 1997).

1.2.1.1.1 Isometric Assessment

Isometric testing has been described as the gold standard in NM testing (Kufel, Pineda, & Mador, 2002; Place, Maffiuletti, Martin, & Lepers, 2007), possibly because of the level of experimenter control and asserted high reliability (Abernethy et al., 1995; Blazeovich, Gill, & Newton, 2002). Many investigations have inferred isometric test

repeatability through intra-class correlation coefficients (ICC), typically observing a high relative reliability (i.e. >0.80) (Blazevich et al., 2002; Gondin, Guette, Ballay, & Martin, 2005; Gondin, Guette, Jubeau, Ballay, & Martin, 2006; Khamoui et al., 2009; McGuigan, Newton, Winchester, & Nelson, 2010; Mirkov, Nedeljkovic, Milanovic, & Jaric, 2004; Requena, González-Badillo, Villareal, & Erelina, 2009; Stone et al., 2004). However, ICC's do not describe test repeatability and can be distorted by a highly heterogeneous subject sample (Hopkins, 2000). The fewer investigations that have determined the CV have, however, generally reported values of around 5% for maximum voluntary contraction (MVC) force (Gondin et al., 2005; Gondin et al., 2006; Howatson & Milak, 2009; Place et al., 2007), and so isometric test repeatability does appear within acceptable limits.

Doubts have repeatedly been raised over the validity of isometric testing with concerns relating to the disparity between isometric and dynamic contractions, and the inability of isometric testing to measure velocity and power (Abernethy et al., 1995; Cairns et al., 2005; Harris, Cronin, & Keogh, 2007; Murphy & Wilson, 1996; Twist & Highton, 2013). Specifically, mechanical profiles and motor unit recruitment patterns of isometric contractions differ markedly to 'real-life' dynamic movements (Harris et al., 2007; Murphy & Wilson, 1996). For example, dynamic contractions typically activate $<50\%$ of muscle mass at a time (Cairns et al., 2005), whereas quadriceps MVC has been associated with $\sim 95\%$ activation (Babault, Pousson, Ballay, & Van Hoecke, 2001). Similarly, there is potential for muscle ischemia to development during an isometric contraction which is largely absent in dynamic exercise (Knicker et al., 2011). Power,

meanwhile, is associated with larger fatigue-induced decreases than force alone (Knicker et al., 2011) because maximum shortening velocity is also subject to fatigue-induced decline (Cairns et al., 2005). Thus, by examining force alone, the degree of functional impairment in response to fatigue may be underestimated when measured isometrically (Cairns et al., 2005).

Despite these doubts, large correlations have been reported between isometric squat and dynamic squat performance (Blazevich et al., 2002), and between an isometric mid-thigh pull test and bench press, squat and vertical jump performance (McGuigan et al., 2010). As similar constructs are suggested to result in higher correlations regardless of the movement involved, these findings may relate to the similarity in examined NM variables (i.e. 1-RM strength/peak force) (Cronin & Hansen, 2005), or possibly in the simplicity of the movement pattern. Accordingly, if the dynamic NM performance variable of interest can be tested isometrically (e.g. peak force), then isometric assessment may be more likely to produce a valid assessment. Conversely, if the isometric test is unable to measure the particular kinematic and/or kinetic variable of interest (e.g. velocity, power) then, regardless of the test performed, the measurement is more likely unrepresentative of 'real-world' performance.

Similarly, the NM fatigue sensitivity of isometric testing may also depend on the fatiguing activity performed and the NM constructs associated with the fatigue-induced decline. Decreased isometric force has been reported immediately following a 50-km cross-country ski time-trial, but function was restored by 24-hour post (Takashima, Ishii, Takizawa, Yamaguchi, & Nosaka, 2007). In contrast, substantial and prolonged

reductions in MVC have been observed following protocols involving repeated running sprints (Bailey et al., 2007; Howatson & Milak, 2009). Although many differences exist between investigations (e.g. endurance vs. high intensity exercise), one possible factor is the muscle damage elicited by each protocol (i.e. running sprints > cross-country skiing) (Takashima et al., 2007). Muscle damage is associated with a reduction in force per cross-bridge and cross-bridge formation (Howatson & van Someren, 2008), whereas isometric force is determined by the force per cross-bridges and number (Fitts, 2008), thus isometric assessment may offer high sensitivity to muscle damage-related fatigue decline. Conversely, the capacity of isometric testing to determine fatigue-induced decline when NM fatigue relates to other components of NM function (e.g. power, velocity) may be limited. Consequently, given the many potential manifestations of NM fatigue, isometric assessment appears inappropriate for most situations of athlete fatigue monitoring.

1.2.1.1.2 Isokinetic Assessment

Like isometric assessment, isokinetic testing is assumed to permit high experimenter control (Abernethy et al., 1995), but may also lack validity in the assessment of dynamic performance due to differences in movement pattern (Cairns et al., 2005; Cronin & Hansen, 2005; Twist & Highton, 2013). Moreover, the high monetary cost of equipment and protracted testing time makes the practicality of the technique prohibitive to regular use in the training environment (Falvo, Schilling, & Weiss, 2006).

Previous investigations into the repeatability of isokinetic knee extension/flexion tests have reported a broad range of CV's (3.6-4.6%, (Wilson, Walshe, & Fisher, 1997); 4.6-8.9%, (Pua, Koh, & Teo, 2006); 0.5-16.4%, (Brown, Whitehurst, & Findley, 2005)), with differences in contraction velocities, testing equipment and software, and assessed NM variables likely to have contributed to the divergent findings. A meta-analytic review did, however, determine isokinetic testing to be one of the least reliable power assessment tools available (e.g. isokinetic vs. isoinertial test CV: >5% vs. ~3%) (Hopkins et al., 2001), thus the greater control over muscular contraction does not appear to have translated into a higher test-retest repeatability.

A factor speculated to affect the repeatability of isokinetic testing is the 'unnaturalness' of movement (Hopkins et al., 2001), is also a concern raised in regards to the validity of isokinetic assessment (Cairns et al., 2005; Cronin & Hansen, 2005; Twist & Highton, 2013). Specifically, 'normal' human movement involves ballistic (i.e. sinusoidal) velocity changes rather than contractions at a constant velocity, and so isokinetic measures of power and torque are likely invalid (Cairns et al., 2005). Similarly, it is also suggested that discrepancies exist between dynamic contraction velocities and the velocities used during isokinetic testing, while the absence of a SSC in isokinetic contractions has also been highlighted (Cronin & Hansen, 2005; Harris et al., 2007). Consequently, the poor relationships reported between isokinetic test and sprint performance (Cronin & Hansen, 2005; Requena et al., 2009) are therefore not unexpected.

Isokinetic testing, like isometric testing, nevertheless appears sensitive to decreases in NM function associated with exercise-induced muscle damage. For example, downhill running (Miller, Bailey, Barnes, Derr, & Hall, 2004) and maximal eccentric contraction-based (Symons, Clasey, Gater, & Yates, 2004) protocols both elicited substantial muscle damage in addition to marked decreases in isokinetic test performance. Meanwhile, in a protocol more representative of athletic activities (i.e. a competitive soccer match), isokinetic peak torque was decreased for up to 57-hours post (Andersson, Raastad, Nilsson, Paulsen, Garthe, & KadiI, 2008). It is notable however that few investigations appear to have utilised isokinetic dynamometry following exercise demands characteristic of dynamic performance. Although the reasons why are unclear, it may reflect the practical difficulties associated with this form of NM assessment. Consequently, given the seeming importance of contraction mode specificity (Harris et al., 2007), and additional concerns over both reliability and validity, it appears unlikely that isokinetic testing would provide increased sensitivity to NM fatigue following dynamic exercise than, for example, a dynamic (i.e. isoinertial) test might.

1.2.1.1.3 Isoinertial Assessment

Dynamic performance is typically comprised of isoinertial movements that incorporate eccentric, isometric and concentric contractions, as well as in their combinative form, the SSC. Thus, isoinertial testing is considered the most representative and valid form of NM testing to assess dynamic performance capacity (Abernethy et al.,

1995; Harris et al., 2007). An associated decreased experimenter control over movement is suggested however to result in a less reliable measurement (Abernethy et al., 1995; Wilson & Murphy, 1996). Still, isoinertial testing may exhibit heightened sensitivity to NM fatigue following typical athletic activities. Although at the time discussing training-induced NM adaptations, Harris et al. (2007) highlighted that the sensitivity of a NM test likely depends on its similarity to the training mode. Thus, it is conceivable that a similar principle may also relate to fatigue-induced NM changes following dynamic exercise.

Typical isoinertial testing methods include those that replicate weight training exercises (e.g. 1-RM squat, 1-RM power clean), and ballistic movements that are typically utilised in performance itself (e.g. vertical jumping, sprinting). A key difference between these methods are the movement profiles involved, with the acceleration-release pattern of ballistic-type movements (e.g. jumps) considered to be of higher validity than the acceleration-deceleration profile of the weight training-based tests (Cronin & Hansen, 2005). Interestingly, similar factors may also influence the repeatability of testing methods. For example, Abernethy et al. (1995) determined isoinertial tests to be unreliable but examined only weight training-based isoinertial tests, whereas Hopkins et al. (2001) determined the opposite (i.e. highly reliable) and was instead referring to acceleration-release type movements.

Acceleration-Deceleration Methods

Although 1-RM squat and clean testing are considered both practical and amongst the most common means of assessing maximal strength in sport (McMaster et al., 2014), their suitability for fatigue detection is less clear. Corresponding with the conclusions of Abernethy et al. (1995), the CV (between-trial and session) of a variably-loaded squat test ranged from 2.5 – 16.3% for velocity, power, and time-related measures (Jidovtseff et al., 2006), with time-related variables associated with the lowest repeatability. Conversely, a CV of 3.9% has also been reported for a 1-RM squat (e.g. kg) (Pallares, Sanchez-Medina, Perez, De La Cruz-Sanchez, & Mora-Rodriguez, 2014). Interestingly, this investigation reported that pausing between eccentric and concentric squat phases improved repeatability (i.e. CV 2.9% vs. 3.9%). Nevertheless, as such practice negates SSC utilisation the usefulness of this technique in terms of test validity would appear questionable.

Despite the observation of large to nearly perfect negative correlations between half-squat (absolute 1-RM) and sprint performance in soccer players (Wisløff, Castagna, Helgerud, Jones, & Hoff, 2004), generally the relationship of acceleration-deceleration tests to performance appear to improve when results are reported relative to body mass. For example, poor correlations have been reported with sprint performance in 3- and 1-RM squat (Brechue, Mayhew, & Piper, 2010; Cronin & Hansen, 2005; Nuzzo, McBride, Cormie, & McCaulley, 2008) and clean (Nuzzo et al., 2008) tests when values are expressed absolutely. However, when expressed in relative terms, large negative relationships have been found with sprint performance (Brechue et al., 2010; Nimphius,

McGuigan, & Newton, 2010; Nuzzo et al., 2008; Sleivert & Taingahue, 2004). The large relationship observed between absolute half-squat and sprint performance (e.g. (Wisløff et al., 2004)) may therefore have been influenced by the homogeneity of the subject population (e.g. BM: 76.5 ± 7.6 kg, half-squat 1-RM: 171.7 ± 21.2 kg), making relative values largely irrelevant. Thus, despite concerns relating to movement profile differences with performance, weight training-based tests appear capable of yielding valid measures of functional performance.

Unfortunately, few investigations appear to have utilised acceleration-deceleration tests to examine post-exercise fatigue responses. This may be due to a greater potential for injury (genuine or not) with maximal weight training-based tests when fatigued, and/or the level of motivation required to maximally lift external loads (Tod, Iredale, McGuigan, Strange, & Gill, 2005). Ratamess et al. (2003) did report decreased 1-RM squat performance during the first week of a 2-week training phase designed to induce a state of overreaching. Notably, despite continued high training loads, and depressed performance in other tests (e.g. squat jump), squat performance was improved in the second week. Although this may indicate lower NM fatigue sensitivity in acceleration-deceleration compared to acceleration-release methods, subject's familiarity with the squat movement may also have increased during the training program. Thus, despite the presence of NM fatigue, increased comfort and/or technique may have contributed to the improved squat performance.

Given the limited research it is difficult to draw conclusions as to the suitability of acceleration-deceleration isoinertial tests. Generally they appear repeatable and valid tests

of dynamic performance. However, it is unclear whether this form of testing is feasible when athletes are exhibiting tiredness and/or NM fatigue given the possible increased potential for injury and/or associated motivational demands (Tod et al., 2005) that may be heavily influenced by factors such as ‘cognitive fatigue’ rather than the capacity of the NM system specifically.

Acceleration-Release Methods

Compared to acceleration-deceleration tests, a larger volume of research has investigated and utilised acceleration-release tests. Although many different types of acceleration-release tests exist, here the discussion will be limited to the most popular forms: 1) sprint, and 2) vertical jump testing, specifically, squat (SJ), drop (DJ) and countermovement jumps (CMJ).

Sprint Testing

Running sprint performance, particularly acceleration (i.e. 0-10m sprint) (Cronin & Hansen, 2005; Lockie, Murphy, Schultz, Jeffriess, & Callaghan, 2013), is considered an essential component of many sporting activities (Lockie et al., 2013). Despite the sprint test being an isoinertial test, confusingly, investigations of test validity often utilise sprint measurement as the performance measure by which other tests are compared (e.g. Brechue et al., 2010; Cronin & Hansen, 2005; Nimphius et al., 2010; Nuzzo et al., 2008; Requena et al., 2009; Sleivert & Taingahue, 2004). Nevertheless, such use indirectly illustrates the perception of sprint testing as a highly valid test of performance.

A variety of methods can be used to perform and analyse sprint testing (e.g. video, force platform, instrumented treadmills) (Girard, Micallef, et al., 2011), however, from a practical perspective, the simple field test with time-based variables is generally the most convenient. This mode of sprint assessment has been found to exhibit very high test-retest repeatability, with reported CV's of 0.7 – 1.0% (Haugen, Tonnessen, & Seiler, 2012), 1.2% (Bradshaw, Maulder, & Keogh, 2007), and 1.9 – 2.0% (Moir, Button, Glaister, & Stone, 2004). Thus, this level of repeatability suggests that sprint testing should permit the detection of very small changes in NM function.

A number of investigations have observed immediate decreases in sprint performance (i.e. slower running velocity) following fatiguing repeated running sprints (Girard, Micallef, et al., 2011; Morin et al., 2006; Morin et al., 2012) and soccer matches (Andersson, Raastad, Nilsson, Paulsen, Garthe, & KadiI, 2008; Krustup et al., 2006). These decreases have been observed alongside alterations in sprint mechanics (i.e. decreased stride rate and increased stride length) (Girard, Micallef, et al., 2011; Morin et al., 2006; Morin et al., 2012). In contrast, fewer investigations appear to have tracked sprint performance during the post-exercise recovery period. One investigation, reporting sprint performance for 69-hours following a soccer match, observed immediate decreases in sprint performance but a return to baseline by 5-hours post (Andersson, Raastad, Nilsson, Paulsen, Garthe, & KadiI, 2008). This was in contrast to CMJ performance (i.e. jump height), which remained diminished for the entire monitoring period. Thus, sprint performance (using time-based measures) may lack the requisite sensitivity for NM fatigue detection during more prolonged recovery monitoring.

Sprint testing therefore appears a highly valid and repeatable NM test that is sensitive to acute fatigue-induced changes in NM function. Doubts remain over the sensitivity of sprint testing to changes in NM function during more prolonged post-exercise recovery phases, with further research required to determine its value for such monitoring situations.

Vertical Jump Testing

Although CMJ, SJ and DJ tests are all vertical jump tests, permitting assessment of similar NM constructs (e.g. force, velocity, power, displacement), each test utilises different movements and so analyses NM function in different conditions. For example, SJ testing assesses concentric muscle performance only, as the movement does not involve a SSC (Byrne & Eston, 2002). Conversely, both CMJ and DJ tests include an SSC component; however the CMJ movement involves a slow SSC, whereas the DJ measures a fast SSC movement (Cronin & Hansen, 2005; Cronin, Hing, & McNair, 2004). These two forms of SSC are thought to influence different aspects of performance. The slow SSC movement is generally assumed as being key to sprint acceleration (where ground contact time is longer), while fast SSC movement may be essential to maximum sprint speed (Cronin & Hansen, 2005). Consequently, although similar, each jump test appears to reveal different NM components (Byrne & Eston, 2002).

Previous investigations of SJ repeatability have reported high repeatability for various force, power and jump height measurements (CV: <5%; e.g. (Cronin et al., 2004) (Markovic, Dizdar, Jukic, & Cardinale, 2004; McGuigan et al., 2006; McLellan, Lovell,

& Gass, 2011c; Moir et al., 2004)). In contrast, lower repeatability is commonly observed in time- and rate-based measures (e.g. time to peak force, rate of force development) (CV: >11%, e.g. (Cronin et al., 2004; McLellan et al., 2011c)). Nevertheless, rate-based variables are considered to require higher sampling frequencies (i.e. 1000 – 2500 Hz) (McMaster et al., 2014), and so this may relate more to the sampling frequency used during testing than the test itself.

Despite the concentric-only movement, strong relationships have been reported between SJ performance and dynamic movements that include an eccentric component. For example, large correlations were observed between performances in loaded (30kg) ($r=-0.56$ -- -0.66 ; Cronin & Hansen, 2005) and unloaded SJ ($r=-0.57$; Requena et al., 2009) tests and sprint and sprint cycling ($r=-0.50$ -- -0.65 ; Stone et al., 2004) performance. The strength of correlation with sprint performance in both investigations was similar to CMJ ($r=-0.56$ -- -0.62 , Cronin & Hansen, 2005; $r=-0.64$, Requena et al., 2009), but was greater than DJ performance ($r=-0.34$ -- -0.38 ; only Cronin & Hansen, 2005). The greater relationship of CMJ and SJ performance to sprint capacity may relate to the sprint distance examined (30m, Cronin & Hansen, 2005; 15m, Requena et al., 2009), which emphasised acceleration (i.e. slow SSC and large concentric component) rather than the fast SSC (i.e. DJ) once maximal sprint speed is reached (Cronin & Hansen, 2005).

Although lacking a SSC component, previous investigations have suggested that the SJ test may actually provide superior sensitivity to NM fatigue. For example, compared to both CMJ and DJ performance, fatiguing exercise has been found to elicit more pronounced and enduring decrements in SJ performance than in either CMJ or DJ

tests (92% of pre-values vs. 95% each, Byrne & Eston, 2002; decreased for 18- vs. 11- and 3-days, Chambers, Noakes, Lambert, & Lambert, 1998). CMJ and DJ performance were considered less affected because of the potentiating effect of the SSC (Byrne & Eston, 2002), suggesting that the eccentric jump phase may limit fatigue-induced decreases in NM function. Opposing observations have however also been made with larger decreases reported in SSC-jump height (i.e. CMJ and DJ) compared to SJ following a soccer-simulation protocol (-1.5 cm, vs. -3.0 & -2.5 cm, Oliver et al., 2008). These conflicting findings have been attributed to the task specificity of fatigue (Oliver et al., 2008), with the marked SJ decrements observed following extreme muscle-damaging protocols (e.g. 100 squats, Byrne & Eston, 2002; 90-km foot race, Chambers et al., 1998) compared to a protocol more representative of athletic activity (simulated-soccer match, Oliver et al., 2008). These investigations nevertheless findings hint at the possibility that the SSC may impair the detection of NM fatigue-induced change, and so the use of the SJ for athlete NM fatigue detection warrants further investigation.

The DJ test is a preferred testing model in investigations assessing SSC fatigue and underlying mechanisms (e.g. Avela & Komi, 1998; Avela et al., 1999; Horita et al., 1996; Nicol et al., 2006). However, the fatiguing protocols associated with such investigations are typically fairly intensive (e.g. marathon running) and/or unrepresentative of common athletic activities (e.g. rebound DJ's), thus the suitability of DJ testing for athlete fatigue detection is unclear. In contrast to both SJ and CMJ testing, the repeatability of DJ testing appears to have been examined less frequently. In a comparison of DJ, CMJ and SJ repeatability, DJ testing exhibited CV's of 8.4, 4.5 and

9.1% (for peak force, mean force and time to peak force, respectively), compared to 3.2, 2.8 and 11.8% for SJ and 2.2, 2.8 and 7.4% for CMJ (Cronin et al., 2004). Excluding time to peak force results, DJ testing therefore appeared the least repeatable vertical jump test method. Similarly, Cronin and Hansen (2005) reported DJ performance to be the least correlated with sprint performance of either SJ or CMJ performance. Although based on limited research, DJ testing may therefore be of lower repeatability than either CMJ or SJ tests.

DJ testing does nevertheless appear sensitive to NM fatigue, as decreases in DJ performance have been observed following both prolonged- (marathon running; Avela & Komi, 1998; Avela et al., 1999) and repeated sprint-based (simulated-soccer match, Oliver et al., 2008) fatigue protocols. Still, despite this apparent sensitivity to NM fatigue, the potentially lower validity and repeatability of DJ testing suggests that other vertical jump tests may be more suitable for regular athlete fatigue monitoring.

The CMJ test, the most commonly utilised vertical jump test, is also a key performance component of many sporting activities (Nedelec et al., 2012). Like sprint testing, some investigators have used the CMJ as the model of functional performance for validity comparisons (e.g. Nuzzo et al., 2008), however it has also been found to exhibit strong relationships with both sprint running (Cronin & Hansen, 2005; Requena et al., 2009) and cycling ($r=-0.54--0.69$; Stone et al., 2004) performance. Consequently, CMJ testing appears to be of high validity.

A number of investigations have examined the test-retest repeatability of CMJ testing (Table 1.1). Notably, some very large CV's have been reported, however these

appear to primarily relate to eccentric phase-, time- and rate-based variables (e.g. eccentric power, time to peak force, rate of force development) (Cronin et al., 2004; McLellan et al., 2011c; Meylan, Nosaka, Green, & Cronin, 2011; Sheppard, Cormack, Taylor, McGuigan, & Newton, 2008; Taylor, Cronin, Gill, Chapman, & Sheppard, 2010). The higher variability of these measures is perhaps understandable given their fleeting nature and the technical component of a CMJ, although, as highlighted previously, an inappropriate sampling frequency may also contribute (McMaster et al., 2014). Other variables (e.g. peak/mean power, force and velocity), in contrast, appear associated with a level of repeatability similar to other jump tests. A consideration with the majority of these investigations (and similarly other NM function tests) is the use of a single CMJ trial within each testing session to determine repeatability. In contrast, Taylor et al. (2010) utilised the mean of multiple jumps within a test session and reported an improvement in test repeatability, attributed to a reduction in test error. Given the high practicality (Twist & Highton, 2013) and low physiological strain of the CMJ (and both SJ and DJ), this manner of repeated testing appears highly feasible within the training environment and warrants further investigation.

Table 1-1: Summary of previously reported coefficient of variation (CV) for CMJ test variables.

Study	Participants	CMJ Variable	Repeatability (CV)
Cronin et al. (2004) [^]	25M; Recreational athletes	Peak/Mean Force	2.8/2.2
		Time to Peak Force	7.4
Sheppard et al. (2008)	26 M; Elite volleyball & Australian rules football	Peak/Mean Power	9.5/7.1
		Peak Force	3.5
		Max RFD	36.3
		Peak Velocity	7.3
		Jump Height	7.2
Meylan et al. (2011)	10 M; Elite soccer	<u>Eccentric phase:</u>	
		Peak Power	9.3
		Time to Peak Power	9.6
		Peak Force	3.4
		Time to Peak Force	8.5
		Total Impulse	8.1
		Minimum Displacement	5.8
		Ground Contact Time	8.1
		<u>Concentric phase:</u>	
		Peak Power	2.3
		Time to Peak Power	5.5
		Peak Force	2.4
		Time to Peak Force	55.3
		Total Impulse	2.2
		Peak Displacement	3.7
		Ground Contact Time	3.9
		<u>Others:</u>	
Total impulse	1.4		
Jump Height	2.8		
Force at zero velocity	3.3		
McLellan et al. (2011c)	23M; Recreational athletes	Peak/Mean Power	2.8/3.7
		Peak Force	3.5
		Time to Peak Force	11.8
		Max/Mean RFD	16.3/17.9
		Peak Displacement	3.3
Cormack, Newton, McGuigan, and Doyle (2008)	15M; Elite Australian rules Football	Peak/Mean Power	2.9/5.5
		Peak/Mean Force	2.2/1.0
		Jump Height	5.0
		Flight time	3.3
		FT:CT	8.2
Taylor et al. (2010) [*]	13M; Elite Rugby Union	Peak/Mean Power	2.5/2.1
		Peak/Mean Force	2.9/0.8
		Peak Velocity	1.7
		Jump Height	4.3
		Max RFD	22.5

[^] : Force platform-derived only; ^{*} : Calculated using mean of multiple jumps; M: Male; RFD: Rate of force development; FT:CT: Flight-to-contraction time ratio

Like the assessment of CMJ reliability, a number of investigations have utilised CMJ measurement to examine acute (i.e. up to 120-hour post) post-exercise changes in NM function (Table 1.2). These investigations have revealed a range of NM changes following fatiguing activity highlighting the diversity of NM fatigue-induced responses. For example, jump height has exhibited increases (Boullosa, Tuimil, Alegre, Iglesias, & Lusquinos, 2011), decreases (Andersson, Raastad, Nilsson, Paulsen, Garthe, & KadiI, 2008; Chambers et al., 1998), or no change (Cormack, Newton, & McGuigan, 2008) following fatiguing activity. The flight-to-contraction time ratio (FT:CT) however appears the most common CMJ-derived fatigue marker, with a decrease of 8% or greater adopted as an indicator of both acute and accumulated NM fatigue (e.g. (Cormack, Mooney, Morgan, & McGuigan, 2013; Cormack, Newton, & McGuigan, 2008; Cormack, Newton, McGuigan, & Cormie, 2008; Mooney, Cormack, O'Brien B, Morgan, & McGuigan, 2013)). Although this approach may be of merit, the use of ratio variables is not without limitation. For example, an unchanged ratio could result if a decreased flight time is accompanied by a similarly decreased contact time (which appears plausible given the seeming variability of time-based measures (Table 1.1)). Similarly, the use of the FT:CT ratio reveals little information regarding underlying NM changes, for example, which variable (flight time, contact time or a combination of both) contributed to a change? Furthermore, was a reduced flight time determined by other NM constructs (e.g. force, power, velocity)?

Table 1-2: Summary of previously reported acute post-exercise fatigue responses in CMJ variables

Study	Fatigue Protocol	CMJ Variable	Acute Fatigue response						
			0-hr	30-min	24-hr	48-hr	72-hr	96-hr	120-hr
Chambers et al. (1998)	90-km running race	Jump Height	↓		↓	↓	↓	↓	↓
Andersson, Raastad, Nilsson, Paulsen, Garthe, and KadiI (2008)	Soccer match	Jump Height	↓	↓ [^]	↓	↓			
Cormack, Newton, and McGuigan (2008)	Australian Rules Football match	Peak Power	↔		↔		↔	↔	↔
		Mean Power	↓		↓		↓	↔	↔
		Peak Force	↔		↔		↔	↔	↔
		Mean Force	↓		↓		↔	↔	↔
		FT:CT	↓		↓		↔	↔	↔
		Flight Time	↓		↓		↔	↔	↔
McLean, Coutts, Kelly, McGuigan, and Cormack (2010)	Rugby League match	Peak Power			↔			↔	
		Flight Time			↓			↔	
Bouloso et al. (2011)	Endurance running test	Peak Power	↑						
		Mean Power	↔						
		Peak Force	↓						
		Jump Height	↑						
McLellan, Lovell, and Gass (2011a)	Rugby League match	Peak Power		↓	↓	↔	↔	↔	↔
		Peak Force		↓	↔	↔	↔	↔	↔
		Peak RFD		↓	↓	↔	↑	↑	↔
Johnston et al. (2013)	Rugby League match	Peak Power		↔ [^]	↔ [^]	↔ [^]	↓ [^]		
		Peak Force		↔ [^]	↔ [^]	↔ [^]	↔ [^]		

FT:CT: Flight-to-contraction time ratio; RFD: Rate of force development; ↓: Decrease, ↑: Increase, ↔: no change/return to baseline [^]: 5-hour post; [˘]: 2-hour post; ^{˘˘}: 12-hour post; ^{˘˘˘}: 36-hour post.

Combined examination of several NM variables is thought to enhance the predictive capacity of NM testing (Cronin & Hansen, 2005). The majority of investigations (Table 1.2) have however utilised only a few CMJ variables to examine NM fatigue, with jump height and peak power amongst the most popular. A key feature of CMJ (and SJ & DJ) testing is that it permits a relatively simple means of performing a

comprehensive analysis of kinetic and kinematic variables. Although the equipment used to perform CMJ testing is an obvious consideration (i.e. jump mat vs. force platform and position transducer), the small number of examined variables is somewhat surprising and may have contributed to the inconsistent responses observed and the uncertainty that exists regarding the most suitable CMJ variables for NM fatigue monitoring (Taylor, 2012).

CMJ performance analyses have typically focused on peak and mean values relating to the concentric jump phase (Cormie, McBride, & McCaulley, 2009). Although at the time discussing isokinetic testing, Cronin and Hansen (2005) suggested that greater information may be provided if a test movement was not limited to a single point (e.g. peak power) but instead examined as a whole (e.g. force-time trace). This approach has been utilised in CMJ testing through the temporal analyses of CMJ force-, velocity-, power-, and displacement-time curves, providing insight into the mechanistic differences associated with better jumping ability and training-induced NM adaptations (Cormie et al., 2009; Cormie, McGuigan, & Newton, 2010a, 2010b). A similar approach to NM fatigue detection may likewise further enhance the capacity of the CMJ test to determine fatigue-induced changes in NM function.

CMJ testing therefore appears a highly valid and practical test of NM function. However, while some variables appear highly repeatable, others are less so, and divergent results have been reported in relation to fatigue sensitivity. Despite this, developments in the use of multiple trials (Taylor et al., 2010) and in the analyses of CMJ performance (Cormie et al., 2009; Cormie et al., 2010a, 2010b) indicate that both the sensitivity and

repeatability of the method can be potentially be enhanced. Consequently, an examination of the effect of these methods on the suitability of CMJ testing for NM fatigue assessment for athlete monitoring purposes appears worthwhile.

1.2.2 Summary of Neuromuscular Function Testing

Owing to their impracticality and/or mechanistic- rather than performance-based focus to fatigue analysis, a large number of NM function tests are unsuitable for athlete fatigue monitoring. Voluntary assessment methods are the most suitable means for regular athlete monitoring. The validity of some voluntary tests (e.g. isometric, isokinetic tests) and the potential injury risk associated with others when fatigued (e.g. isoinertial acceleration-deceleration tests), indicate that isoinertial acceleration-release type tests are the most useful approach available to practitioners.

Compared to other forms of NM function assessment (e.g. isometric, isokinetic), both sprint- and vertical jump-based acceleration-release tests generally appear highly valid and repeatable. However, the sensitivity of these tests to acute and accumulated fatigue, as well as post-exercise recovery changes, is largely unclear. For example, sprint testing appears highly sensitive to immediate post-exercise fatigue, but may be less so to NM changes during the prolonged recovery phase (>5-hour post). It has been suggested that the absence of a SSC may improve the sensitivity of SJ testing to NM fatigue. Conversely, DJ testing is a frequent method for examining SSC fatigue precisely because of the large SSC component. Meanwhile, despite frequent utilisation in the assessment of

NM fatigue state, previous investigations have reported varied CMJ responses following fatiguing exercise, thus the suitability of CMJ remains uncertain.

Nevertheless, analytic and data collection techniques have been proposed that appear to improve the usefulness of vertical jump testing. Test-retest repeatability appears improved through the utilisation of multiple jump trials within a test session (Taylor et al., 2010). A more comprehensive analysis of NM constructs that can be measured during jump testing may also enhance the capacity of these tests to detect NM fatigue. Similarly, temporal analyses of various kinetic and kinematic traces during jump testing (Cormie, McBride, & McCaulley, 2008; Cormie et al., 2009; Cormie et al., 2010b) may provide greater information regarding the mechanisms underlying NM fatigue responses, as well as improving the fatigue-detection capacity. Given the high validity, repeatability, and practicality of these testing methods, an improvement in the capacity of these tests to detect NM fatigue would appear of great value to athlete monitoring practice.

1.3 Dissertation objectives

Despite the frequent use of NM function testing in athlete fatigue monitoring practice, their usefulness for NM fatigue detection still remains largely uncertain. A factor in this uncertainty is clearly the complexity of fatigue and its many possible manifestations. Additionally, the relative lack of research comparing the sensitivity of various tests to bouts of fatiguing exercise is apparent. Previous methods that have been adopted to examine NM fatigue may have had limited scope to detect fatigue-induced changes (i.e. use of single variables). Consequently, this dissertation aims to address these gaps in our understanding, in order to ultimately improve athlete fatigue monitoring practice.

The specific objectives of dissertation are therefore:

1. To determine the suitability of four common NM function tests (e.g. CMJ, SJ, DJ, and 20-m sprint testing) for the detection of NM fatigue in athletes following prolonged high-intensity intermittent running exercise.
2. Using the most suitable NM test as identified in study 1, perform a thorough examination of NM function in relation to NM fatigue associated with different circumstances, specifically: a) acute fatigue, b) accumulated fatigue, and c) post-exercise recovery. Identifying the NM variables most sensitive to the NM changes displayed in each condition.
3. Utilising methods previously suggested to enhance test repeatability (e.g. the use of multiple trials; Taylor et al., 2010) and improve the information gathered

from a NM test in relation to contributing NM mechanisms (e.g. the examination of mechanical changes associated with the whole movement; Cormie et al., 2009; Cormie et al., 2010a, 2010b), determine whether the capacity of the test to monitor NM fatigue state can be enhanced.

2 Comparison of three vertical jump tests and 20-m sprint testing for neuromuscular fatigue detection¹

2.1 Abstract

Purpose: The suitability of vertical jump (countermovement, CMJ; squat, SJ; and drop, DJ) and 20-m sprint (SPRINT) testing for the detection of NM fatigue was compared. Comparisons were based on test intra- and inter-day repeatability, and the magnitude of responses observed in each test following a fatiguing exercise bout.

Methods: Eleven male collegiate level team-sport athletes performed six CMJ, SJ, DJ, and three SPRINT trials on six occasions. SPRINT performance was examined using time-based measures, while a comprehensive assessment of jump tests was performed (e.g. force, velocity, power, time). Repeatability (coefficient of variation; CV) was examined on participant's first three visits, with the following three visits (0-, 24- and 72-hour post) following a fatiguing high-intensity intermittent exercise running protocol (repeated yo-yo intermittent running tests). Linear mixed modeling and effect sizes (ES) were used to examine between-test differences in repeatability and magnitude of fatigue-induced response.

¹ Gathercole, R.J., Sporer, B., & Stellingwerff, T. Manuscript in preparation.

Results: SPRINT performance was most repeatable (mean CV; $\leq 2\%$), while DJ testing (4.8%) was significantly less repeatable than CMJ (3.0%) and SJ (3.5%). Each test displayed large decreases at 0-hour (33 of 49 total variables; mean ES: 1.82), with fewer and smaller decreases at 24- (13 variables; 0.75) and 72-hour (19 variables; 0.78). SPRINT displayed the largest decreases at 0-hour (3.65), but was subsequently unchanged, while SJ performance recovered by 72-hour. In contrast, CMJ and DJ performance displayed moderate (12 variables; 1.18) and small (6 variables, 0.53) reductions at 72-hour, respectively.

Conclusions: In the tests compared, the high repeatability and marked fatigue-induced changes suggest that the CMJ is the most suitable test for the detection of NM fatigue.

2.2 Introduction

Although performance is the most valid indicator of an athlete's physiological condition (Bishop et al., 2008), its assessment can be impractical and may impede the recovery process. As such, neuromuscular (NM) function tests are considered the most suitable means of NM fatigue assessment available to practitioners (Hubal et al., 2007). Effective monitoring requires valid, reliable and sufficiently sensitive tests to discern the functional changes that will impact performance (Reilly et al., 2009). Due to the similarities with movements involved in athletic performance, isoinertial testing, defined

as the movement of a constant gravitational load (Murphy & Wilson, 1997), is considered the most valid form of NM testing (Falvo et al., 2006; 2008).

Vertical jump tests, such as the countermovement (CMJ), squat (SJ), and drop (DJ) jumps, as well as the 20-m sprint test (SPRINT) are popular isoinertial tests used in the field. Of these tests, the CMJ may offer the greatest sensitivity to NM fatigue as: a) the movement is common to many sporting activities (unlike SJ and DJ), b) consists of stretch-shortening cycle (SSC) movement (unlike SJ), which may be important for detection of NM fatigue following demanding SSC activities, and c) force plate and position transducer systems permit a comprehensive and comparatively convenient analysis of NM function (unlike SPRINT).

Previous investigations into the sensitivity of these tests to NM fatigue have reported contrasting findings. For example, following a muscle damaging exercise protocol, SJ performance was observed to exhibit the largest changes compared to both CMJ and DJ (Byrne & Eston, 2002). Conversely, a test simulating soccer performance decreased CMJ, SJ and DJ performance, but sprint performance was maintained (Oliver et al., 2008). Although these tests permit assessment of various NM components, extrapolation of these results is also limited by: 1) examination of only jump height (Byrne & Eston, 2002) or force-related variables (Oliver et al., 2008), 2) examination of immediate fatigue-induced changes only (Oliver et al., 2008), and 3) unrepresentative exercise protocols (e.g. 100 barbell squats) (Byrne & Eston, 2002). The capacity to track fatigue and subsequent recovery profile would be of significant value to practitioners.

The purpose of the investigation was thus to examine the suitability of the CMJ, SJ, DJ and SPRINT tests for the detection of NM fatigue following a fatiguing exercise bout representative of team-sport performance. A comprehensive assessment of NM variables associated with each test was performed 0- 24- and 72-hours post in order to provide a clearer representation of each test's suitability for fatigue detection. We hypothesized that the CMJ test would exhibit the greatest sensitivity to NM fatigue, owing to the comprehensive NM assessment it permits, and its high ecological validity.

2.3 Methods

2.3.1 Experimental design

A two-part experimental design was implemented to examine the suitability of the four tests for the detection of fatigue-induced declines in NM function. In part one we examined the intra- and inter-day repeatability (days 1-5), while in part two we looked at the sensitivity to fatigue-induced changes in NM function (days 6-9; Fig. 3.1). Participants visited the testing facility at the same time of day (± 1.5 hours) on 7 total occasions, featuring a familiarisation, 3 separate repeatability testing days, a fatigue protocol and then 2 days of post-fatigue monitoring (Fig. 3.1). Participants did not perform any additional exercise beyond the requirements of this investigation throughout the course of testing. As fully described below, during each test session participants performed, in order, SPRINT (3 trials), then CMJ, SJ, and DJ (6 trials each) testing.

2.3.2 Participants and familiarization

Eleven male collegiate level team-sport athletes (mean \pm SD, 23.8 \pm 3.9yrs, 182 \pm 6cm, 80.3 \pm 6.6Kg) participated in the study. Eight participants (23.0 \pm 3.7yrs, 184 \pm 6cm, 80.6 \pm 6.2Kg) completed both repeatability and fatigue sensitivity portions of the study whereas three completed just the repeatability section. Ethical approval was obtained from the University of Victoria Human Ethics Review Board, with participants providing written informed consent and completing a 'Physical Activity Readiness Questionnaire' and a familiarization session at least 7 days prior to study commencement. Participants adopted a high carbohydrate diet throughout testing, consuming the same meal, at the same time, prior to every testing session. Familiarization consisted of a warm-up and then practice of the four tests, with subject comfort and consistency of performance emphasized with each test. This was determined via visual inspection for the SPRINT test, whereas for vertical jump testing, a combination of visual inspection in addition to the assessment of peak and minimum displacement and peak power (values within 10% for four repeated jump trials) was utilised.

2.3.3 Testing sessions

Participants performed a 20 min dynamic warm-up consisting of light jogging (~10 min.), dynamic stretching, 10m & 20m sprints (5 each) of progressive speed completed within 5 min. Between warm-up and SPRINT testing, and between all other

tests, participants actively rested for 5 minutes. In the first 2 min (of 5 min total) prior to jump testing, participants performed 10 practice trials of increasing intensity.

2.3.3.1 SPRINT test

SPRINT testing was performed outside on a marked standardized concrete track. Sprint time was measured using timing gates (Brower ID XS Training System; Brower Timing Systems, Utah, USA) placed at 0, 10 and 20m, allowing measurement of 0-10m, 10-20m and 0-20m time. Participants began in a standing position with their forward foot 0.5m behind the 0m timing gates. Participants performed three SPRINT trials, walking back to the start-line from each sprint and actively resting, with a total of 1.5 min between each trial.

2.3.3.2 Vertical jump tests

Following SPRINT testing, participants performed six trials of each CMJ, SJ and DJ, with 1.5min rest between each trial and 5-min between each test. Trials were sampled at 200Hz using the Ballistic Measurement System and software (BMS; Fitness Technology, Adelaide, Australia; Version 2012.3.7), consisting of a force-plate (400 series, Fitness Technology, Adelaide, Australia) and position transducer (Celesco, PT5A-0150-V62-UP-1K-M6, Chatsworth, CA, USA). Excluding DJ testing (which consisted of just the force-plate), CMJ and SJ testing utilised a ceiling-mounted position transducer suspended directly above the force plate and attached to the center of a wooden dowel placed on participants back similar to a back squat. Participants were instructed to limit dowel movement and the position transducer was zeroed to participant height prior to

every jump. Data was collected immediately after zeroing until the jump was completed. For CMJ testing, participants were directed to perform the CMJ ‘as they normally would’ with an emphasis on a quick countermovement, as a quick transition between eccentric to concentric movement is essential to the SSC (Nicol et al., 2006), to a comfortable depth. SJ testing, in contrast, began with the participant in a squat position at a self-selected depth of $\sim 90^\circ$, holding this position for a researcher’s count of 3, prior to jumping. If any dipping movement was subsequently detected via the BMS displacement trace (a change of $>0.02\text{m}$) then the trial was repeated. For the DJ, participants began standing on a platform 35cm above the force-plate, with hands placed on hips. Participants then stepped off the platform, landing on the force-plate before jumping as high as possible while keeping hands on hips. Participants were directed to ‘step, not jump’ off the platform, and to ‘jump as high and as quickly as possible’. Prior to each jump test, participants performed 10 submaximal practice trials of increasing intensity to ensure they were comfortable with their most familiar jumping technique.

2.3.4 Fatiguing protocol

A three-stage Yo-Yo fatiguing protocol (Fig. 3.1) was performed on an outdoor concrete track to elicit a neuromuscular load similar to team-sport activities (Yo-Yo intermittent recovery level 2 (Yo-Yo IR 2) and Yo-Yo intermittent endurance level 2 (Yo-Yo IE 2) tests (Bangsbo, n.d.)). Briefly, the Yo-Yo IR 2 was performed twice consecutively and involved repeated 20-m shuttle runs performed at increasing velocities

(10 sec recoveries). Yo-Yo IE 2, performed once, involved 20-m shuttle runs at slower velocities (5 sec recoveries). Between Yo-Yo tests participants performed five minutes of active recovery with water provided *ad libitum*. To encourage the development of NM fatigue, participants performed each test to volitional exhaustion, while repeated tests were utilised to ensure the presence of NM fatigue even if participants adopted pacing strategies and/or did not perform each test to maximal capacity. Following the fatigue protocol, participants performed 5 min of active recovery, before beginning the test session (i.e SPRINT, CMJ, SJ, & DJ testing).

2.3.5 Vertical jump test variables

BMS software was used to determine all SJ and DJ variables, and the typically derived CMJ variables (CMJ-TYP; Fig. 2.2). CMJ alternative variables (CMJ-ALT) variables were calculated using previous methods (Gathercole, Sporer, & Stellingwerff, 2014; Gathercole, Sporer, Stellingwerff, & Sleivert, 2014; Gathercole, Stellingwerff, & Sporer, 2014). Force and power (mean and peak) values were converted to values relative to body mass. Description of all variables can be found in (Table 3.1).

2.3.6 Statistical analysis

For all vertical jump tests, the four most consistent trials from the six collected were used in further analysis. To improve test-retest repeatability, the mean of multiple

jump trial data was used (Taylor et al., 2010). Observations made during pilot testing (e.g. (a) jumps are completed within a short duration (~1-sec), (b) there is little experimenter control over movement, and that (c) subtle modifications in jumping technique can elicit pronounced changes in both kinetic and kinematic jump variables) indicated the potential for ‘uncharacteristic’ jump trials, and the possible influence these on mean jump data. Accordingly, this process was undertaken to limit the potential for skewed mean data and improve the utility of the tests.

CMJ trial selection was based on the variable EccConMP (the mean power during both eccentric and concentric phases divided by jump duration), while SJ and DJ trials were both determined by calculating the peak power divided by the duration of the jump. These variables were adopted as selection criteria in order to characterise similar jump trials, in terms of both the power produced during the entire movement and the movement duration. The four most consistent jumps were then identified by subtracting these values by the mean of all six trials and determining the four trials with the smallest difference.

The coefficient of variation (CV) was calculated using raw data collected during pre-fatigue testing days only. The mean of each within-day CV was used to calculate intra-session CV, while inter-session CV was determined using results (mean and SD) from each testing day. Between-test differences and differences in intra- and inter-session repeatability were examined using CV's for the same NM variables derived from each vertical jump test. Significant differences were examined through linear mixed modeling (IBM SPSS Statistics, vers.20, IBM Corp, USA), while effect sizes (ES) based on

between-subject SD, with appropriate inferences (Hopkins, Marshall, Batterham, & Hanin, 2009), were calculated to examine the magnitude of difference. An ES of moderate or greater (i.e. ± 0.6) was used to indicate a substantial change.

To examine fatigue sensitivity, data was log-transformed, and then ES (mean and 90% confidence intervals) were calculated for post-fatigue changes (i.e. 0-, 24- and 72-hour post). ES were based on typical within-individual variability (i.e. mean inter-day CV), with CV multiplied by 0.3, 0.9 and 1.6 for small, moderate and large effects, respectively (Twist & Highton, 2013). For the fatigue analyses and pre-exercise time point, the results of day 3 were used and referred to as 'baseline'. A substantial change was determined as either an ES of moderate or greater (i.e. ± 0.9), or confidence intervals that did not extend across both trivial boundaries (i.e. ± 0.3).

2.4 Results

2.4.1 Test Repeatability

No significant or substantial differences were found between intra- and inter-session repeatability of the same variables. Intra- and inter-session repeatability (coefficient of variation; CV) of the vertical jump (i.e. CMJ, SJ, DJ) and 20-m sprint test variables over the three pre-fatigue days are shown in figure 2.1 and table 2.1, respectively. For the vertical jump test comparison, the same trends were evident in both intra- and inter-session repeatability, with DJ testing generally associated with the highest CV, while the CV in CMJ and SJ testing were generally very similar. 20-m sprint test variables were, however, the most repeatable, with all CV's less than 2%.

Table 2-1: Mean \pm SD intra- and inter-session coefficient of variation for the SPRINT variables

	Intra-session	Inter-session
0-10m time	1.3 \pm 0.1	1 \pm 0.7
10-20m time	2 \pm 0.6	1.3 \pm 0.9
0-20m time	0.9 \pm 0.1	0.8 \pm 0.4

DJ repeatability significantly differed to CMJ and SJ testing in eleven of the eighteen intra-session comparisons, and was substantially worse in all but one (only SJ vs. DJ: mean power). The number of inter-session repeatability differences with DJ testing was less, with only three significant differences observed (CMJ vs. DJ: peak power; flight time; SJ vs DJ: peak power), and seven substantial changes (CMJ vs. DJ: peak and mean power, flight time, jump height; SJ vs. DJ: peak power, peak and mean force).

Differences between CMJ and SJ testing were fewer, with only intra- and inter-session mean power CV significantly different, and substantially lower in CMJ testing. In contrast, although not significant, the inter-session CV for mean force was substantially lower in SJ testing.

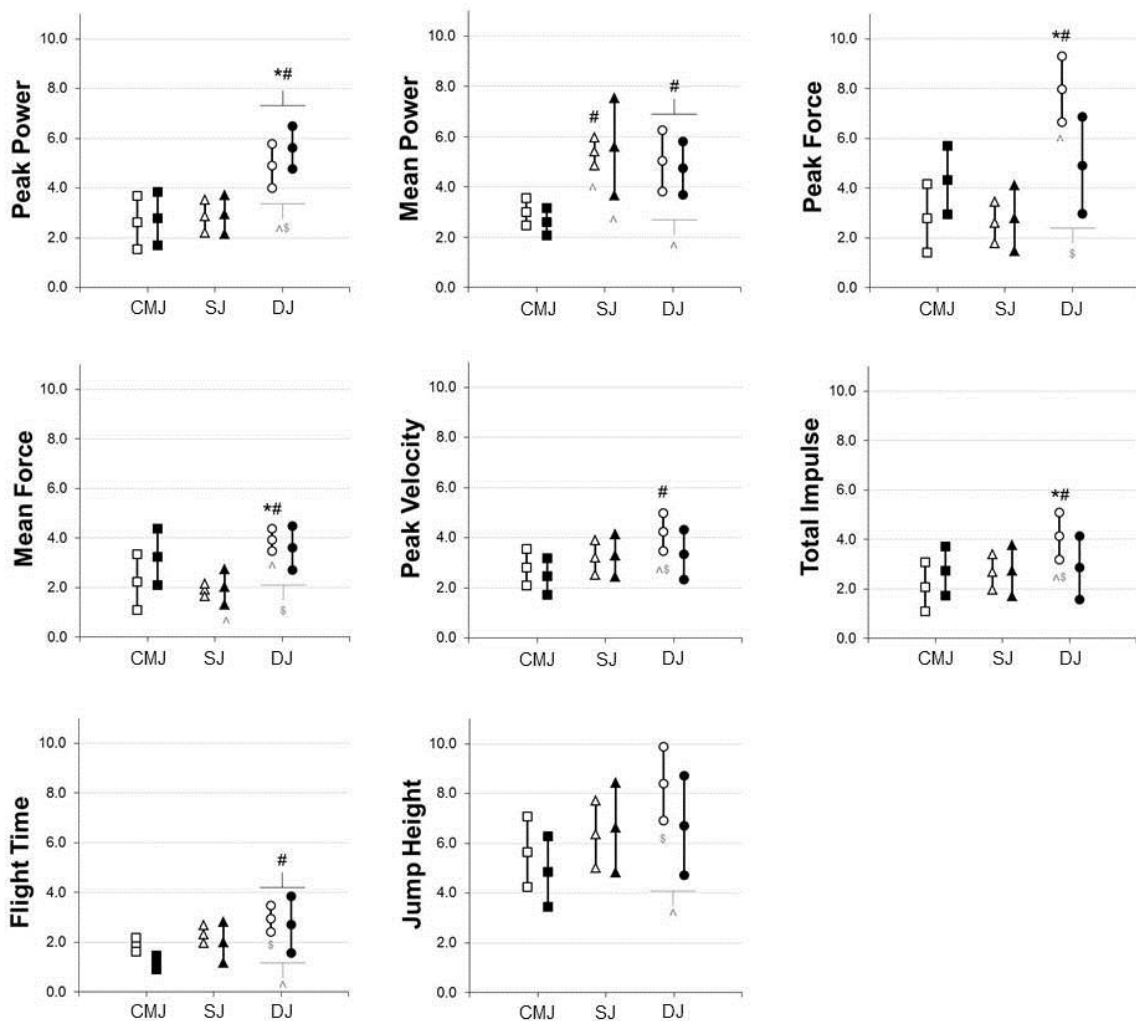


Figure 2-1: Mean and 90% confidence intervals for the intra- (white markers) and inter-session (black markers) coefficient of variation (CV) for CMJ (squares), SJ (triangles) and DJ (circles) testing. Significant between-test differences (above in black; # $p < 0.05$ vs. CMJ; * $p < 0.05$ vs. SJ) and the magnitude of effect (effect size; ES) between tests (below in grey; ^ \geq moderate ES vs. CMJ; \$ \geq moderate ES vs. SJ) are shown.

2.4.2 Fatigue sensitivity

Fatigue sensitivity results are shown in figure 2.2. Across all tests, the most pronounced and widespread changes were displayed immediately following the fatiguing protocol (i.e. at 0-hour). Although most variables had returned to baseline levels by 24-hour, at 72-hour, a small number displayed improved function, with an even larger number again exhibiting diminished function.

At 0-hour, most CMJ test variables exhibited substantially diminished function. Both force- (i.e. peak/mean force, maxRFD) and velocity-based (peak/minimum velocity, velocity at peak power) variables exhibited moderately diminished values however, of the power variables only mean power was diminished (albeit large ES; -1.7). Flight time and eccentric function-based variables (i.e. F@0V, F-V AUC, EccConMP) also displayed decreases (\geq moderate ES). At 24-hour, most CMJ variables appeared to have returned to baseline, with only five variables (i.e. mean power, time to peak power, maxRFD, velocity at peak power, flight time, EccConMP) still displaying substantially diminished function from 0-hour. In contrast, total impulse displayed small improvement. At 72-hour, diminished function was again observed in all force-based variables. Similarly, a number of eccentric function- and time-based variables (i.e. F@0V, EccConMP, time to peak power/force, Ecc/Con/Total duration) showed moderate and large changes indicative of diminished function. In contrast, improved function was exhibited by total impulse, minimum velocity, and F-V AUC.

In contrast to the other tests, SJ peak force and time to peak force/power demonstrated substantially improved function at 0-hour. Power, displacement and velocity variables were still however substantially diminished along with flight time and impulse. At 24- and 72-hour, most variables had returned to baseline, with only peak power, velocity, displacement and flight time (only flight time also at 72-hour) remaining substantially diminished.

Excluding total impulse, all DJ variables were at least moderately diminished at 0-hour. At 24-hour, most variables showed no marked change, with only flight time and FT:CT still substantially diminished and total impulse small but substantially increased. However, at 72-hour, power, velocity and flight time-based variables again showed small decreases in function.

SPRINT results displayed the largest decreases at 0-hour (mean ES: 3.7), with all lower 90% confidence intervals extending beyond the moderate ES threshold (i.e. 0.9). By 24-hour, however, all SPRINT variables were returned to baseline, with 0-10m and 0-20m then demonstrating small and moderate substantial improvements by 72-hour.

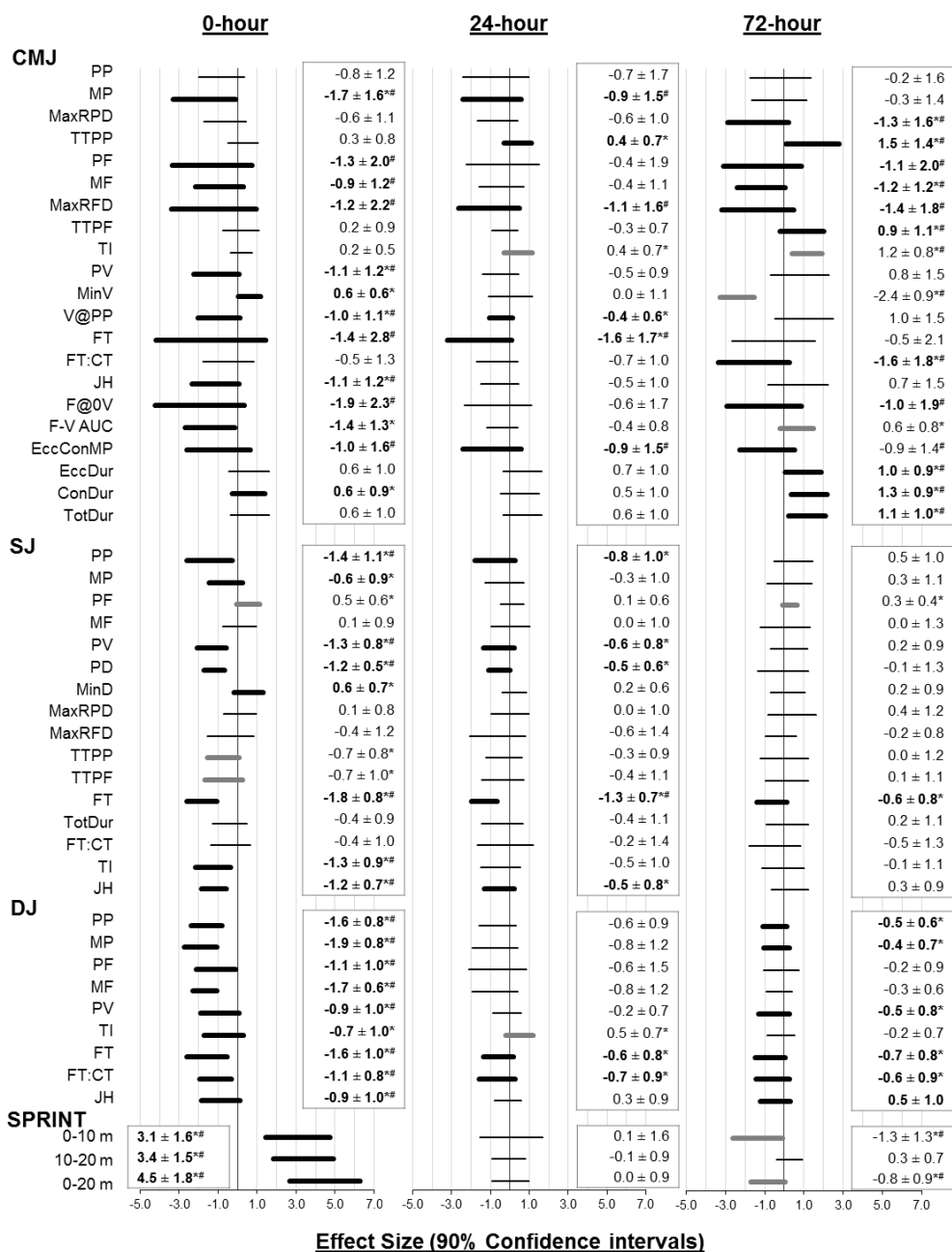


Figure 2-2: Fatigue Sensitivity) 90% confidence intervals (CI) of the effect sizes (ES) for the group changes in CMJ, DJ, SJ and 20m sprint test variables at 0-, 24- and 72-hour post-exercise. Bold CI's signify a substantial change (i.e. that mean ES was greater than ± 0.9 (moderate ES; indicated by *), or the ES CI does not extend across both trivial ES boundaries (± 0.3 ; indicated by #)). Black and grey CI's illustrate changes indicative of diminished or improved neuromuscular function, respectively. CMJ-TYP: Typical (or BMS-derived) CMJ variables; CMJ-ALT: Alternative CMJ variables.

2.5 Discussion

Although this is not the first investigation to compare fatigue-induced changes between CMJ, SJ, DJ and SPRINT testing (Byrne & Eston, 2002; Oliver et al., 2008), novel features of the present study are: a) the between-test comparison of intra- and inter-day repeatability, b) the comprehensive analysis of NM variables from each test, and c) up to 72-hour post-fatigue assessment allowing comparison of suitability between tests for fatigue detection immediately following exercise as well as during the recovery process. Results suggest that the repeatability of the same NM constructs (i.e. power, force, velocity) differs between the tests, with CMJ and SJ performance more repeatable than DJ testing, while SPRINT performance appeared the most repeatable overall. The fatiguing exercise produced marked changes immediately following the exercise bout across all tests, with SPRINT performance exhibiting the largest decreases. However, by 72-hour, despite SPRINT performance being restored, only CMJ and DJ results still demonstrated diminished jump function.

2.5.1 Repeatability of varying NM testing approaches

Previous NM repeatability investigations have utilised a threshold of <10% as indicative of a reliable test (Cormack, Newton, McGuigan, & Doyle, 2008; Taylor et al., 2010). Performance in each test examined here can thus be considered sufficiently repeatable. We utilised standardised jump trial selection criteria to enhance the

repeatability of the jump tests, which appears likely to have influenced these results. As with all CV calculations, our results are unique to the specifics of the investigation (e.g. participants or population examined, procedures utilised); however the repeatability of jump performance determined here could thus be considered artificially low. Moreover, these methods may obscure differences in the variability of jump performance, which may be an important feature of NM function. Consequently, despite the seemingly enhanced consistency of jump performance data, it is recommended that the use of these procedures be further scrutinised to determine their efficacy.

With mean CV's of <2% (Table 2.1), SPRINT test performance appeared the most repeatable overall, closely corresponding with the results of previous investigations (Bradshaw et al., 2007; Moir et al., 2004). Of the vertical jump tests, the lowest intra- and inter-session CV's were associated with CMJ- and SJ-derived variables, with most values around 5% or less (Fig. 2.1). CMJ and SJ performance therefore appears associated with a fairly similar repeatability, with these results in general agreement with the CV values reported previously for CMJ (Cormack, Newton, McGuigan, & Doyle, 2008; McLellan et al., 2011c; Sheppard et al., 2008; Taylor et al., 2010); and SJ (Cronin et al., 2004; McGuigan et al., 2006; McLellan et al., 2011c) testing.

To our knowledge, the only investigation to have reported the repeatability of CMJ, SJ and DJ test performance in the same group of subjects is that of Cronin et al. (2004). Corresponding with our results, they observed the highest CV (i.e. lower repeatability) to be associated with DJ peak and mean force. Although speculative, it is

possible that both the technical complexity of a DJ and our test set-up may have contributed to the greater variability. Technique is considered to profoundly influence DJ performance, with a number of variants of DJ recognized (e.g. countermovement drop jump, bounce drop jump) (Bobbert, 1990). Moreover, participants may have been less familiar with the DJ than, for example, the CMJ which is an important feature of team-sport performance (Nedelec et al., 2012). In contrast to CMJ and SJ, our DJ test configuration utilised a force-platform only, and required participants to stand next to the force plate at the start of a DJ rather than on it. As a result, DJ performance was inferred through reverse data integration, while displacement was indirectly measured; thus the additional calculations required may have introduced further measurement error (McMaster et al., 2014). DJ test repeatability may therefore have been influenced by the technical complexity, exacerbated by lower familiarity, and the measurement system utilised.

2.5.2 Fatigue sensitivity

The fatiguing protocol was developed to induce a similar form and degree of fatigue as elicited by typical team-sport activities (Bangsbo, Iaia, & Krstrup, 2008; Bradley et al., 2011; Krstrup et al., 2003). Fatigue effects following both soccer and rugby league matches have been attributed to muscle damage, muscle glycogen depletion, and increased perception of effort (Nedelec et al., 2012; Twist & Highton,

2013). Although indicative of both central and peripheral fatigue mechanisms, these descriptors provide little clarity as to how such changes may influence NM function, both immediately and during the subsequent recovery phase.

Determining NM adjustments in response to fatigue is challenging as fatigue responses are influenced by inter-individual differences (Morio et al., 2011) and the task performed (Nicol et al., 2006). Although much uncertainty remains regarding the underlying mechanisms (Sanchez-Medina & Gonzalez-Badillo, 2011), fatigue resulting from SSC exercise appears due to neural, structural and mechanical changes in NM function. These changes appear acutely and persist for multiple days depending on the test, the type of fatigue and the training status of the athlete (Dousset et al., 2007; Nicol et al., 2006). Both centrally and peripherally-originating neural factors are thought to either protect fatigued muscles and/or compensate for contractile failure (Millet & Lepers, 2004; Nicol et al., 2006). Structural changes conversely appear primarily due to muscle damage and subsequent remodeling (Dousset et al., 2007; Nicol et al., 2006) resulting in, for example, decreased muscle stiffness (Girard, Micallef, et al., 2011) and changes in the torque-velocity relationship (Byrne et al., 2004). Finally, flexible mechanical adjustments are utilised in response to neural and structural changes to permit the functional requirements of the task to be met (Dousset et al., 2007; Nicol et al., 2006). Consequently, fatigue-related effects may be revealed through changes in movement strategy.

Our results reveal large and widespread NM function decreases immediately following the fatiguing protocol (Fig. 2.2). It seems unlikely that the primary cause of this reduced NM capacity was due to limitations in energy supply as neither decreased muscle glycogen nor phosphocreatine breakdown are considered the primary fatigue mechanism following Yo-Yo test performance (Krustrup et al., 2003). Similarly, following repeated sprints, 6-minutes of rest has been observed to be sufficient for phosphocreatine restoration (Mendez-Villanueva, Edge, Suriano, Hamer, & Bishop, 2012), while the most maximal of phosphocreatine breakdown rates are suggested to reach only ~11% of intramuscular stores per second (Bishop et al., 2008). Thus as the tests performed here were relatively brief (i.e. completed in <3 seconds), and recovery time was provided immediately following fatiguing protocol cessation (5-min) and between repeated trials (1.5-min), it seems unlikely that insufficient energy supply contributed to the diminished NM function. Consequently, these immediate decreases may relate to metabolic disturbances (Girard, Mendez-Villanueva, et al., 2011; Nicol et al., 2006) (e.g. decreased muscle pH (Mendez-Villanueva et al., 2012), increased ROS (Perrey et al., 2010)), structural disruptions (e.g. muscle damage (Byrne et al., 2004)), and/or central fatigue mechanism (e.g. decreased central activation (Abbiss & Laursen, 2005), altered brain neurotransmitter concentrations (Meeusen et al., 2006)).

The most pronounced immediate post-exercise changes were observed in SPRINT performance (mean ES: 3.7; Fig. 2.2). This corresponds with the decreased sprint ability reported previously following fatiguing running-based protocols (Andersson, Raastad,

Nilsson, Paulsen, Garthe, & KadiI, 2008; Girard, Micallef, et al., 2011; Morin et al., 2006; Morin et al., 2012). Despite the magnitude of immediate post-exercise decrease, restoration of SPRINT performance appeared complete by 24-hour post. This is in agreement with observations made following a soccer match, where sprint capacity was recovered much faster (5-hour post) than jump performance (>69-hours post) (Andersson, Raastad, Nilsson, Paulsen, Garthe, & KadiI, 2008). Restoration of sprint ability therefore appears relatively quick; in which case other factors may limit performance in a fatigued state. Alternatively, the assessment of sprint performance via time-based variables may lack the required sensitivity for detection of NM fatigue during later phases of post-exercise recovery (i.e. >0-hour post).

In contrast to most of the other NM variables, SJ peak force, and time to peak force and power were substantially improved immediately following the fatiguing protocol (Fig. 2.2). These findings differ to previous investigations that have observed no changes in SJ peak force following a soccer-simulation protocol (Oliver et al., 2008), or significant decreases in SJ jump height immediately following muscle damaging exercise (Byrne & Eston, 2002). Reasons for the improvement in these SJ variables are unclear. SJ testing took place ~30 minutes following exercise cessation, and so as post-activation potentiation is considered to dissipate within 5-6 minutes, this appears an unlikely explanation (Macintosh, Robillard, & Tomaras, 2012). Moreover, similar changes would likely have been observed in the other tests. Alternatively, these changes may relate to alterations in SJ mechanics. Subjects were instructed to squat deeply and consistently,

however a fatigue-related NM adjustment appears evident in the decreased minimum displacement, indicating that participants did not squat as deeply. This change may have directly contributed to the decreased time to peak force/power, while peak force production may have been enhanced, albeit at the expense of movement velocity (evident in the substantially decreased peak velocity/power).

At 24-hour, smaller effect sizes were displayed by most test variables, indicating a trend towards a return to baseline performance (Fig. 2.2). These results may reflect the restoration of more transient fatiguing factors (e.g. central activation, muscle pH). However, following this time-point, although sprint performance and SJ appeared to recover completely, CMJ and DJ appeared to exhibit secondary decreases. Together, CMJ and DJ performance appeared to display similar fatigue time-courses; widespread and pronounced decreases at 0-hour, a general return to baseline at 24-hour, followed by a secondary decrease at 72-hour. These responses mirror the biphasic recovery profile associated with SSC fatigue (Dousset et al., 2007; Komi, 2000; Nicol et al., 2006). Although the causes of this biphasic trend are unclear, it has been speculated that they relate to neural and mechanical responses that result from muscle damage, and the corresponding inflammatory and structural remodeling processes (Dousset et al., 2007). Anecdotally, the adoption of ‘back-to-back’ high-intensity/speed based training sessions (e.g. high NM load) followed by multiple days recovery may exploit such transient changes, maximizing training performance while minimizing the impact on subsequent recovery.

Neural and mechanical NM fatigue responses may manifest as altered NM strategies, serving to limit performance deteriorations in the face of fatigue-induced NM deficits (Dousset et al., 2007; Nicol et al., 2006). The increased CMJ duration (i.e. eccentric, concentric and total duration, time to peak force/power, FT:CT) and decreased eccentric function (e.g. F@0V) at 72-hour may be indicative of altered CMJ and DJ strategies, and possibly decreased NM efficiency (Fig. 2.2). We have reported similar CMJ-specific changes previously (Gathercole, Sporer, & Stellingwerff, 2014; Gathercole, Stellingwerff, et al., 2014), while NM efficiency (torque/average EMG) has been reported to take at least twice as long (5 vs. >10 days) to recover following muscle damaging exercise (Deschenes et al., 2000). Decreases in NM efficiency may have important performance implications, for example, increasing the energy expenditure of movement (McBride & Snyder, 2012) leading to accelerated fatigue development (Gathercole, Sporer, & Stellingwerff, 2014; Gathercole, Stellingwerff, et al., 2014).

Despite the apparent decreases in CMJ and DJ performance, SPRINT performance improved at 72-hour (Fig. 2.2). Although this may indicate the absence of NM fatigue, it could also relate to the predominantly concentric demands of sprint acceleration (Mero, 1988). Alternatively, force demands during each push-off phase of a sprint are less than when jumping (e.g. sprint push-off force: 608N per leg (Girard et al, 2011), vs. CMJ peak force: 2061N (*in this investigation*)), thus sprinting demands may have been insufficient for the fatigue-induced NM changes to manifest. Similar disagreements between vertical jump and sprint performance are not uncommon. For

example, decreases in CMJ, SJ and DJ performance were observed following a soccer-simulation protocol despite the maintenance of sprint performance (Oliver et al., 2008). The lack of change in sprint performance was considered due to a shift in sprint mechanics (i.e. decreased stride rate and increased stride length), rather than an absence of fatigue. Similar changes in sprint mechanics have also been observed elsewhere (Girard, Micallef, et al., 2011). Consequently, the assessment of sprint performance through time-based variables alone may lack the requisite sensitivity to determine NM fatigue state.

It has been suggested that non-SSC jump tests (i.e. SJ) may provide greater sensitivity to fatigue-related change (Byrne & Eston, 2002; Byrne et al., 2004), and that eccentric function may limit and mask concentric performance declines (Byrne & Eston, 2002). These conclusions were based on the observation that SJ performance was decreased to a greater extent following muscle damaging exercise than either CMJ or DJ performance (Byrne & Eston, 2002). As highlighted by Oliver et al. (2008) however, these differences appear due to the task performed (i.e. 100 barbell squats; and so reduced SSC component) rather than superior sensitivity *per se*. Corresponding with our results, Oliver et al. (2008) found immediate decreases in all CMJ, SJ and DJ tests following a soccer-simulation test. Thus, test specificity to the task performed appears key to a test's sensitivity to the associated fatigue (Nicol et al., 2006).

It is therefore perhaps little surprise that, as our fatiguing protocol was comprised of SSC-intensive exercise, the SSC-inclusive jump tests (i.e. CMJ and DJ) exhibited the

longest and most pronounced NM decreases. Despite eccentric function potentially limiting the extent of concentric performance deterioration, eccentric function itself appeared to reveal fatigue-induced NM manipulations. The usefulness of the SJ test to the assessment of NM fatigue thus appears limited by the absence of an SSC. Similarly, SPRINT testing and analysis as performed here appears insensitive to subtle NM changes. Conversely, both CMJ and DJ tests permit assessment of eccentric function and appear to show a similar high sensitivity to fatigue resulting from SSC exercise. However, the lower repeatability associated with DJ performance in addition to the greater ecological validity of the CMJ, indicates that CMJ test is likely the most suitable tool for the monitoring of fatigue-induced NM changes.

2.5.3 Conclusions

Fatigue effects representative of those experienced following team-sport exercise appear to elicit widespread and pronounced decreases in NM function immediately following exercise. This is followed by a temporary, near restoration, at 24-hours, and then a secondary drop at 72-hour post. The extent of immediate post-exercise changes indicates reductions in most aspects of NM function, whereas the 72-hour decreases indicate a depression in predominantly eccentric-based NM variables, possibly suggestive of reduced NM efficiency.

Of these tests, both SJ and SPRINT performance appear to lack sensitivity to NM fatigue, possibly due to the absence of an SSC component (SJ) and obscured fatigue effects through adjusted sprint mechanics (SPRINT). Meanwhile, in comparison to the CMJ, the suitability of DJ testing appears limited by its repeatability. Consequently, given its high repeatability and sensitivity to NM fatigue, the CMJ test appears the test most suitable for regular athlete fatigue monitoring.

3 Alternative countermovement jump analysis to quantify acute neuromuscular fatigue²

3.1 Abstract

Purpose: To examine the repeatability and magnitude of change following fatiguing exercise in the countermovement jump (CMJ) test and determine its suitability for the assessment of fatigue-induced changes in neuromuscular (NM) function. A secondary aim was to examine the usefulness of a set of alternative CMJ variables (CMJ-ALT) related to CMJ mechanics.

Methods: Eleven male collegiate level team-sport athletes performed six CMJ trials on six occasions. A total of 22 variables, 16 typical (CMJ-TYP) and 6 CMJ-ALT were examined. CMJ repeatability (coefficient of variation; CV) was examined on participant's first three visits. The next three visits (at 0-, 24- and 72-hour post-) followed a fatiguing high-intensity intermittent exercise running protocol. Meaningful differences in CMJ performance were examined through effect sizes (ES), and comparisons to inter-day CV.

² Gathercole, R., Sporer, B., Stellingwerff, T., & Sleivert, G. (2014). Alternative Countermovement Jump Analysis to Quantify Acute Neuromuscular Fatigue. *International Journal of Sports Physiology and Performance*. Epub ahead of print.

Results: Most CMJ variables exhibited intra- (n=20) and inter-day (n=21) CV <10%. ES ranging from trivial to moderate were observed in eighteen variables at 0-hour (immediately post-fatigue). Mean power, peak velocity, flight time, force at zero velocity and area under the force-velocity trace showed changes greater than the CV in most individuals. At 24-hour, most variables displayed trends towards a return to baseline. At 72-hour small increases were observed in time-related CMJ variables, with mean changes also greater than the CV.

Conclusions: The CMJ test appears a suitable athlete monitoring method for NM fatigue detection. However, the current approach (i.e. CMJ-TYP) may overlook a number of key fatigue-related changes and so practitioners are advised to also adopt variables that reflect the NM strategy utilised.

3.2 Introduction

The countermovement jump (CMJ) test is a practical athlete monitoring tool used to examine neuromuscular (NM) status. Examining measurements from a CMJ test can provide insight into numerous components of NM function, however the variables most sensitive to NM fatigue remain unclear (Taylor, 2012). CMJ analysis is generally limited to gross values (i.e. peak, mean) relating to the concentric CMJ phase (Cormie et al., 2009). Given the complex nature of NM fatigue (Knicker et al., 2011), this approach may

overlook a number of fatigue-related NM changes, or lack sensitivity and/or repeatability, contributing to the current state of uncertainty.

The high practicality and low physiological strain of a CMJ test permits repeated assessment of multiple individuals over a short period of time. Previous investigations have typically examined CMJ reliability using the information from one jump in each testing occasion (Cormack, Newton, McGuigan, & Doyle, 2008; McLellan et al., 2011c; Sheppard et al., 2008). However, averaging multiple jumps within a test session has been found to improve CMJ repeatability (Taylor et al., 2010). A similar approach may therefore also improve the sensitivity of the CMJ test to NM fatigue.

Cormie and associates (Cormie et al., 2009; Cormie et al., 2010b) used temporal CMJ analysis to examine the mechanical changes related to NM training adaptations. A similar approach may permit the same for fatigue-related NM changes. These methods provide insight into eccentric loading behaviors and the strategies used to perform a CMJ (Cormie et al., 2010b). Traditional CMJ analysis typically overlooks eccentric CMJ performance, however it is a fundamental component of stretch-shortening cycle (SSC) movement and NM function (Nicol et al., 2006). Athletic performance consists of SSC movements (Kallerud & Gleeson, 2013), with SSC fatigue related to a number of metabolic, mechanical and/or neural factors (Avela et al., 1999; Komi, 2000; Nicol et al., 2006). Recovery following SSC fatigue is considered biphasic, with an immediate decrease in NM function that is recovered within 1-2 hours, and then a secondary decrease at around 2 days that is recovered within 4-8 days (Komi, 2000). A validated

and sensitive monitoring tool should track such changes, and provide valuable and immediate feedback to coaches and athletes.

Many investigations that have used the CMJ test to examine NM fatigue report only a few CMJ variables (Boullosa et al., 2011; Cormack, Money, Morgan, & McGuigan, 2012; Cormack, Newton, & McGuigan, 2008; Johnston et al., 2013; McLean et al., 2010; McLellan et al., 2011a; Mooney et al., 2013), with a number also observing changes that appear to conflict with conventional thinking (i.e. improved results in fatigued condition) (Boullosa et al., 2011; Cormack, Newton, & McGuigan, 2008; Johnston et al., 2013). These diverse findings, along with the biphasic SSC recovery pattern, highlight the complexity of NM fatigue assessment and suggest that a more thorough CMJ analysis may provide greater insight into fatigue-related NM changes.

The purpose of the present study was to determine the suitability of the CMJ test for the assessment of fatigue-induced changes in NM function. The assessment therefore began with a 3-day assessment of intra- and inter-day repeatability followed by an analysis of the magnitude and consistency of change across individuals following a bout of fatiguing SSC exercise. A secondary aim was to examine the usefulness of alternative CMJ variables (CMJ-ALT), based on previous methods (Cormie et al., 2009; Cormie et al., 2010b), for post-exercise fatigue-detection and recovery.

3.3 Methods

3.3.1 Experimental design

A two-part experimental design was implemented to examine the suitability of the CMJ test for the detection of fatigue-induced declines in NM function. In part one we examined the intra- and inter-day repeatability (days 1-5), while in part two we looked at the sensitivity to fatigue-induced changes in NM function (days 6-9; Fig 3.1). Participants visited the testing facility at the same time of day (± 1.5 hours) on 7 total occasions, featuring a familiarisation, 3 separate repeatability testing days, a fatigue protocol and then 2 days of post-fatigue monitoring (Fig. 3.1). Participants did not perform any additional exercise beyond the requirements of this investigation throughout the course of testing. The original methods design also included 20m sprint testing (3 trials) prior to the CMJ testing, and then squat jump (6 trials) and drop jump (6 trials) testing during each test session. Only CMJ data is reported here.

3.3.2 Participants and Familiarization

Eleven male collegiate level team-sport athletes (mean \pm SD, 23.8 \pm 3.9yrs, 182 \pm 6cm, 80.3 \pm 6.6Kg) participated in the study. Eight participants (23.0 \pm 3.7yrs, 184 \pm 6cm, 80.6 \pm 6.2Kg) completed both repeatability and fatigue sensitivity portions of the study whereas three completed just the repeatability section. Ethical approval was obtained from the University of Victoria Human Ethics Review Board, with participants

providing written informed consent and completing a 'Physical Activity Readiness Questionnaire' and a familiarization session at least 7 days prior to study commencement. Participants adopted a high carbohydrate diet throughout testing, consuming the same meal, at the same time, prior to every testing session. Familiarization consisted of a warm-up and then CMJ practice with an emphasis on the speed of jump, until demonstration of consistent CMJ technique ($n=10\pm 4$ attempts). Consistency was determined by visual inspection and an assessment of peak and minimum displacement and velocity and peak power, ensuring that values were within 10% of each other over four consecutive jumps.

3.3.3 Countermovement Jump Testing Session

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

Subjects performed six CMJ trials with 1.5 min rest between. Trials were sampled at 200Hz using the Ballistic Measurement System and software (BMS; Fitness Technology, Adelaide, Australia; Version 2012.3.7), consisting of a force plate (400 series, Fitness Technology, Adelaide, Australia) and position transducer (Celesco, PT5A-0150-V62-UP-1K-M6, Chatsworth, CA, USA). A ceiling-mounted position transducer

was suspended directly above the force plate and attached to the center of a wooden dowel, which was placed on the participants back similar to a back squat. Participants were instructed to limit dowel movement and the position transducer was zeroed to participant height prior to every jump. Data was collected immediately after zeroing until the jump was completed.

3.3.4 Fatiguing Protocol

A three-stage Yo-Yo fatiguing protocol (Fig. 3.1) was performed on an outdoor concrete track to elicit a neuromuscular load similar to team-sport activities (Yo-Yo intermittent recovery level 2 (Yo-Yo IR 2) and Yo-Yo intermittent endurance level 2 (Yo-Yo IE 2) tests (Bangsbo, n.d.)). Briefly, the Yo-Yo IR 2 was performed twice consecutively and involved repeated 20-m shuttle runs performed at increasing velocities (10 sec recoveries). Yo-Yo IE 2, performed once, involved 20-m shuttle runs at slower velocities (5 sec recoveries). Between Yo-Yo tests participants performed five minutes of active recovery with water provided *ad libitum*. Post-fatigue protocol, participants performed five minutes of active recovery, followed by 20m sprint testing (3 trials), and then ten practice CMJ trials before beginning final CMJ testing.

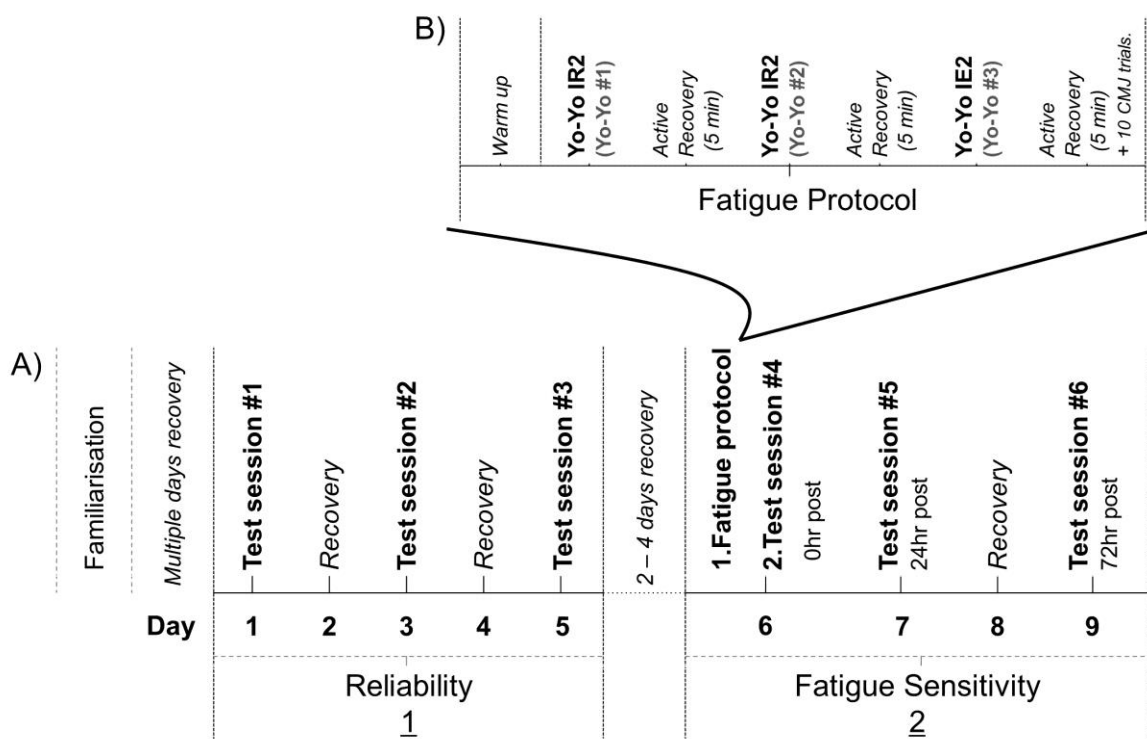


Figure 3-1 (A) Schematic Representation of the study timeline including familiarization, repeatability (i.e. 'Reliability'), and fatigue sensitivity portions; (B) The fatigue protocol

3.3.5 CMJ Variables

BMS software calculated typically-derived CMJ variables (CMJ-TYP), with time-based variables using a jump start threshold based on a >5% decrease in body mass. CMJ-ALT variables were calculated by extraction of raw CMJ data from the BMS software and then analysis through custom-designed software. All CMJ variables are described in Table 3.1. Force and power (mean and peak) values were converted to values relative to body mass. F@0V and FV-AUC were calculated using the force-

velocity trace (Fig. 3.3A), with other CMJ-ALT variables relating to the power-time trace (Fig. 3.3B).

To prevent distortion of power-time trace-derived CMJ-ALT variables, an alternative start time was determined (Fig. 3.2A). The thresholds used in the alternative start time detection were determined through trial and error and developed to standardize and ensure the CMJ countermovement had begun, while also minimizing the amount of removed data. To enable computation of mean force-velocity and power-time traces, the custom software modified every CMJ trial to a set number of 200 data points. Mean power-time traces were calculated through reintegration of time by calculating the mean start and end jump time, dividing this by 200 (to determine the time interval between consecutive data points), and then offsetting the start time to zero.

Table 3-1: Description of A) typical (CMJ-TYP) and B) alternative (CMJ-ALT) CMJ variables

	Abbr.	Description
	PP	Greatest power achieved during the jump.
	MP	Mean power (concentric phase only)
	mRPD	Greatest rate of power increase during a 30ms epoch.
	TTPP	Time from jump initiation to peak power.
	PF	Greatest force achieved during the jump.
	MF	Mean force (concentric phase only).
	mRFD	Greatest rate of force increase during a 30ms epoch.
	TTPF	Time from jump initiation to peak force
A	TI	Total force exerted multiplied by time taken (concentric phase only)
	RNI	Total impulse divided by participant's body mass.
	PV	Greatest velocity achieved during the jump.
	MinV	Peak eccentric velocity
	V@PP	Velocity recorded at peak power.
	FT	Time spent in the air from jump take-off to landing.
	FT:CT	Ratio of flight-to-contraction time. Contraction time is the duration from jump initiation to take-off.
	JH	Max. jump height (calculated using peak velocity).
	F@0V	Force exerted at concentric phase onset (i.e. velocity is at zero).
	FV-AUC	Area under the eccentric phase of the force-velocity trace.
B	EccDur	Duration of the eccentric CMJ phase.
	ConDur	Duration of the concentric CMJ phase.
	TotDur	Duration of the entire CMJ.
	EccConMP	Mean power (during both eccentric and concentric phases; eccentric power converted to absolute values) divided by the total duration (in ms) of the jump.

Abbr, abbreviation;

3.3.6 Statistical analysis

The four most consistent CMJ's from the six collected were used for analysis (Figure 3.2B). Selection was individualized and based on the CMJ-ALT variable, EccConMP. This variable reflects both the total CMJ duration and the mean power produced both eccentrically and concentrically throughout the jump and so we therefore determined it as representative of the entire jump performance. The four most consistent jumps were identified by subtracting the EccConMP for each individual CMJ by the mean EccConMP of the six trials and determining the four trials with the smallest difference.

The coefficient of variation (CV) was calculated using raw data. Other analyses were performed using log-transformed data, with back transformation post statistical analysis. To determine where differences had occurred the magnitude of change was examined through effect size calculation (Batterham & Hopkins, 2006) with appropriate inferences (Rhea, 2004). For the fatigue analyses and pre-exercise time point, the results of day 3 were used and referred to as 'baseline'. Inter-individual variability in fatigue response was examined by calculating the mean individual and 90% confidence limits (CL) for the percent change between testing sessions. Comparison of the mean individual change with the inter-day CV was used to investigate the likelihood of detecting a fatigue-induced change.

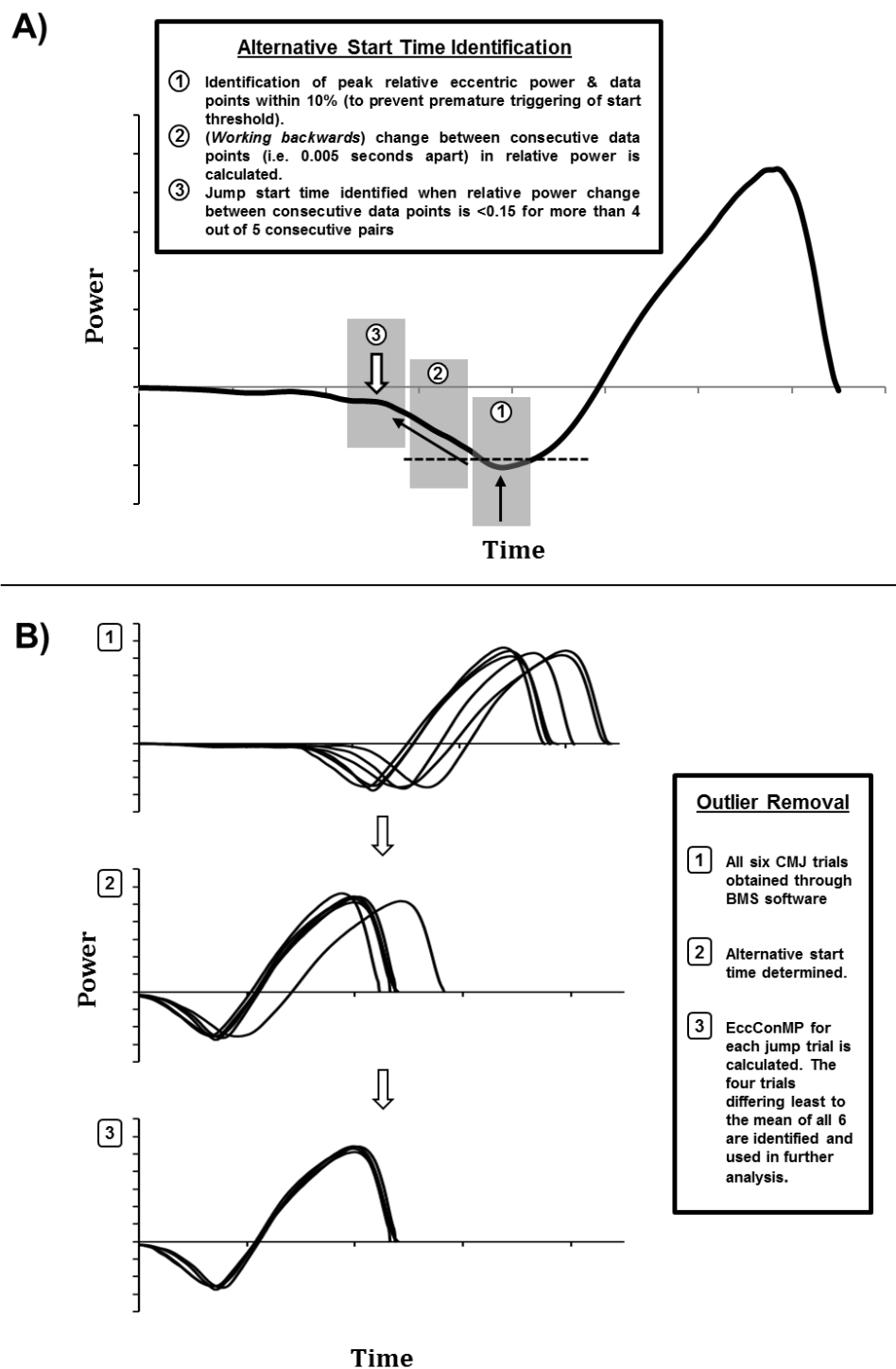


Figure 3-2: Description of (A) alternative start time and (B) outlier removal techniques

3.4 Results

3.4.1 Repeatability

Excluding mRFD, CMJ-TYP and CMJ-ALT variables exhibited similar intra-day and inter-day CV's (Table 3.2). Comparisons of intra-day repeatability between testing day's 1, 2, and 3 revealed trivial effect sizes, indicating an absence of systematic changes in CMJ repeatability.

Comparisons of CMJ performance revealed one change of small magnitude between testing day's 1 and 3 for MinV (Day 1: -1.80 ± 0.25 ; Day 3: -1.84 ± 0.32), whereas other comparisons were trivial. Therefore generally CMJ performance did not appear to systematically change over the course of repeatability testing.

Table 3-2: Mean and SD of the intra-day and inter-day coefficient of variation (CV) for A) CMJ-TYP and B) CMJ-ALT variables.

	Intra-day CV (mean \pm SD)	Inter-day CV (mean \pm SD)
PP	2.3 \pm 1.6	2.7 \pm 1.7
MP	3.0 \pm 1.9	2.8 \pm 1.0
mRPD	4.6 \pm 1.7	7.3 \pm 3.7
TTPP	4.1 \pm 1.7	5.4 \pm 3.4
PF	2.8 \pm 1.6	4.3 \pm 2.3
MF	2.2 \pm 1.1	3.1 \pm 1.9
mRFD	16.0 \pm 8.6	16.2 \pm 7.8
TTPF	6.8 \pm 5.5	7.7 \pm 4.0
A TI	2.2 \pm 1.1	2.7 \pm 1.5
RNI	3.1 \pm 1.4	1.6 \pm 0.9
PV	2.7 \pm 1.8	2.5 \pm 1.2
MinV	4.7 \pm 2.7	5.9 \pm 3.3
V@PP	2.9 \pm 2.0	2.7 \pm 1.7
FT	1.7 \pm 0.8	1.1 \pm 0.4
FT:CT	4.0 \pm 1.5	5.2 \pm 3.2
JH	5.3 \pm 3.6	4.9 \pm 2.4
F@0V	3.9 \pm 2.3	4.4 \pm 2.2
F-V AUC	10.6 \pm 6.0	7.4 \pm 3.7
B EccDur	6.2 \pm 3.2	8.0 \pm 3.7
ConDur	3.6 \pm 2.0	5.1 \pm 3.4
TotalDur	4.0 \pm 2.0	6.1 \pm 3.3
EccConMP	6.3 \pm 3.2	7.9 \pm 3.5

3.4.2 Fatigue Sensitivity

Distance covered during the fatigue protocol was 8613 ± 1249 m. Mean force-velocity and power-time traces, respectively, for baseline, 0-, 24- and 72-hour post-exercise are presented in Figure 3.3A and B. F@0V shows marked differences between time points, with the highest value at baseline, the lowest at 0-hour, and 24- and 72-hour in between. The power-time trace highlights the differences in PP and jump duration between time points, with 0- and 24-hour showing reductions in PP and increases in duration. At 72-hour, PP appeared to have returned to baseline, however jump duration was still extended.

At 0-hour, fourteen CMJ-TYP (Table 3.3) and four CMJ-ALT (Table 3.4) variables displayed small to moderate changes compared to baseline. At 24-hour, only EccConMP displayed a small change, with other differences all trivial. Nine CMJ-TYP and three CMJ-ALT variables displayed small changes with baseline at 72-hour. Compared to baseline, two variables displayed improved values (TI and MinV), whereas ten variables displayed changes indicative of diminished neuromuscular function.

The mean percent change and 90% CL at 0, 24 and 72-hour post-exercise compared to baseline for select variables are presented in Figure 3.4; highlighting the between-participant variability in response as well as the percent change post fatiguing exercise compared to baseline inter-day CV.

At 0-hour compared to baseline, five variables displayed mean changes and CL's greater than inter-day variability, whilst seven other variables displayed mean changes but not CL's that were greater than inter-day variability. At 24-hour FT was the only variable to display a mean change greater than inter-day CV. In contrast, at 72-hour, six variables displayed mean changes greater than inter-day CV.

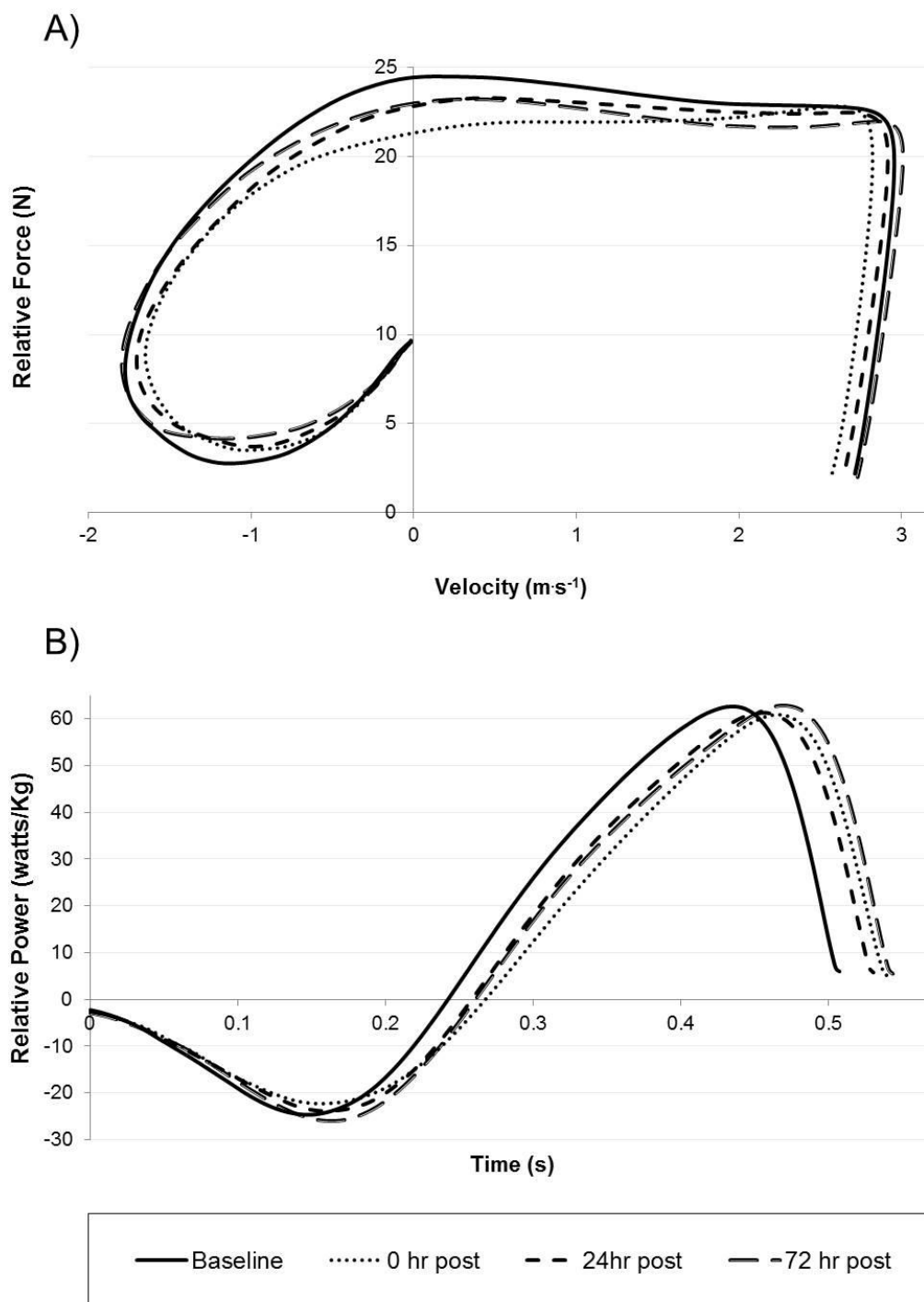


Figure 3-3: (A) Force-velocity and (B) power-time trace at baseline, 0-hour, 24-hour and 72-hour post-exercise (n=8; 16 CMJ trials from each participant).

Table 3-3: CMJ-TYP Variables: Mean and SD, effect size (ES) & inferences for baseline (day 3) and 0-hour, 24-hour and 72-hour post-exercise (n=9; 24 CMJ per participant).

	Baseline	0-hr post		24-hr post		72-hr post	
	(mean \pm SD)	(mean \pm SD)	ES [^]	(mean \pm SD)	ES [^]	(mean \pm SD)	ES [^]
PP	65.1 \pm 7.9	62.8 \pm 8.3	-0.29, S \downarrow	63.9 \pm 7.1	-0.15, T	64.7 \pm 8.2	0.04, T
MP	38.0 \pm 4.1	35.1 \pm 4.6	-0.69, M \downarrow	37.0 \pm 4.2	-0.24, T	37.6 \pm 4.7	-0.09, T
mRPD	7977 \pm 1669	7451 \pm 1268	-0.32, S \downarrow	7660 \pm 1407	-0.19, T	7284 \pm 1054	-0.42, S \downarrow
TTPP	0.655 \pm 0.143	0.674 \pm 0.132	0.13, T	0.671 \pm 0.133	0.11, T	0.713 \pm 0.093	0.41, S \uparrow
PF	25.8 \pm 4.9	24.5 \pm 3.1	-0.27, S \downarrow	25.5 \pm 4.3	-0.06, T	24.9 \pm 2.7	-0.19, T
MF	20.1 \pm 2.1	19.3 \pm 2.1	-0.36, S \downarrow	19.8 \pm 2.4	-0.15, T	19.4 \pm 1.8	-0.34, S \downarrow
mRFD	14926 \pm 9118	12190 \pm 6008	-0.30, S \downarrow	12958 \pm 7643	-0.22, T	12666 \pm 5630	-0.25, S \downarrow
TTPF	0.536 \pm 0.153	0.588 \pm 0.150	0.34, S \uparrow	0.530 \pm 0.132	-0.04, T	0.579 \pm 0.118	0.28, S \uparrow
TI	433.4 \pm 48.2	430.7 \pm 53.4	-0.05, T	438.0 \pm 52.8	0.09, T	447.1 \pm 47.6	0.28, S \uparrow
RNI	2.79 \pm 0.16	2.68 \pm 0.21	-0.69, M \downarrow	2.76 \pm 0.16	-0.20, T	2.75 \pm 0.32	-0.26, S \downarrow
PV	2.94 \pm 0.35	2.81 \pm 0.29	-0.37, S \downarrow	2.91 \pm 0.31	-0.09, T	3.01 \pm 0.24	0.18, T
MinV	-1.84 \pm 0.32	-1.75 \pm 0.27	0.30, S \uparrow	-1.84 \pm 0.33	0.02, T	-1.94 \pm 0.23	-0.31, S \downarrow
V@PP	2.85 \pm 0.43	2.72 \pm 0.35	-0.29, S \downarrow	2.82 \pm 0.40	-0.07, T	2.94 \pm 0.29	0.21, T
FT	0.544 \pm 0.045	0.520 \pm 0.044	-0.53, M \downarrow	0.534 \pm 0.046	-0.21, T	0.540 \pm 0.050	-0.08, T
FT:CT	0.753 \pm 0.131	0.701 \pm 0.123	-0.40, S \downarrow	0.729 \pm 0.117	-0.18, T	0.695 \pm 0.106	-0.44, S \downarrow
JH	0.44 \pm 0.11	0.40 \pm 0.09	-0.34, S \downarrow	0.43 \pm 0.10	-0.08, T	0.46 \pm 0.08	0.18, T

[^]Effect sizes represent comparisons with baseline values only; T: Trivial, S: Small, M: Moderate, \uparrow : Increase, \downarrow : Decrease

Table 3-4. CMJ-ALT Variables: Mean and SD, effect size (ES) & inferences for baseline (day 3) and 0-hour, 24-hour and 72-hour post-exercise (n=9; 24 CMJ per participant).

	Baseline (mean \pm SD)	0-hr post (mean \pm SD)	ES [^]	24-hr post (mean \pm SD)	ES [^]	72-hr post (mean \pm SD)	ES [^]
F@0V	24.4 \pm 5.0	21.7 \pm 3.3	-0.55, M \downarrow	23.9 \pm 4.2	-0.11, T	23.5 \pm 3.7	-0.19, T
F-V AUC	27.5 \pm 7.7	23.1 \pm 7.3	-0.57, M \downarrow	26.5 \pm 9.0	-0.13, T	28.6 \pm 8.7	0.14, T
EccDur	0.238 \pm 0.085	0.263 \pm 0.074	0.29, S \uparrow	0.253 \pm 0.077	0.17, T	0.259 \pm 0.074	0.25, S \uparrow
ConDur	0.259 \pm 0.057	0.267 \pm 0.058	0.14, T	0.264 \pm 0.067	0.09, T	0.276 \pm 0.052	0.31, S \uparrow
TotalDur	0.498 \pm 0.138	0.531 \pm 0.128	0.24, T	0.518 \pm 0.138	0.15, T	0.536 \pm 0.122	0.27, S \uparrow
EccConMP	11.13 \pm 3.26	9.49 \pm 2.99	-0.50, M \downarrow	10.33 \pm 3.05	-0.25, S \downarrow	10.34 \pm 3.27	-0.24, T

[^] Effect sizes represent comparisons with baseline values only; T: Trivial, S: Small, M: Moderate, \uparrow : Increase, \downarrow : Decrease

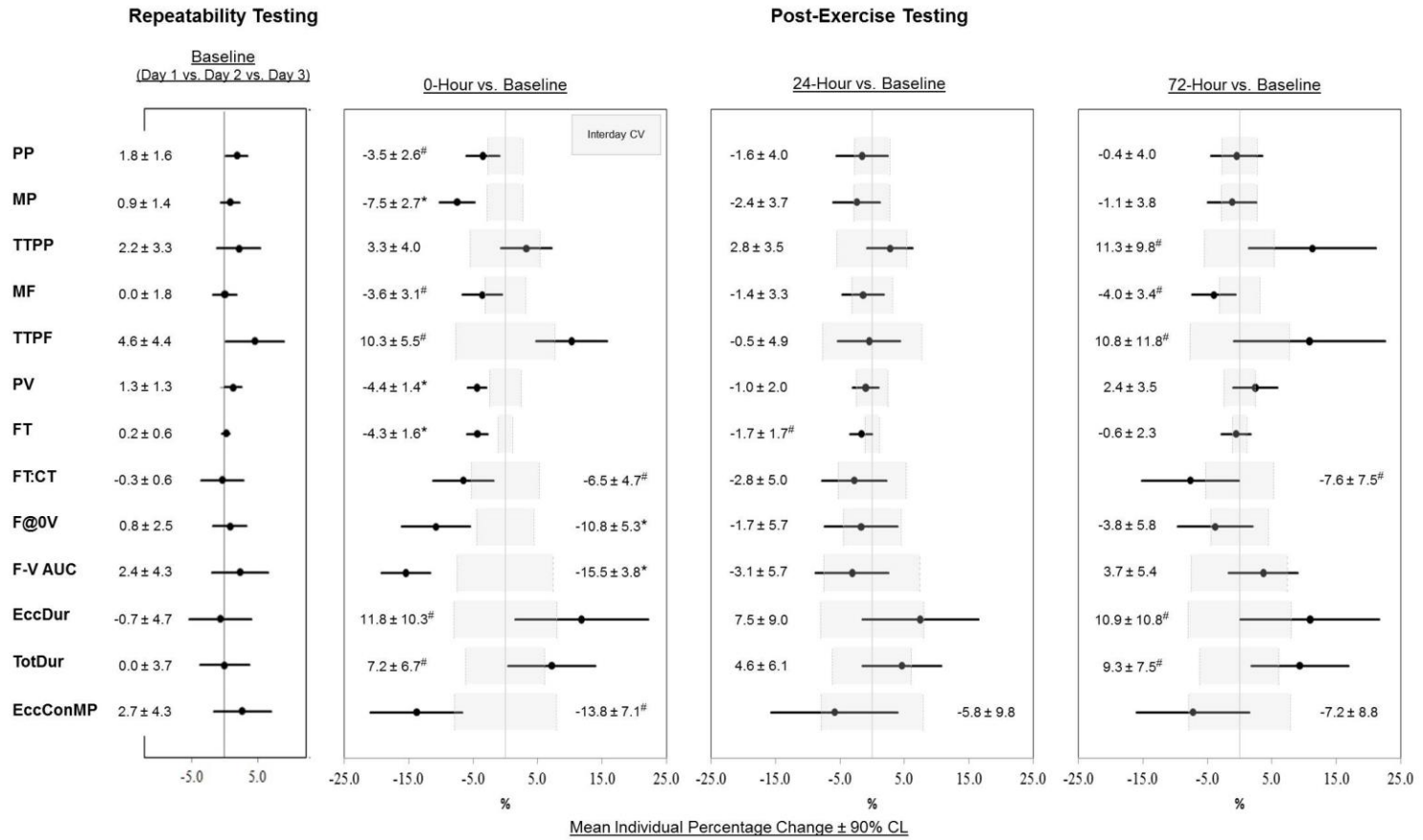


Figure 3-4: Mean and 90% confidence level (CL) for the percent change between baseline, 0-hour, 24-hour & 72-hour (select variables only), and the inter-day CV. Inter-day CV is shown in light grey. *mean ± CL change ≥ inter-day CV, #mean change ≥ inter-day CV.

3.5 Discussion

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

3.5.1 Repeatability

To our knowledge, this is the first study to have undertaken three consecutive days of controlled baseline testing on a multitude of CMJ parameters to assess repeatability, with previous studies using only one or two days (Cormack, Newton, McGuigan, & Doyle, 2008; Cronin et al., 2004; Meylan et al., 2011; Sheppard et al., 2008; Taylor et al., 2010). Attempts were made to enhance CMJ repeatability by averaging the most similar jumps within each session in terms of power output and jump duration, as determined by standardised selection criteria. This appears the first time that such an approach has been adopted with CMJ testing and, despite the relatively small sample (N=12), this novel approach provides insight into the practical value of such CMJ data manipulation processes.

Intra- and inter-day CV's of CMJ variables ranged from very low to quite high (1.1% - 16.2%; Table 3.2). Previous studies have adopted a CV of <10% as indicative of a reliable test measure (Cormack, Newton, & McGuigan, 2008; Cormack, Newton, McGuigan, & Doyle, 2008; Meylan et al., 2011; Sheppard et al., 2008; Taylor et al., 2010), and so, according to this criterion, most of the CMJ variables examined here can be considered reliable. Furthermore, out of the twenty-two CMJ variables assessed, sixteen intra-day and eleven inter-day exhibited CV's of <5%, suggesting that the CMJ test can produce highly consistent results. Our methods therefore appeared to enhance CMJ performance repeatability in collegiate athletes. Therefore, although elite athletes are generally associated with superior performance repeatability (Hopkins et al., 2001), we hypothesize that CMJ repeatability in elite athletes may also benefit from this approach.

Notably, the variables associated with an inter-day CV >5% are related to the eccentric phase of the jump and time (Table 3.2). Other investigations report similar findings for time-related variables (Cormack, Newton, McGuigan, & Doyle, 2008; Cronin et al., 2004; McLellan et al., 2011a; Meylan et al., 2011; Sheppard et al., 2008; Taylor et al., 2010). In the current study, participants were instructed to perform a quick countermovement before jumping as high as possible, and so power generation was emphasized. Variables such as PP, FT and JH (CV<5%) could therefore be considered representative of the CMJ 'outcome' or 'output'. In contrast, time- and eccentric function-related variables (CV>5%) relate to the movement preceding or producing these

outputs and have been used previously to examine CMJ mechanics (Cormie et al., 2009; Cormie et al., 2010b), and so may reflect the NM strategy of the jump. CMJ movement strategy may therefore be more variable than CMJ output. Interestingly, skilled performers are considered to exhibit greater movement variability in order to achieve consistent performance outcomes (Davids, Araújo, Vilar, Renshaw, & Pinder, 2013). The greater variability in NM strategy may therefore be a direct consequence of a propensity to maintain output, and so examination of movement behavior may provide key insight into fatigue-induced NM changes.

3.5.2 Fatigue Sensitivity

The mean distance covered by participants during the fatiguing protocol was less than elite soccer matches ($10950 \pm 1044\text{km}$ (Osgnach, Poser, Bernardini, Rinaldo, & di Prampero, 2010) and $10994 \pm 396.4\text{km}$ (Dellal et al., 2011)), but more than elite rugby league matches ($5573 \pm 1128\text{km}$ (McLellan, Lovell, & Gass, 2011b)). The protocol therefore likely elicited a level of neuromuscular load and fatigue to that typically experienced by the sub-elite participants.

Immediately post fatigue (0-hour) most CMJ variables demonstrated diminished function (Table 3.3 and 3.4). As previous investigations tend to report fewer CMJ variables (Boullosa et al., 2011; Johnston et al., 2013; McLean et al., 2010; McLellan et al., 2011a; Mooney et al., 2013) it is difficult to ascertain whether such widespread

fatigue-induced changes are typical. However, as noted by the authors, a “surprising” lack of change in CMJ variables was reported following an Australian Rules Football match, even though decreased MP, MF, FT and FT:CT and increased PP were observed (Cormack, Newton, & McGuigan, 2008). In spite of a significantly decreased PF, increased PP and JH were also reported following a fatiguing intermittent running protocol (Boullosa et al., 2011). Other researchers have also observed conflicting changes (Johnston et al., 2013; McLean et al., 2010).

Most variables drifted towards a return to baseline levels at 24-hour, with only EccConMP still displaying a small decrease (Table 3.3 and 3.4). Fewer studies appear to have examined fatigue-induced changes in CMJ performance 24-hour post-exercise. Rugby League matches decreased mRFD and PP (McLellan et al., 2011a), and FT (Twist, Waldron, Highton, Burt, & Daniels, 2011) at 24-hour, whilst an Australian Rules Football match was associated with diminished PP, MP, MF, and FT:CT (Cormack, Newton, & McGuigan, 2008). Interestingly, differences with baseline were greater at 24-hour following the Australian Rules Football match than at 0-hour, suggesting that NM function was more diminished than immediately post-match.

Conversely, at 72-hour, a host of variables exhibited divergent responses with baseline, implying contrasting effects on recovery, and possibly performance capacity. While CMJ output variables (i.e. PP, FT, PF) did not differ to baseline, MinV and TI were enhanced, suggesting improved NM function, but time- and rate-related variables revealed that the CMJ took longer to perform (Table 3.3 and 3.4; Fig. 3.4). Consequently,

despite improvements in some variables, participants took longer to produce the same output and so could still be considered fatigued. We did not test after this time-point, and so are unable to determine precisely when baseline NM function was restored, however recovery of FT following a Rugby League match has been reported to take 4 days (McLean et al., 2010), whilst changes in FT, MP, MF and FT:CT following an Australian Rules Football match were recovered by 72-hours (Cormack, Newton, & McGuigan, 2008). Recovery from fatiguing high-intensity intermittent exercise therefore appears to require at least 72-hours.

Also apparent in our results is the considerable between-individual variability in response to the fatiguing protocol (Fig. 3.4). For example, clearly detectable changes in most individuals were only evident at 0-hour and only for a select few variables. This appears to be the first time that attention has been paid to this feature of NM recovery, particularly in regards to CMJ testing; however, these results suggest that individuals exhibit marked differences in recovery profile, thus supporting the use of individualized monitoring, as well as recovery strategies. These CMJ monitoring strategies should include a battery of CMJ variables, reflecting the CMJ output and movement strategy, as well as individualized inter-day CV's and fatigue-detection thresholds.

3.5.3 Altered Movement Strategy in Response to Stretch-Shortening Cycle Fatigue

Our results show an immediate decrease in CMJ performance, a trend towards recovery at 24-hour, followed by another decrease at 72-hour, thereby mirroring the recovery time-course of SSC fatigue as shown previously (Komi, 2000; Nicol et al., 2006). SSC fatigue immediately decreases NM function through metabolic disturbances, impaired excitation-contraction coupling, and a stretch reflex sensitivity-related reduction in muscle stiffness (Avela et al., 1999; Nicol et al., 2006). The subsequent quick recovery relates to restoration of metabolic factors, although low frequency fatigue results if contractile failure has occurred (Avela et al., 1999). Mechanisms responsible for the changes subsequent to these are less clear with many neural and structural processes speculated to be involved (Nicol et al., 2006). Decreased reflex sensitivity is one process that is thought to protect fatigued muscle fibres from further damage (Avela et al., 1999). This mechanism primarily affects eccentric function and so may have contributed to the increased EccDur and time-related variables at 72-hour. Conversely, the small improvement in MinV at the same time-point suggests enhanced eccentric velocity production, possibly serving to limit concentric performance decrement during the secondary recovery phase.

As suggested previously, changes in time-related variables may reveal a shift in NM strategy of a CMJ, and so the increased time requirement at 72-hour could indicate that an alternative movement strategy was utilised. Previous studies have not directly

reported time-related variables, however a -7.8% change in FT:CT was reported alongside a -0.8% change in FT 24-hour following an Australian Rules Football match (Cormack, Newton, & McGuigan, 2008). Increased contraction time therefore appeared the primary factor in the decreased FT:CT. Strikingly similar results were observed here at 72-hour, with a -0.7% change in FT and a -7.7% change in FT:CT observed along with a 7.6% increase in TotDur.

The effect of fatigue on CMJ strategy has been examined using electromyography (Rodacki, Fowler, & Bennett, 2002). Although CMJ strategy was unchanged immediately following fatiguing exercise, the authors suggested that more time may be required to re-optimize neural strategies and alter CMJ technique. The 72-hour time point in the present study may therefore have provided sufficient time for an alternative strategy to develop. Skilled performers are considered capable of adjusting strategy in order to avert decreased task output (Knicker et al., 2011). However, different NM strategies may lead to decrements in other performance factors. For example, during an Australian Rules Football match NM fatigue has been found to alter how high speed running was performed (e.g. fewer accelerations/decelerations) but not the volume. This decreased movement economy was reflected in coaches' ratings of poor performance (Cormack et al., 2012; Mooney et al., 2013). The maintenance of CMJ output alongside increased jump duration in the present study may demonstrate similar changes in movement economy.

3.5.4 Alternative Analysis Methodology

Rather than one averaged value, we used four jumps from each participant at each time point, enhancing the sensitivity to differences compared to more traditional methods. Previous research has suggested that the use of multiple trials improves CMJ repeatability (Taylor et al., 2010). We utilised multiple trials, along with a unique standardized outlier removal procedure, to manage the influence of individual variability, and limit distortion of the *true* state of NM function by *uncharacteristic* trials. To our knowledge, this is the first time such procedures have been utilised with CMJ testing, with the method appearing to result in highly repeatable data.

Based on previously utilised methods (Cormack, Newton, McGuigan, & Doyle, 2008; Cormie et al., 2009; Cormie et al., 2010b), we examined fatigue-induced effects on time and eccentric-function (i.e. CMJ-ALT variables; Fig. 3.3 and 3.4, & Table 3.4), finding that NM fatigue induces extensive changes in CMJ mechanics. A novel start threshold based on a continuous change in power was also used to ensure that gross CMJ movement had begun. Previous investigations have used or suggested start thresholds related to absolute (McLellan et al., 2011a) or relative force changes (Cormack, Newton, & McGuigan, 2008; Cormack, Newton, McGuigan, & Doyle, 2008; Meylan et al., 2011), however these methods are prone to ‘false-starts’, where the onset of negative power development does not always occur instantly. Thus this approach may better standardize jump initiation time.

3.5.5 Practical Applications

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

3.5.6 Conclusions

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

4 Effect of acute fatigue and training adaptation on countermovement jump performance in elite snowboard cross athletes³

4.1 Abstract

Countermovement jump performance was examined in response to acute neuromuscular (NM) fatigue (study I) and chronic training (study II) in elite snowboard cross (SBX) athletes, through both typical (CMJ-TYP) and alternative (CMJ-ALT) CMJ variables. Seven (4M & 3F) elite (Olympic-level) SBX athletes participated in study I, and five of the same athletes (2M & 3F) participated in study II. CMJ variables relating to force, velocity, power and time were measured during both eccentric and concentric jump phases, with CMJ-TYP variables reflecting CMJ output and CMJ-ALT variables reflecting CMJ mechanics. In study I, CMJ performance was assessed before and after a fatiguing lower-body exercise protocol, and in study II) CMJ performance was examined before and after a 19-week structured training block. Meaningful differences in CMJ performance were examined using the magnitude of change (effect sizes; ES) for group

³ Gathercole, R.J., Stellingwerff, T., & Sporer, B.C. (Accepted June 2014) Effect of acute fatigue and training adaptation on countermovement jump performance in elite snowboard cross athletes. *Journal of Strength and Conditioning Research*. A version of this chapter was presented in poster format at the 36th National Strength and Conditioning Association Annual Conference in Las Vegas in July 2013.

and individual changes. Acute fatigue decreased peak force and eccentric function, while the duration of the jump increased. The structured training block increased peak force and eccentric function, while jump duration markedly decreased. In both study I and II, the largest ES were associated with CMJ-ALT variables. The CMJ test appears a suitable monitoring tool in elite SBX athletes for detection of both acute fatigue and training-adaptation. Compared to CMJ output, CMJ mechanics exhibit more marked and divergent changes following both acute NM fatigue and a structured training block. CMJ-ALT variables should therefore be incorporated into CMJ analysis.

4.2 Introduction

The countermovement jump (CMJ) test is commonly utilized in high performance sport to determine changes in neuromuscular (NM) function resulting from training and NM fatigue. CMJ analysis is typically limited to analyses of CMJ output (i.e. peak/mean values specifically relating to the concentric phase) such as jump height and peak power (Cormie et al., 2009). However, this approach provides limited information regarding the mechanical changes associated with longitudinal training-adaptation (Cormie et al., 2009) and fatigue.

The CMJ test variables most sensitive to fatigue in elite athletes is unclear (Taylor, 2012). Previous investigations have reported no decreases in CMJ output and concentric variables (e.g. jump height, peak power) following fatiguing exercise

(Boullosa et al., 2011; Cormack, Newton, & McGuigan, 2008); these variables may therefore lack the requisite sensitivity to detect fatigue-induced changes in NM function. In contrast, NM fatigue may also manifest as a deviation in technique or strategy (Gathercole, Sporer, Stellingwerff, et al., 2014; Knicker et al., 2011), which could have important implications for all activities, with a strong technical component, planned by coaches and/or conditioning specialists. Examination of CMJ force-velocity and power-time traces can provide insight into CMJ mechanics (Cormie et al., 2009; Gathercole, Sporer, Stellingwerff, et al., 2014); thus incorporation of such analyses into CMJ testing practice may reveal important information regarding athlete fatigue state.

Cormie and associates (Cormie et al., 2008, 2009; Cormie et al., 2010a, 2010b) have used analysis of CMJ mechanics to examine chronic training-induced changes in NM function, gaining insight into the nature of training-adaptation and the differences between athletes and untrained individuals (Cormie et al., 2009). However, no examination has yet been performed on the effect of structured training in an elite athlete group. Given their highly trained status, it is possible that elite athletes may exhibit different training effects compared to lesser trained athletes.

The 2014 Olympics in Sochi marked the third appearance of snowboard cross (SBX) at an Olympic games. However, at the time of writing, only seven articles have been published on the sport, with five of these focused specifically on injury rates. Evidently, while associated injury risks are clearly of significance, published research on SBX also appears lacking.

SBX is a demanding sport requiring high levels of aerobic fitness and leg power (Platzer, Raschner, Patterson, & Lemberg, 2009). SBX athletes therefore typically experience high levels of fatigue during training and competition. SBX also includes a large jumping component, with technical errors at jump take-off considered the cause of most SBX injuries (Bakken, Bere, Bahr, Kristianslund, & Nordsletten, 2011). Accordingly, fatigue-induced changes in jump mechanics as we (Gathercole, Sporer, Stellingwerff, et al., 2014), and others (Schmitz, Cone, Copple, Henson, & Shultz, 2013), have previously observed may be of much importance to both SBX performance and the injury risks associated. Moreover, given the importance of jumping to SBX performance, the assessment of CMJ mechanics may provide an additional means of identifying potentially beneficial training-induced adaptations. Consequently, utilization of acute and longitudinal CMJ testing could provide a highly relevant feedback tool in elite SBX training periodization.

The present study reports on two sub-investigations using a small cohort of elite SBX athletes (Olympic level), in which the suitability of the CMJ test to examine the effect of acute fatigue (Study I) and the effect of a 19-week training program on CMJ test performance (Study II) are examined. Here CMJ test performance is analyzed in two ways; through typical CMJ (CMJ-TYP) variables that typically relate to the CMJ output (i.e. concentric performance focused on jump outcomes; e.g. jump height, peak power), and alternative CMJ (CMJ-ALT) variables, referring to those variables that are less

common in CMJ analysis and relate to CMJ mechanics (i.e. the movement as a whole, describing both eccentric and concentric performance as well as jump duration).

4.3 Methods

4.3.1 Experimental Approach to the Problem

This investigation adopted a longitudinal descriptive design. Subjects were Olympic-caliber SBX athletes examined during their daily training environment; consequently participant numbers were small and no control group was included. In study I, participants performed CMJ testing prior to and 30-minute following a lower body fatiguing exercise protocol involving repeated stair climbs to fatigue. Pre-session data from study I was used in study II, with study II post-testing performed following a 19-week structured training period.

4.3.2 Subjects

Four male (26.5 ± 5.8 yrs, 86.2 ± 3.4 kg, 183.4 ± 3.8 cm) and three female (26 ± 6.1 yrs, 64.4 ± 4.5 kg, 165.7 ± 4.4 cm) national level snowboard-cross athletes participated in study I ($n=7$), whereas two of the same males (28.5 ± 9.2 yrs, 88.9 ± 2.1 kg, 181.6 ± 4.7 cm) and the same three female athletes participated in study II ($n=5$). Four athletes had at least one Olympic, World Championships or World Cup podium, and all had been on the World

Cup circuit a minimum of 3 years, recording multiple top 16 finishes. Informed consent and all aspects of data collection and management were conducted in accordance with the Declaration of Helsinki.

4.3.3 Procedures

In all testing sessions participants performed a set of six CMJ's. In study I, pre-testing was performed at approximately 0800 hours, with post-testing taking place at approximately 1030 hours, 30-minutes following the lower body fatiguing exercise protocol. On the day prior to Study I, participants performed a full body power workout and 60-minutes of low intensity cycling. The same pre-test data was used in both Study I and II. Post-testing in study II was performed at approximately 0800 hours. On the day prior to the post-training test session, participants performed an upper body max strength workout (approx. 1 hour 15 min) and 60-minutes of low intensity cycling, so a similar level of acute fatigue was present in athletes prior to testing. The same standardized warm-up was performed prior to all testing sessions.

4.3.3.1 Countermovement Jump Testing Session

Participants performed a 15-min dynamic warm-up consisting of light cycling (~5-min.), dynamic stretching (~5-min), 10m & 20m sprints (5 each) of progressive speed completed within 5 min. Participants then performed 5 practice CMJ trials of increasing intensity, with session testing beginning ~2 min after. The CMJ was a familiar

training exercise for participants, thus additional familiarization was deemed unwarranted.

Subjects performed six CMJ trials with 1 min rest between. Trials were sampled at 200Hz using the Ballistic Measurement System and software (BMS; Fitness Technology, Adelaide, Australia; Version 2012.3.7), consisting of a force plate (400 series, Fitness Technology, Adelaide, Australia) and position transducer (Celesco, PT5A-0150-V62-UP-1K-M6, Chatsworth, CA, USA) situated to the side of the force plate and attached to a wooden dowel. The dowel was placed across participants back, as in a back squat. Participants were instructed to limit dowel movement and the position transducer was zeroed to participant height prior to every jump. Data was collected immediately after zeroing until the jump was completed.

4.3.3.2 Experimental Protocols

The fatigue protocol performed in study I consisted of repeated stair climbs of different work-recovery durations. Participants were instructed to work at a perceived exertion of 9 out of 10. This approach has been found to be an adequate gauge of exercise intensity in elite athletes (Seiler & Sjørsen, 2004). Work-recovery durations comprised of a 1-min sprint followed by 5-min rest, 3x 45s with 4-min rest between, 3x 30s with 3-min rest between, 3x 10s with 1-min rest between and a final 1-min sprint. Total protocol time was ~35-min with 6-min 15s being all out maximal effort (~29-min of recovery time). The chronic training block performed in study II (Fig. 4.1) consisted of 19-weeks of various loading and unloading weeks as well as maintenance phases whilst athletes were

training on snow. Total hours of conditioning sessions are included in Figure 4.1. Study II took place during the precompetitive phase, and was directed by the head-coach to maximize performance outcomes and so was not a dependent variable in study II.

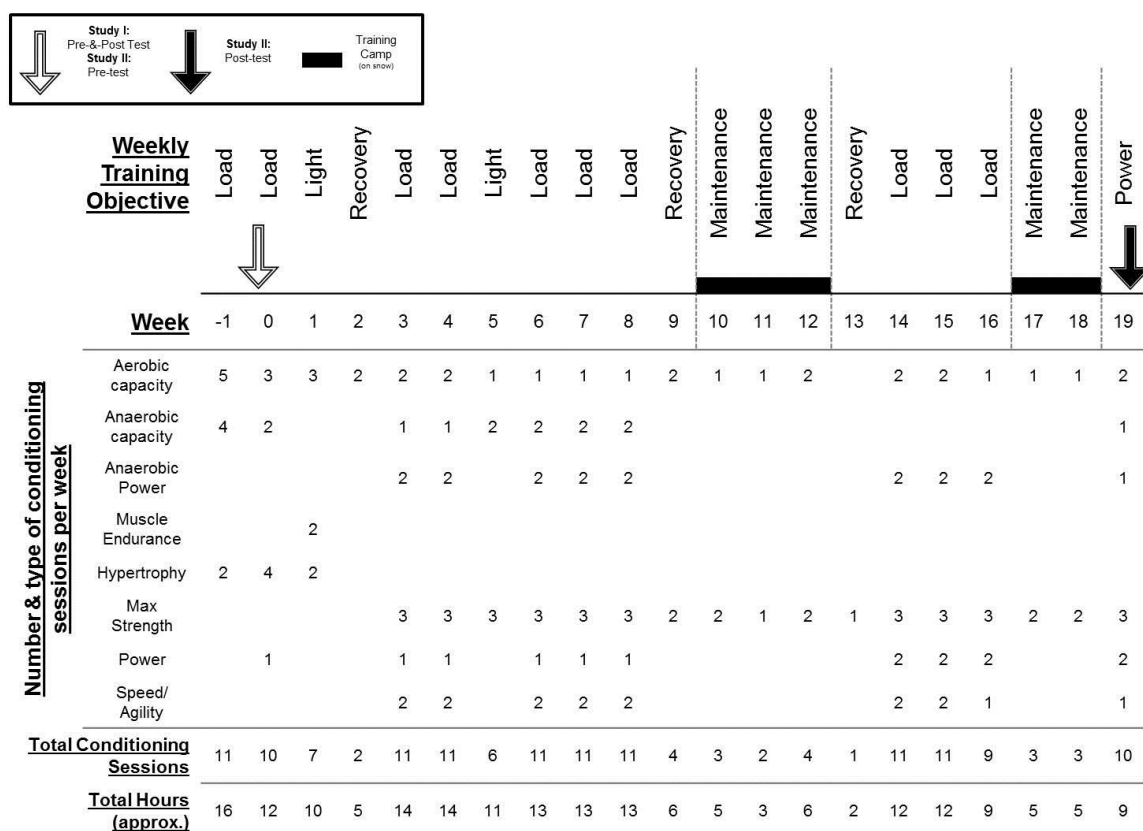


Figure 4-1: The 19-week training program, the number, type and total hours of conditioning sessions, and the period of pre-and post-testing for study I and II.

4.3.3.3 Countermovement Jump Variables

The techniques used to derive these variables have been described in detail by our laboratory previously (Gathercole, Sporer, Stellingwerff, et al., 2014). Briefly, the BMS software was used to calculate CMJ-TYP variables, while CMJ-ALT variables were calculated using custom-designed software written in Python (Python Software Foundation, www.python.org, USA). Relative force at zero velocity (F@0V) and area under the eccentric phase of the relative force velocity trace (F-V AUC) were calculated using the force-velocity trace (Fig. 4.2A). Mean relative eccentric and concentric power (EccConMP) and eccentric (EccDur), concentric (ConDur) and total duration (TotalDur) were calculated using the power-time trace (Fig. 4.2B).

4.4 Statistical Analyses

The four most consistent CMJ's from the six collected were used for analysis. Selection was based on our previously utilized methods which determined the four most similar jumps in terms of jump duration and mean power output using the EccConMP variable (Gathercole, Sporer, Stellingwerff, et al., 2014). The coefficient of variation (CV) was calculated using raw data. Other analyses were performed using log-transformed data, with back transformation post statistical analysis. Pre-to-post differences were examined through the magnitude of change. Effect sizes (ES) were based on within-individual variability (i.e. typical error; TE). Group ES were determined

using the mean TE in the pre-test session, whereas individual ES were determined using the TE for each individual within the pre-test session. The following inference thresholds used (trivial: <0.3 ; small: <0.9 ; moderate: <1.6 ; large: <2.5 ; very large: <4.0 ; extremely large: ≥ 4.0) (Hopkins et al., 2009; Twist & Highton, 2013). ES were based on previously utilized methods (Cormack, Newton, & McGuigan, 2008) and classified as substantial, probable, trivial or unclear. Substantial changes were identified when $\pm 90\%$ confidence intervals (CI) of the ES did not exceed either trivial ES boundaries (i.e. ± 0.3). Probable changes were determined when there was a $>75\%$ likelihood of the $\pm 90\%$ CI of the ES being equal to or greater than trivial ES boundaries. If the likelihood of the $\pm 90\%$ CI of the ES were $<75\%$ then ES were deemed trivial, while if the $\pm 90\%$ CI of the ES spanned both trivial ES boundaries then changes were deemed unclear.

4.5 Results

4.5.1 Study I

The intra-session CV ranged from 2.0% to 16.2% for all variables (Table 4.1), with smaller CV's generally observed for CMJ-TYP variables (intra-session CV's $<5\%$ (excluding JH)). Figure 4.2 shows the mean force-velocity and power-time traces for pre- and post-exercise for all athletes. The power-time trace clearly shows an increase in jump duration (EccDur and TotalDur; Table 4.1), while the force-velocity trace highlights the decreases in eccentric function (F@0V and FV-AUC; Table 4.1) post-exercise.

Body mass decreased pre-to-post exercise (pre: 76.0 \pm 12.8Kg; post: 75.1 \pm 12.7Kg). Eight CMJ-TYP and all CMJ-ALT variables displayed changes with ES greater than trivial (Table 4.1), while moderate and large changes were observed in peak and mean force, F@0V, F-V AUC, EccConMP, EccDur and TotalDur. Small increases were also observed in peak power, peak velocity and jump height.

Figure 4.3 illustrates the mean and 90% CL for the individual ES between pre- and post-exercise in comparison to the mean intra-session CV for select variables. Five variables (peak power, F@0V, EccConMP, EccDur and TotalDur) displayed probable or greater changes.

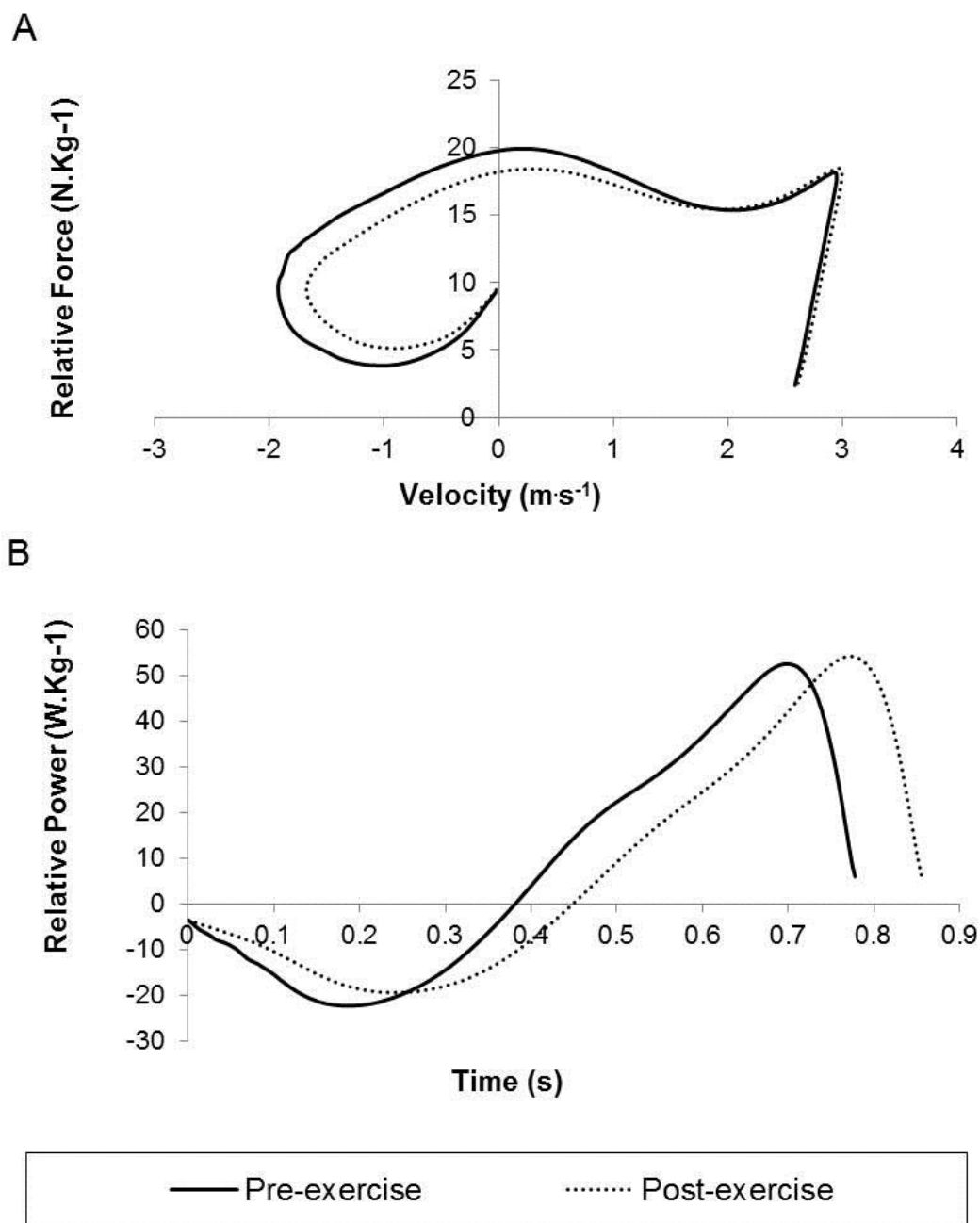


Figure 4-2: Acute fatigue (Study I): (A) Force-velocity and (B) power-time trace at pre- and post-exercise (n=7; 8 CMJ trials from each participant). Mean jump traces were calculated by normalizing each jump to the same number of data points. For the power-time trace, time was then reintegrated, with each jump standardized to the same 0-second start

Table 4-1: Acute fatigue effect (Study I): Group mean and SD, effect size (ES) and interpretation between pre- and post-exercise (n=7; 8 CMJ per participant) for A) CMJ-TYP and B) CMJ-ALT variables

	Pre (Mean ±SD)	Post (Mean ±SD)	%CV	ES (ES; interpretation)	
Absolute Peak Power (watts)	4093.9 ±1027.6	4205.8 ±998.5	3.9	0.70	Small ↑
Absolute Mean Power (watts)	2298.1 ±642.4	2287.9 ±632.0	3.1	-0.14	Trivial
Absolute Peak Force (N)	1571.4 ±395.8	1493.7 ±343.4	2.3	-2.15	Large ↓
Absolute Mean Force (N)	1220.8 ±253.0	1201.3 ±254.3	1.3	-1.23	Moderate ↓
Relative Peak Power (watts/Kg)	53.9 ±5.5	56.0 ±5.4	5.0	0.78	Small ↑
Relative Mean Power (watts/Kg)	30.2 ±3.9	30.5 ±3.9	4.0	0.25	Trivial
Relative Peak Force (N/Kg)	20.7 ±2.3	19.9 ±1.4	3.1	-1.25	Moderate ↓
Relative Mean Force (N/Kg)	16.1 ±0.8	16.0 ±0.9	2.0	-0.31	Small ↓
Peak Velocity (m.s ⁻¹)	2.98 ±0.30	3.03 ±0.24	4.7	0.36	Small ↑
Jump Height (m)	0.45 ±0.09	0.47 ±0.08	9.4	0.47	Small ↑
F@0V (N/Kg)	20.0 ±2.8	18.6 ±2.1	4.6	-1.52	Moderate ↓
F-V AUC (N/m.s/Kg)	21.2 ±10.4	16.9 ±8.0	16.2	-1.25	Moderate ↓
B EccConMP (watts/ms/Kg)	5.93 ±1.57	5.14 ±1.38	6.6	-2.02	Large ↓
EccDur. (s)	0.38 ±0.09	0.43 ±0.09	6.9	1.91	Large ↑
ConDur. (s)	0.39 ±0.01	0.40 ±0.02	2.9	0.88	Small ↑
TotalDur. (s)	0.77 ±0.09	0.83 ±0.11	4.1	1.90	Large ↑

F@0V: Force at zero velocity; F-V AUC: Force-velocity area under the curve; EccConMP: Mean eccentric and concentric power; EccDur: Eccentric duration; ConDur: Concentric duration; TotalDur: Total duration.

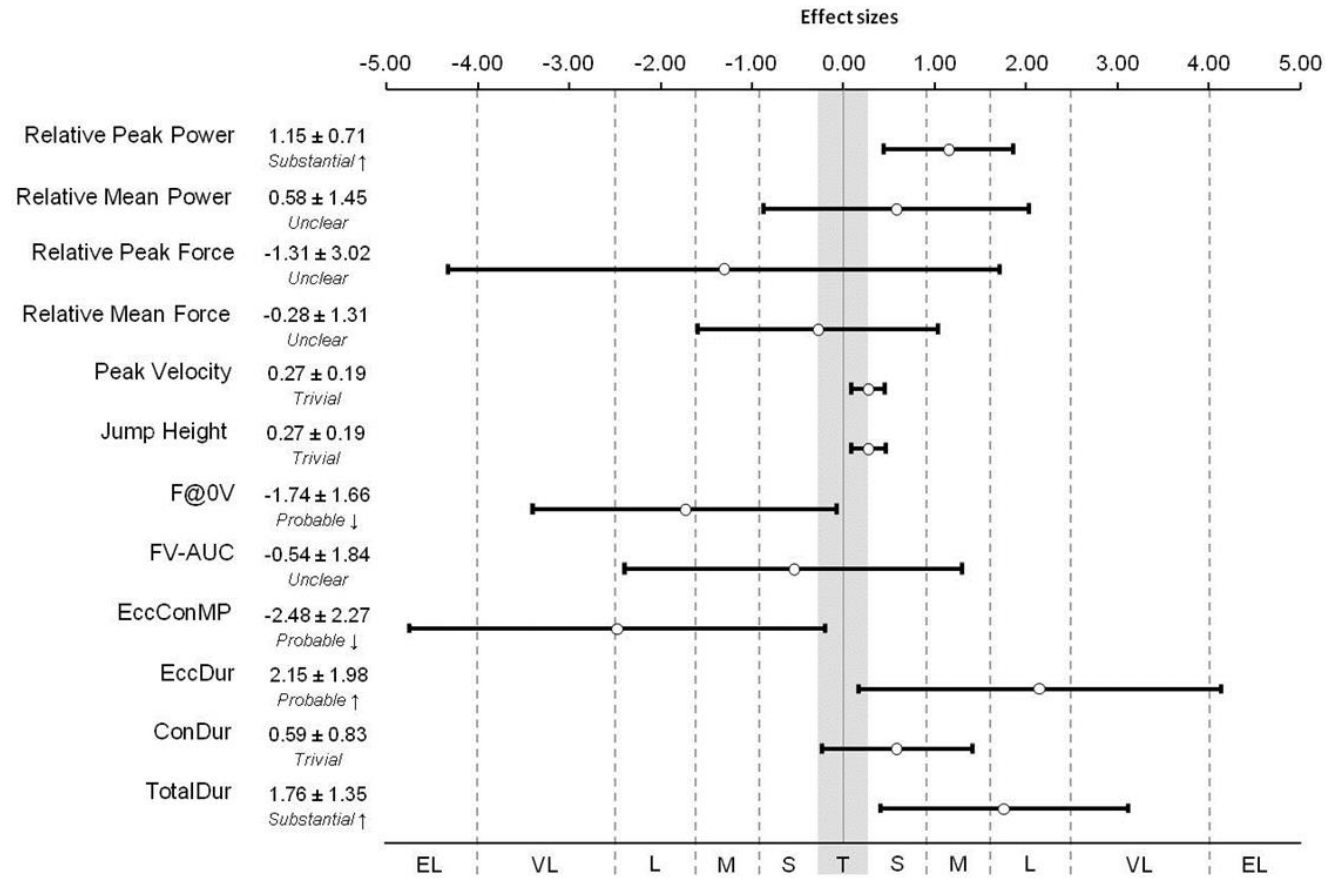


Figure 4-3: Acute fatigue (Study I): Effect sizes (ES) (mean ± 90% confidence limits (CL)) for the change between pre- and post-exercise. ↑: Increase, ↓: decrease; Substantial: ±90% CL's exceeds either ±0.3 (i.e. trivial ES); Probable: if >75% of ±90% CL exceeds beyond either ±0.3 ES; Trivial: if <75% of ±90% CL exceeds beyond either ±0.3 ES; Unclear: if ±90% CL exceeds both ±0.3 ES thresholds; T: Trivial, S: Small, M: Moderate, L: Large, VL: Very large, EL: Extremely large; Trivial ES boundaries are shaded in grey.

4.5.2 Study II

The intra-session CV ranged from 1.7% to 12.0% for all variables (Table 4.2). The mean force-velocity and power-time traces for pre- and post-training for all athletes are shown in Figure 4.4. The power-time trace highlights the increase in eccentric and concentric relative power production as well as decreased jump duration, while the force-velocity trace highlights the increase in eccentric loading and take-off velocity post-training.

Body mass was decreased post-training ($73.2 \pm 13.5\text{Kg}$; post: $71.1 \pm 14.3\text{Kg}$). Nine CMJ-TYP variables (all but absolute peak power) displayed post-training increases (Table 4.2), with large increases in peak force (absolute and relative), mean force, and peak and mean power (relative only). All CMJ-ALT variables exhibited large post-training changes, with increases in F@0V, F-V AUC and EccConMP, and decreases in EccDur, ConDur and TotalDur.

Nine variables (peak power, mean power, peak force, mean force, F@0V, F-V AUC, EccConMP, EccDur, ConDur, TotalDur) showed probable or greater changes (Fig. 4.5).

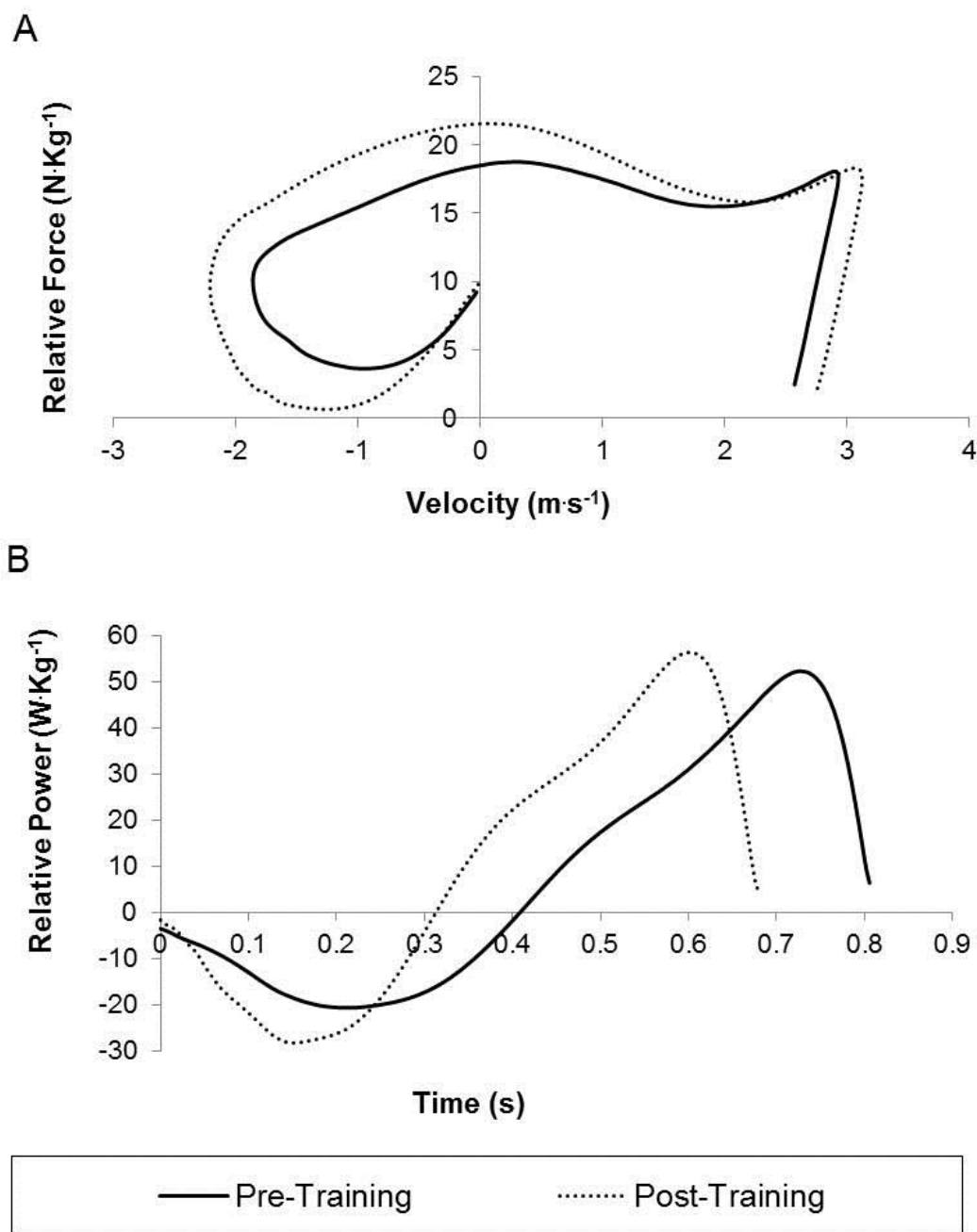


Figure 4-4: Chronic training (Study II): (A) Force-velocity and (B) power-time trace at pre- and post-training (n=5; 8 CMJ trials from each participant). Mean jump traces were calculated by normalizing each jump to the same number of data points. For the power-time trace, time was then reintegrated, with each jump standardized to the same 0-second start

Table 4-2: Chronic training effect (Study II): Group mean and SD, effect size (ES) and interpretation between pre- and post-exercise (n=7; 8 CMJ per participant) for A) CMJ-TYP and B) CMJ-ALT variables

	Pre (Mean ±SD)	Post (Mean ±SD)	%CV	ES (ES; interpretation)	
Absolute Peak Power (watts)	4093.9 ±1027.6	3938.2 ±969.3	4.7	0.17	Trivial
Absolute Mean Power (watts)	2298.1 ±642.4	2238.3 ±562.2	4.2	0.78	Small ↑
Absolute Peak Force (N)	1571.4 ±395.8	1559.1 ±353.6	3.0	2.93	Very Large ↑
Absolute Mean Force (N)	1220.8 ±253.0	1168.7 ±241.6	1.7	0.37	Small ↑
Relative Peak Power (watts/Kg)	53.9 ±5.5	56.9 ±4.9	4.3	1.52	Moderate ↑
Relative Mean Power (watts/Kg)	30.2 ±3.9	32.2 ±2.9	3.9	2.25	Large ↑
Relative Peak Force (N/Kg)	20.7 ±2.3	21.5 ±1.8	3.0	3.23	Very Large ↑
Relative Mean Force (N/Kg)	16.1 ±0.8	16.5 ±0.8	1.8	2.10	Large ↑
Peak Velocity (m.s ⁻¹)	2.98 ±0.30	3.08 ±0.28	5.1	0.59	Small ↑
Jump Height (m)	0.45 ±0.09	0.48 ±0.09	10.3	0.42	Small ↑
F@0V (N/Kg)	20.0 ±2.8	20.9 ±1.7	4.6	2.43	Large ↑
F-V AUC (N/m.s/Kg)	21.2 ±10.4	29.1 ±7.6	12.0	4.57	Extremely Large ↑
EccConMP (watts/ms/Kg)	5.93 ±1.57	7.45 ±0.80	5.5	6.58	Extremely Large ↑
EccDur. (s)	0.38 ±0.09	0.34 ±0.05	6.1	-2.80	Very Large ↓
ConDur. (s)	0.39 ±0.01	0.37 ±0.04	3.2	-1.60	Large ↓
TotalDur. (s)	0.77 ±0.09	0.71 ±0.08	4.0	-3.09	Very Large ↓

F@0V: Force at zero velocity; F-V AUC: Force-velocity area under the curve; EccConMP: Mean eccentric and concentric power; EccDur: Eccentric duration; ConDur: Concentric duration; TotalDur: Total duration.

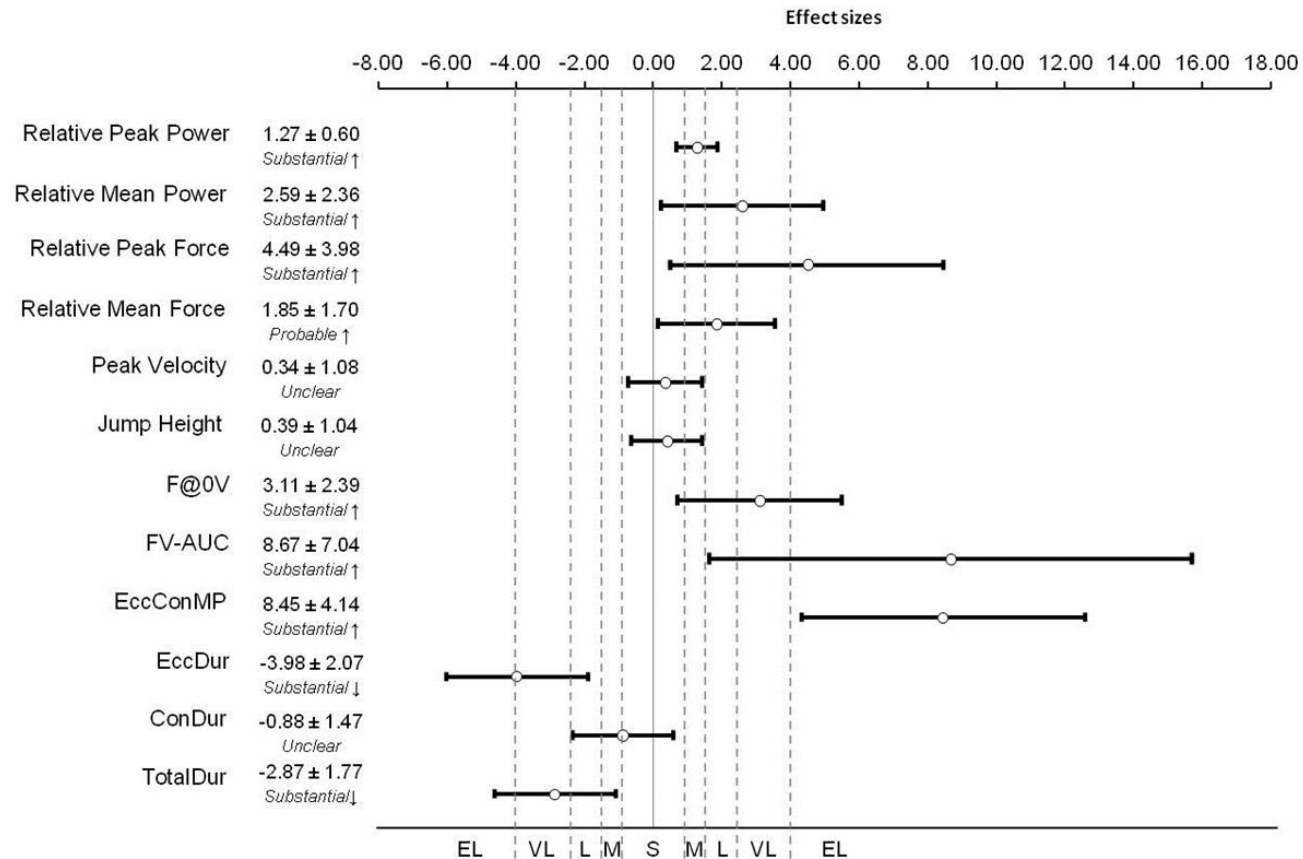


Figure 4-5: Chronic training (Study II): Effect sizes (ES) (mean \pm 90% confidence limits (CL)) for the change between pre- and post-training. \uparrow : Increase, \downarrow : decrease; Substantial: $\pm 90\%$ CL's exceeds either ± 0.3 (i.e. trivial ES); Probable: if $>75\%$ of $\pm 90\%$ CL exceeds beyond either ± 0.3 ES; Trivial: if $<75\%$ of $\pm 90\%$ CL exceeds beyond either ± 0.3 ES; Unclear: if $\pm 90\%$ CL exceeds both ± 0.3 ES thresholds; S: Small, M: Moderate, L: Large, VL: Very large, EL: Extremely large; Trivial ES not shown; Note: ES are calculated using pre-test within-session SD instead of inter-session SD. This may have contributed to the high ES observed.

4.6 Discussion

This two-part investigation examined the suitability of the CMJ test to monitor acute fatigue- (study I) and chronic training-induced changes (study II) in NM function in a group of world-class SBX athletes. Our results suggest that the acute fatiguing protocol decreased CMJ force production and prolonged jump duration. Conversely, chronic training decreased jump duration and increased force and power production. The larger magnitude of change typically evident with CMJ-ALT variables indicates that the changes associated with CMJ mechanics were greater than the CMJ output. CMJ testing, with examination of both CMJ-TYP and CMJ-ALT variables, therefore appears a useful athlete monitoring tool for both acute fatigue and training-induced adaptive responses in highly trained populations, particularly for athletes involved in large jumping-component sports such as SBX.

4.6.1 Effect of Acute Fatigue on CMJ Performance

To our knowledge this is the first investigation to examine fatigue-induced changes in CMJ mechanics (i.e. CMJ-ALT variables) specifically in a group of elite athletes. The workload, described in the methods, was targeted to an athlete's RPE score of 9 out of 10, which has been shown to induce significant fatigue previously (Seiler & Sjursen, 2004). We therefore speculate that athletes were acutely fatigued by the protocol.

CMJ-TYP variables displayed trivial to large group changes pre-to-post exercise in response to acute fatigue, with small increases observed in peak-power (PP), peak velocity and jump height. Previous studies have reported various PP changes following fatiguing exercise, with increases (Boullosa et al., 2011; Cormack, Newton, & McGuigan, 2008), no changes (Cormack, Newton, & McGuigan, 2008; Hoffman et al., 2002; Hoffman, Nusse, & Kang, 2003; Johnston et al., 2013; Thorlund, Michalsik, Madsen, & Aagaard, 2008) and decreases (Gathercole, Sporer, Stellingwerff, et al., 2014; McLellan et al., 2011a) all observed. These investigations utilised either specifically designed fatiguing protocols or competitive matches, and so the degree of fatigue likely differed. Interestingly, Cormack et al (Cormack, Newton, & McGuigan, 2008) reported increased relative PP but no change in absolute PP following a competitive Australian Rules Football match. The alternating use of absolute and relative values may therefore have also contributed to differences in the literature. Nevertheless, our results show similar changes for both relative and absolute PP and so it appears that PP production was perhaps enhanced, or at least maintained, despite acute fatigue.

In contrast, both absolute and relative peak force (PF) displayed large and moderate decreases post-exercise indicating decreased force-generating capacity. Previous research has reported decreased PF (Boullosa et al., 2011; Cormack, Newton, & McGuigan, 2008; McLellan et al., 2011a) or no changes (Hoffman et al., 2002; Hoffman et al., 2003; Johnston et al., 2013; Thorlund et al., 2008) following fatiguing exercise. In the current study, peak velocity and jump height both exhibited small increases post-

exercise. Although increased jump height and decreased PF appear contradictory, jump height was indirectly determined using take-off velocity and body mass, and so, as take-off velocity was fairly maintained (evident in Fig. 4.2) but post-exercise body mass decreased, so was jump height. Decreased peak velocity has been observed following a simulated handball match (Thorlund et al., 2008) and a fatiguing running protocol (Gathercole, Sporer, Stellingwerff, et al., 2014), while jump height has been found to increase (Boullosa et al., 2011), remain the same (Krustrup, Zebis, Jensen, & Mohr, 2010), or decrease (Andersson, Raastad, Nilsson, Paulsen, Garthe, & Kadi, 2008; Cormack, Newton, & McGuigan, 2008; Thorlund et al., 2008; Webb, Harris, Cronin, & Walker, 2012) following various fatiguing activities. Accordingly, fatiguing exercise appears to elicit inconsistent responses in CMJ-TYP variables, with factors such as athlete training status and genetic make-up, the multi-factorial mechanisms of fatigue, the activity performed, and the time following the fatiguing exercise bout, likely to contribute to the varied responses.

CMJ-ALT variables tended to be associated with larger post-exercise changes (Table 4.1 & Fig.4.2) and so may provide greater insight and sensitivity to NM fatigue compared to CMJ-TYP. In a previous study, we observed decreased F@0V, F-V AUC and EccConMP, and increased EccDur and TotalDur following a fatiguing running protocol (Gathercole, Sporer, Stellingwerff, et al., 2014). In contrast, Thorlund et al. (2008) reported no changes in eccentric, concentric and total CMJ duration following a simulated handball match. However, Thorlund et al. (2008) did not use the same

standardized jump start threshold as the present study and examined only one jump per participant, thus they may have lacked the sensitivity to detect such changes.

In the current study, post-exercise testing took place 30 minutes following exercise cessation. Post-activation potentiation dissipates after 5-6 minutes (Macintosh et al., 2012) and so the small increases in PP and peak velocity appear unlikely the result of a potentiating effect. Wadden, Button, Kibele, and Behm (2012) concluded that, at around 40 minutes following fatiguing stretch-shortening cycle exercise, decreases in PF were the result of mechanical changes within the muscle rather than central or metabolic changes. Meanwhile, excitation-contraction coupling failure has also been suggested to affect force production (Abbiss & Laursen, 2005), and so these mechanisms may explain the decreased PF observed here. Post-exercise changes in CMJ-ALT variables suggest that participants took longer to perform the jump and that eccentric function had diminished. The mechanical efficiency (i.e. the ratio of work performed to energy expenditure) of a CMJ is determined by the force produced and duration of the eccentric phase (McBride & Snyder, 2012). Our findings therefore indicate mechanical efficiency was decreased post-exercise, possibly through decreased elastic energy storage and utilisation (McBride & Snyder, 2012).

Changes in CMJ-ALT variables point to the adoption of an alternative CMJ NM strategy. Interestingly, our results suggest that concentric CMJ variables are not necessarily decreased as a result of a fatigue-induced shift in CMJ technique. Similar observations have recently been made by Schmitz et al (Schmitz et al., 2013), who found no change in jump height in response to fatiguing exercise, even though CMJ

biomechanics were markedly altered. Given that NM fatigue may elicit deviations in technique without decreases in capacity (Knicker et al., 2011), such observations likely reveal important information about an athlete's NM fatigue state. Accordingly, the detection of acute NM fatigue and its interpretation may be enhanced through incorporation of CMJ-ALT variables into CMJ analyses.

4.6.2 Effect of Chronic Training on CMJ Performance

To our knowledge, this is the first investigation to examine the effect of training on both CMJ mechanics and output in elite SBX athletes. Chronic training markedly improved CMJ performance, with moderate and greater improvements in both CMJ-TYP and CMJ-ALT variables (Table 4.2 & Fig. 4.5).

Notably, the post-training decrease in body mass contributed to many of the CMJ-TYP changes, as the largest changes tended to be demonstrated by the CMJ-TYP variables in their relative forms. Nevertheless, these changes would still confer a competitive edge in SBX. Previous investigations have reported increases in CMJ PP, PF, velocity and jump height following 10- (Cormie et al., 2010a, 2010b) and 12-weeks (Cormie et al., 2009; Jakobsen et al., 2012) of varied strength and power training regimens. However these investigations examined non-elite cohorts and so the extent of change, or potential room for increase, was likely greater than in trained elite athletes. For example, 4-weeks of strength- and speed-power training produced no change in absolute PP in elite rugby athletes (Argus, Gill, Keogh, McGuigan, & Hopkins, 2012).

These results mirror our findings, as we also observed no change in absolute PP post-training. It has been suggested that the extent of power development slows after a year of high performance training (McMaster, Gill, Cronin, & McGuigan, 2013), and so these SBX athletes may have had limited capacity to improve PP. Nevertheless, our results do highlight that although PP development may have been trivial, other components of NM function can still show marked improvements.

One such example is PF, which demonstrated very large improvements in both absolute and relative values, while individual mean ES showed extremely large changes (Fig.4.5). Training-induced improvements in PF are considered to result from morphological changes increasing contractile capacity (Cormie et al., 2010a; McMaster et al., 2013); therefore the chronic training performed here appeared to elicit such adaptations in the SBX athletes. Although the improvements in both PF and, to a lesser extent, peak velocity, may seem incompatible with the unchanged absolute PP, this is because PF does not occur at the same time as PP. This is illustrated in Figure 4.4A, which also displays the similarity in force produced at PP at pre- and post-training, despite the distinctly different PF. These results highlight that changes can occur within the CMJ movement that may be overlooked in traditional analyses.

Large changes in CMJ-ALT variables reveal that CMJ mechanics differed markedly between pre- and post-training, with post-training jumps taking substantially less time to perform with greater eccentric power production (Figure 4.4A & B). Previous studies have reported improved eccentric power production (Cormie et al., 2009; Cormie et al., 2010b) alongside decreased (Cormie et al., 2010a; Jakobsen et al., 2012) or

unchanged (Cormie et al., 2009; Cormie et al., 2010a) jump duration, following strength and power training. Determining the specific NM adaptations behind these observed changes in CMJ mechanics is complicated by many factors (e.g. muscle fibre composition or neural activation) (Cormie et al., 2010a), however the enhanced eccentric function and decreased jump duration point to a more time-efficient NM strategy. Improved eccentric capacity is considered the result of enhanced stretch-shortening cycle function, possibly through increased musculotendinous stiffness (Cormie et al., 2010b), and/or superior mechanical efficiency. Optimization of the stretch-shortening cycle is also thought to increase PF (Cormie et al., 2010a), possibly contributing to the large improvements in PF observed here. Therefore chronic training appeared to elicit marked changes in CMJ mechanics, possibly through improved stretch-shortening cycle function, thus the inclusion of CMJ-ALT variables into CMJ analysis appears to permit clearer interpretation of chronic training-induced changes in NM function.

A limitation of the present study design is the lack of control group. Since participants comprised of more than half of the nation's elite SBX athletes, and were in the midst of preparing for World and Olympic championships, an elite control group was not feasible and the use of a general population control group is unsuitable, as comparisons between these groups would be meaningless. To account for the small sample size, we have however based our analyses and interpretations on the magnitude of change. In addition, we collected four CMJ trials from each athlete at each time point, reducing the typical error of measurement (Taylor et al., 2010), and so we believe the precision of our measures to be greater than most previous CMJ investigations. Although

we lack a control group, the repeatability of CMJ-TYP variables is well established (Cormack, Newton, McGuigan, & Doyle, 2008; Gathercole, Sporer, Stellingwerff, et al., 2014; McLellan et al., 2011c; Meylan et al., 2011; Taylor et al., 2010), and has also been reported for CMJ-ALT variables (Gathercole, Sporer, Stellingwerff, et al., 2014). Moreover, Cormie and associates (Cormie et al., 2010b) observed that a control group maintaining normal activity levels displayed no changes in CMJ force-velocity data over a 10-week period. As such, the changes that we have observed here appear due to training effects alone.

These investigations clearly demonstrate that acute NM fatigue and a training block elicit marked changes in CMJ mechanics (i.e. CMJ-ALT), with the magnitude of these changes typically greater than associated with CMJ output (CMJ-TYP) variables. It is therefore recommended that practitioners incorporate CMJ-ALT variables into CMJ analyses practice in order to better determine the acute fatigue state of their athletes and/or to longitudinally assess NM training adaptations over weeks to months.

4.6.3 Practical Applications

Our investigations suggest that the CMJ test is a useful tool for monitoring both acute fatigue- and chronic training-induced changes in NM function. Nevertheless, current CMJ methodology (i.e. CMJ variables focusing on single-points (e.g. peak power) and/or jump output (e.g. jump height)) may overlook a wealth of information. For example, NM fatigue appeared to influence the CMJ strategy (i.e. mechanical and time-

efficiency of movement) more so than the CMJ output (Fig. 4.2), while chronic training elicited opposing effects (Fig. 4.4). Incorporation of CMJ mechanics (CMJ-ALT variables) into CMJ test analysis is therefore likely to enhance the usefulness of the CMJ test.

Given the importance of movement speed, timing, and mechanical efficiency in many sports, these results have many important performance and training implications. For example, in SBX, a longer duration spent achieving maximal push-off in response to a passing move or avoiding another rider will likely affect race outcome. Similarly, an indirect effect of decreased mechanical efficiency when fatigued may be an acceleration of further fatigue-induced performance declines through increased energy expenditure performing the same movement. Interestingly, the greatest injury risk in SBX is associated with technical error at jump take-off (Bakken et al., 2011). Fatigue-induced shifts in NM strategy, as revealed through CMJ testing approaches highlighted in this paper, may therefore directly relate to enhanced monitoring and the potential for reduced injury susceptibility. Consequently, in highly technical sports such as SBX, where altered or mistimed movement can result in injury, it is perhaps ill-advised for athletes to perform technical practices in a fatigued state.

5 Longitudinal countermovement jump performance with increased training loads in elite female rugby players⁴

5.1 Abstract

Purpose: CMJ performance was examined in elite female Rugby Sevens players during a training block involving progressively increased training loads. It was hypothesized that variables reflecting CMJ neuromuscular strategy would undergo marked changes in response to accumulated fatigue.

Methods: Twelve elite female Rugby Sevens athletes undertook weekly CMJ testing throughout a 6-week training block. Athletes self-reported training load (TRIMP) and wellness daily. 22 CMJ variables were assessed, incorporating analyses of force, velocity, power and time measured during both eccentric and concentric jump phases. Athletes were divided into overreached (OR) and non-overreached (Non-OR) groups *post-hoc* based on changes in peak power to provide insight into individual responses. Effect sizes (ES) based on between- and within-individual variability were used to examine between-group and time differences, respectively.

Results: From week 3, athlete wellness decreased (mean group ES: -0.35) while large increases in TRIMP (+2.11) were observed. Alongside these changes, group results

⁴ Gathercole, R.J., Sporer, B., & Stellingwerff, T. Manuscript in preparation.

showed marked responses indicative of diminished neuromuscular function in variables primarily reflecting CMJ output (flight time: -1.17; peak displacement: -1.42) and mechanics/eccentric function (time to peak force: +1.07; force at zero velocity: -1.15). OR group results mirrored overall group changes, however decreases were also demonstrated in some concentric CMJ variables (mean power: -1.48; peak/mean force: -1.43 and -1.62).

Conclusions: Neuromuscular fatigue accumulated through progressively increased training loads elicited marked changes in CMJ output and mechanics. To improve fatigue detection, practitioners should incorporate assessment of these neuromuscular components into current CMJ analysis practices.

5.2 Introduction

The countermovement jump (CMJ) test is a popular athlete monitoring tool, providing simple and practical means of assessing neuromuscular (NM) function and fatigue (Twist & Highton, 2013). CMJ testing has been utilised in both acute (Cormack, Newton, & McGuigan, 2008; Gathercole, Sporer, Stellingwerff, et al., 2014; Gathercole, Stellingwerff, et al., 2014; McLellan et al., 2011a) and longer-term (Cormack et al., 2013; Cormack, Newton, McGuigan, & Cormie, 2008; Coutts, Reaburn, Piva, & Rowsell, 2007; McLean et al., 2010; Mooney et al., 2013) settings to infer fatigue-induced NM changes. Although CMJ movement involves complex interaction of several components of NM function (McLellan et al., 2011c), including the stretch-shortening cycle (SSC),

most investigations typically examine only gross CMJ variables (i.e. peak, mean) relating to the concentric CMJ phase (Cormie et al., 2009). Consequently, the SSC (or eccentric) component and the strategies (or ‘mechanics’) used to perform a CMJ are not assessed (Gathercole, Sporer, Stellingwerff, et al., 2014), possibly contributing to the uncertainty in CMJ responses to training and fatigue (Cormack, Newton, McGuigan, & Cormie, 2008).

Fatigue is generally defined as an exercise-induced performance decrease, however it may also manifest as altered sport-specific or testing technique without deteriorated performance (Knicker et al., 2011). For example, maintenance of jump height has been observed alongside fatigue-induced shifts in the CMJ movement (Schmitz et al., 2013). Although NM output is maintained, fatigue-induced shifts in movement strategy may have important performance implications; for example, decreases in mechanical efficiency would increase the energy expenditure of movement (Byrne et al., 2004; McBride & Snyder, 2012) while increased movement duration may hamper performance in sports where timing is crucial (Gathercole, Sporer, Stellingwerff, et al., 2014; Gathercole, Stellingwerff, et al., 2014). Accordingly, through utilisation of techniques developed by Cormie and associates (Cormie et al., 2009; Cormie et al., 2010b) we have previously demonstrated acute fatigue-induced changes in eccentric function and CMJ strategy (Gathercole, Sporer, Stellingwerff, et al., 2014), however the effect of accumulated fatigue on these NM components remains unclear.

Further compounding interpretation is the variability in individual responses. The same training stimuli often elicits considerably different responses between individuals (Vollaard et al., 2009), while varying environments and activities performed all contribute to the type and extent of fatigue (Knicker et al., 2011). Therefore, given the many influencing factors and the between- and within-individual variability in response, it seems unlikely that a single CMJ variable can appropriately reveal NM fatigue in all circumstances. As such, most previous CMJ analysis methodologies may be inadequate. Instead, an approach capturing both outcome performance and CMJ NM mechanics (e.g. eccentric function) may be required, which we have recently published (Gathercole, Sporer, Stellingwerff, et al., 2014). Therefore the purpose of this investigation was to evaluate weekly changes in CMJ performance in elite female rugby 7's players over the course of a 6-week training block of progressively increasing training loads. We hypothesized that responses to increased training loads would be more evident in variables associated with CMJ mechanics and eccentric function than those reflecting concentric CMJ performance and jump output.

5.3 Methods

5.3.1 Participants and Familiarization

Twelve elite female national-team Rugby Sevens athletes (23.6 ± 4.3 yrs, 169.0 ± 5.6 cm, 69.5 ± 4.9 Kg, 89.9 ± 15.0 mm (sum of 7 skinfolds), participated in this 6-week longitudinal study. Following the study, nine athletes were selected for an

international tour, while the remaining three participated in a developmental tour. Ethical approval was obtained from the University of Victoria Human Ethics Review Board, with participants providing written informed consent. Initial familiarization took place fourteen days prior to week 1 testing and consisted of a standardized warm-up followed by at least 3 CMJ's or until participants were able to demonstrate consistent CMJ technique ($\sim 5 \pm 2$ attempts). CMJ's were considered consistent when displacement, velocity and peak power were within 10% of each other (Gathercole, Sporer, Stellingwerff, et al., 2014). A total of 2 to 3 familiarization sessions were performed 7 to 12 days prior to week 1 testing. During all CMJ trials, the speed of jump was emphasized rather than the depth achieved. Anthropometric assessment was performed prior to the first familiarization session. Leading in to the investigation, all athletes had completed a general preparatory training phase followed by a 4-day recovery phase featuring low intensity and volume training to minimize baseline residual fatigue.

5.3.2 Countermovement Jump Testing Session

CMJ testing was performed at the same time and day each week (Wednesday, 10:30am), while training load and wellness questionnaires were performed daily. Each participant performed similar activities prior to every weekly test session. Participants performed three practice CMJ trials, followed by three CMJ trials with 1 min rest between in the same testing groups of ~ 5 athletes/group. Trials were sampled at 200Hz using the Ballistic Measurement System and software (BMS; Fitness Technology,

Australia; Version 2012.3.7), consisting of a force plate (400 series, Fitness Technology, Australia) and position transducer (Celesco, PT5A-0150-V62-UP-1K-M6, Chatsworth, USA). The position transducer was suspended directly above the force plate and attached to the center of a wooden dowel; this dowel was positioned on the participants back similar to a back squat. Participants were instructed to limit dowel movement and the position transducer was zeroed to participant height prior to every jump. Data was collected immediately after zeroing until jump completion.

5.3.3 CMJ variables

BMS software was used to calculate typical CMJ variables (Table 5.2A) whereas alternative CMJ variables (Table 5.2B) were calculated using custom-developed software written in Python (Python Software Foundation, www.python.org, USA). The variables and techniques used to derive these variables have been described in detail by our laboratory previously (Gathercole, Sporer, Stellingwerff, et al., 2014). Briefly, relative force at zero velocity ($F@0V$; see arrow in Fig. 5.1A) and area under the eccentric phase of the relative force velocity trace ($F-V$ AUC; see shading in Fig.5.1A) were calculated using the force-velocity trace, whereas mean relative eccentric and concentric power (EccConMP) and eccentric, concentric and total duration were calculated using the power-time trace (Fig.5.2).

5.3.4 Training Load and Wellness

Training load was quantified by participants via multiplication of training duration (minutes) by intensity (ratings of perceived exertion, scale 1-10, easy to maximal) and referred to as the training impulse (TRIMP) (Foster et al., 2001). A 7-point scale questionnaire, based on the Hooper-Mackinnon questionnaire (Hooper & Mackinnon, 1995), examining sleep, stress, fatigue, soreness, illness, pain and desire to train was used to determine subjective ratings of wellness (1: very, very bad; 7: very, very good). Questionnaires were completed first thing in the morning, and a 7-day average wellness and 7-day cumulative TRIMP score for each week was used in further analysis.

5.3.5 Statistical analysis

To reduce the skew of mean data by uncharacteristic outlier jumps, two (of three) CMJ trials were used in further analysis with selection standardized and based on previous methods (Gathercole, Sporer, Stellingwerff, et al., 2014). Mean inter-session coefficient of variation (CV) and smallest worthwhile change (SWC; 0.2 multiplied by baseline standard deviation) for each CMJ variable were calculated using baseline testing sessions.

Peak power is considered vital to Rugby 7's performance (Ross, Gill, & Cronin, 2013) and sensitive to overreaching (Meeusen et al., 2013), and so was selected *post hoc* as the discriminating variable for overreaching (OR) and non-overreaching (Non-OR), as

no direct measure of Rugby 7's performance exists. OR and Non-OR grouping were based on whether peak power increased from baseline to week 6, with an increase determined as a change greater than peak power CV (Non-OR) or a change less than the CV (OR). OR and Non-OR classifications were based on decreased performance or stagnation of improvement specified in the definition of overreaching syndrome (Buchheit et al., 2010; Meeusen et al., 2013).

Excluding CV, data was log-transformed, with CMJ data modelled via linear mixed modeling (IBM SPSS Statistics, vers.20, IBM Corp, USA). Differences over time were examined through comparison with baseline. Between-group comparisons were performed at each time-point. A confidence interval based approach (Hopkins et al., 2009) was used to identify substantial changes, when confidence limits (CL) did not extend beyond baseline or group means. For TRIMP, wellness and between-group CMJ comparisons, effect sizes (ES) were based on between-individual variability, with associated inferences as described by Hopkins (Hopkins et al., 2009). For within-group CMJ comparisons over time, ES were based on within-individual variability, with CV multiplied by 0.3, 0.9 and 1.6 for small, moderate and large effects (Twist & Highton, 2013), respectively.

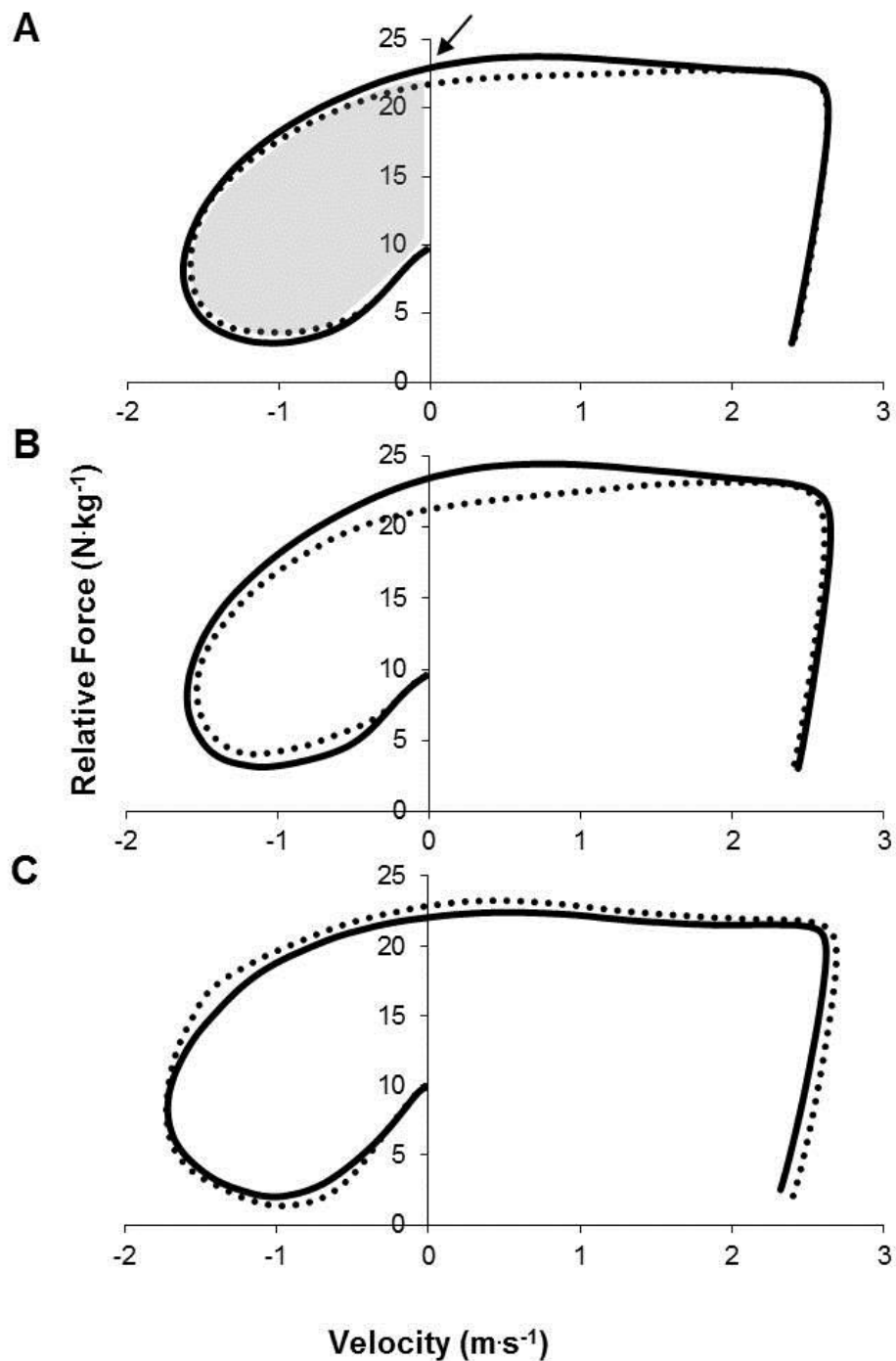


Figure 5-1: The mean force-velocity trace for A) all group, B) OR and C) Non-OR groups at baseline (black line) and week 6 (dotted line). The arrow and grey shading indicate force at zero velocity ($F@0V$) and area under the force velocity trace ($F-V$ AUC), respectively.

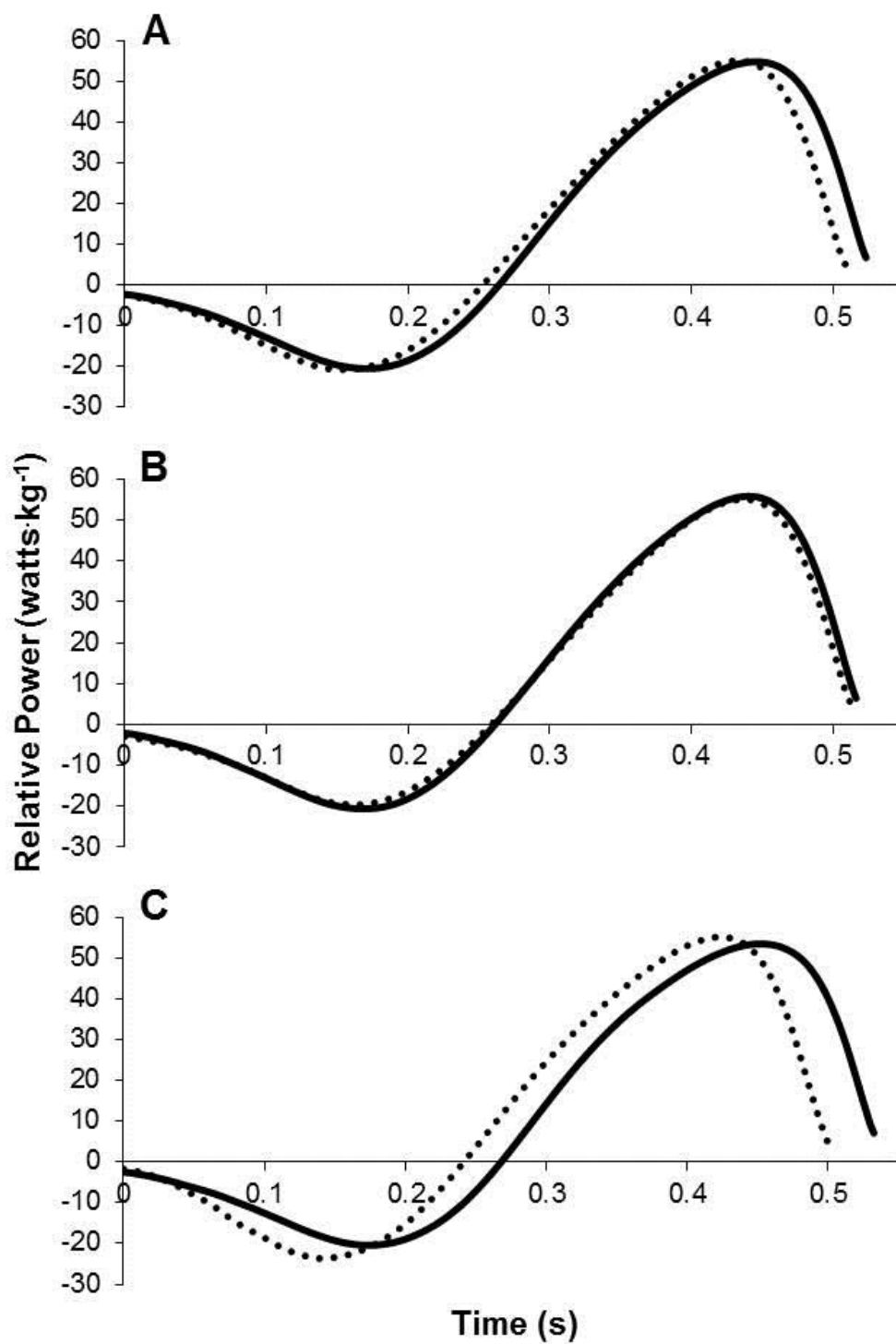


Figure 5-2: The mean power-time trace for A) all group, B) OR and C) Non-OR groups at week 1 (black line) and week 6 (dotted line).

5.4 Results

5.4.1 Participants

Twelve subjects completed 5 ± 1 CMJ monitoring sessions over the 6 weeks, with seven completing all sessions. At week 6, five participants exhibited peak power changes ($+3.3\%$) greater than the CV (Table 5.1) and so were classified as Non-OR. Peak power changes for OR and Non-OR groups were $-98\pm 120\text{W}$ (*Mean \pm SD*; $-2.6\pm 3.2\%$) and $244\pm 129\text{W}$ ($6.1\pm 3.2\%$), respectively. Statistical analysis revealed no differences in subject characteristics between OR and Non-OR groups, however first year athletes appeared disproportionately grouped in the Non-OR (3 of 5) compared to OR (1 of 7 athletes).

5.4.2 Training loads and wellness

TRIMP and wellness results for the group and OR and Non-OR groups are shown in figures 5.3 and 5.4, respectively. Group TRIMP substantially increased from week 2 onwards, with large increases at weeks 2, 3, 4 and 6 (Fig. 5.3). Compared to baseline, TRIMP substantially increased from week 1 and week 2 for OR and Non-OR groups, respectively (Fig. 5.4). Large increases were observed at weeks 2, 3, 4 and 6 for both OR and Non-OR groups. Substantial between group differences were evident at weeks 1, 3 and 6; while effect sizes compared to baseline TRIMP were typically larger in the OR group (all weeks excluding week 5). Group wellness displayed small decreases at weeks

3, 5 and 6 (Fig 5.3). Excluding baseline, the OR group reported substantially lower wellness scores than Non-OR.

5.4.3 CMJ variables

Table 5.1 shows the mean inter-session CV and SWC for all CMJ variables. Mean Group, OR, and Non-OR baseline and week 6 force-velocity and power-time traces are shown in figures 5.1 and 5.2, respectively. Group mean traces show small decreases in F-V AUC and F@0V (Fig. 5.1A), and a shortened total duration (Fig. 5.2A) at week 6. Decreases in F-V AUC and F@0V were evident in OR group week 6 mean trace (Fig. 5.1B), whereas the power-time trace was largely unchanged (Fig. 5.2B). In contrast, the Non-OR week 6 traces showed increased F-V AUC (Fig. 5.1C), and peak power, as well as decreased duration variables (Fig. 5.2C).

5.4.4 CMJ performance during monitoring period

Compared to baseline, group results revealed several variables displaying moderate to large changes indicative of decreased performance (Table 5.2). Other variables displayed no notable changes. Moderate decreases were found in peak and mean force on week 3 (ES: -1.10, -1.03), and FT:CT on weeks 3 and 6 (-1.15 & -1.03). Substantial changes were observed in F@0V, time to peak force (TTPF), peak displacement and flight time (Fig. 5.3). Moderate changes were displayed in TTPF (Mean

ES: +1.07) and peak displacement (Mean ES: -1.42) from week 3 and 4, respectively. Flight time (Mean ES: -1.17) and F@0V (Mean ES: -1.15) decreased on weeks 3, 5 and 6.

5.4.5 OR and Non-OR groups during monitoring period

For variables with meaningful changes, time and between OR and Non-OR group differences are displayed in Table 5.2, with selected variables shown in Figure 5.4. All OR group changes were indicative of diminished performance. Peak displacement, TTPF, flight time and FT:CT substantially decreased from week 3. Mean power, peak and mean force, and F@0V also decreased on weeks 3, 5 and 6, while peak power decreased on week 5 only.

The Non-OR group exhibited two changes indicative of diminished performance (week 1: FT:CT; week 3: TTPF). A number of variables exhibited improved function, with peak power and F-V AUC increased on multiple weeks from week 1. Mean power, peak and mean force, FT:CT, F@0V and total duration also exhibited improvement from week 4.

Baseline between-group comparisons revealed larger peak displacement and flight time in the OR group (Table 5.2), however subsequent differences were not observed. From week 1, OR group peak and mean power were lower, while peak force was lower on weeks 1, 3, 5 and 6. Multiple between-group differences were also evident for mean

force, TTPF, F@0V and F-V AUC, with all differences indicative of superior Non-OR group function.

Table 5-1: Mean and SD for the intra-session coefficient of variation (CV) and the smallest worthwhile change (SWC). A) Typical and B) Alternative variables

	Inter-Session CV		SWC	
	Mean \pm SD (%)	raw	%	raw
A				
Peak Power (W)	3.3 \pm 0.7	131.2	1.7	67.6
Mean Power (W)	4.3 \pm 1.1	101.7	2.1	48.4
Max RPD (W·s ⁻¹)	6.1 \pm 2.3	384.1	4.5	294.3
Time to Peak Power	4.8 \pm 2.3	0.030	3.2	0.020
Peak Force (N)	3.1 \pm 1.6	52.1	2.9	49.3
Mean Force (N)	2.5 \pm 0.8	34.2	2.4	32.4
Max RFD (N·s ⁻¹)	17.2 \pm 9.6	1631.8	7.0	716.4
Time to Peak Force (s)	8.4 \pm 6.9	0.042	3.7	0.019
Peak Velocity (m·s ⁻¹)	3.0 \pm 0.8	0.08	0.8	0.02
Minimum Velocity (m·s ⁻¹)	6.1 \pm 2.5	0.10	2.4	0.04
Velocity at Peak Power (m·s ⁻¹)	3.3 \pm 0.9	0.09	1.0	0.03
Peak Disp. (m)	4.8 \pm 2.3	0.018	1.6	0.006
Minimum Disp. (m)	6.6 \pm 3.1	0.028	4.1	0.017
Total impulse	3.3 \pm 1.2	11.79	1.6	5.62
Flight Time (s)	2.5 \pm 0.8	0.012	1.0	0.005
FT:CT (s)	4.9 \pm 2.6	0.034	3.4	0.024
B				
Relative F@0V (N·Kg ⁻¹)	3.7 \pm 2.3	0.84	2.0	0.45
Relative F-V AUC (N·m ⁻¹ ·Kg ⁻¹)	13.6 \pm 6.6	2.93	3.6	0.79
EccConMP (W·Kg ⁻¹ ·s)	9.2 \pm 4.5	0.83	6.2	0.60
Eccentric Duration (s)	8.1 \pm 3.5	0.021	5.7	0.016
Concentric Duration (s)	4.4 \pm 2.1	0.011	3.3	0.009
Total Duration (s)	5.5 \pm 2.5	0.028	4.5	0.024

Only the data relating to the 12 subjects included in further analysis is shown. Raw values are based on the group mean at baseline. Peak Disp: Peak displacement; FT:CT: Flight-to-contraction time ratio; Rel. F@0V: Relative force at zero velocity; Rel. F-V AUC: Area under the eccentric phase of the relative force-velocity trace. EccConMP: Mean Eccentric and Concentric peak power.

Table 5-2: Qualitative inferences and mean effect size for the differences over time compared to baseline within OR and Non-OR groups and OR versus Non-OR groups (Vs. line) for the CMJ variables.

	Baseline	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
Peak Power (W)	OR					-1.25; M↓	
	Non-OR	1.05; M↑	1.03; M↑			¥2.32; L↑	1.80; M↑
	Vs.	¥-1.00; M↓	¥-1.00; M↓	¥-1.03; M↓	¥-0.89; M↓	¥-1.83; L↓	¥-1.45; L↓
Mean Power (W)	OR			-1.12; M↓		¥-1.73; L↓	-1.58; M↓
	Non-OR					1.01; M↑	0.91; M↑
	Vs.	-0.89; M↓	-0.78; M↓	¥-1.08; M↓	-0.77; M↓	¥-1.71; L↓	¥-1.60; L↓
Peak Force (N)	OR			-1.69; L↓		-1.54; M↓	-1.06; M↓
	Non-OR					1.52; M↑	1.53; M↑
	Vs.	-0.66; M↓		-0.77; L↓		¥1.08; M↓	¥-0.98; M↓
Mean Force (N)	OR			-1.45; M↓		-1.85; L↓	-1.56; M↓
	Non-OR					1.50; M↑	1.18; M↑
	Vs.					¥-0.98; M↓	¥-0.85; M↓
Time to Peak Force (s)	OR			0.99; M↑	1.08; M↑	¥1.60; M↑	¥2.14; M↑
	Non-OR			0.99; M↑			
	Vs.				0.66; M↑	0.85; M↑	¥1.51; L↑
Peak Disp. (m)	OR		¥-1.12; M↓	¥-1.08; M↓	¥-1.77; L↓	¥-2.29; L↓	¥-1.89; L↓
	Non-OR						
	Vs.	0.80; M↑					
Flight Time (s)	OR			¥-1.62; L↓	-1.44; M↓	¥-2.31; L↓	¥-2.30; L↓
	Non-OR						
	Vs.	¥1.14; M↑					
FT:CT (s)	OR			-1.44; M↓	-0.90; M↓	-1.90; L↓	-2.27; L↓
	Non-OR					1.09; M↑	
	Vs.						
Rel. F@0V (N·Kg ⁻¹)	OR			¥-1.91; L↓		¥-2.68; L↓	¥-2.47; L↓
	Non-OR				1.08; M↑		
	Vs.			-0.65; M↓		-0.84; M↓	¥-1.11; M↓
Rel. F-V AUC (Nm ⁻¹ ·Kg ⁻¹)	OR						
	Non-OR		0.95; M↑	1.06; M↑	1.03; M↑		1.21; M↑
	Vs.			¥-1.18; M↓	-0.65; M↓	¥-0.87; M↓	¥-1.51; L↓
Total Duration (s)	OR						
	Non-OR						-1.27; M↓
	Vs.						

Peak Disp: Peak displacement; FT:CT: Flight-to-contraction time ratio; Rel.F@0V: Relative force at zero velocity; Rel.F-V AUC: Area under relative force-velocity trace during eccentric phase. ¥ indicates substantial change. Effect sizes: M= Moderate; L= Large; ↑: Increase; ↓: Decrease; Note: Decrease in between-group comparisons indicates that OR group is lower than Non-OR group, vice-versa.

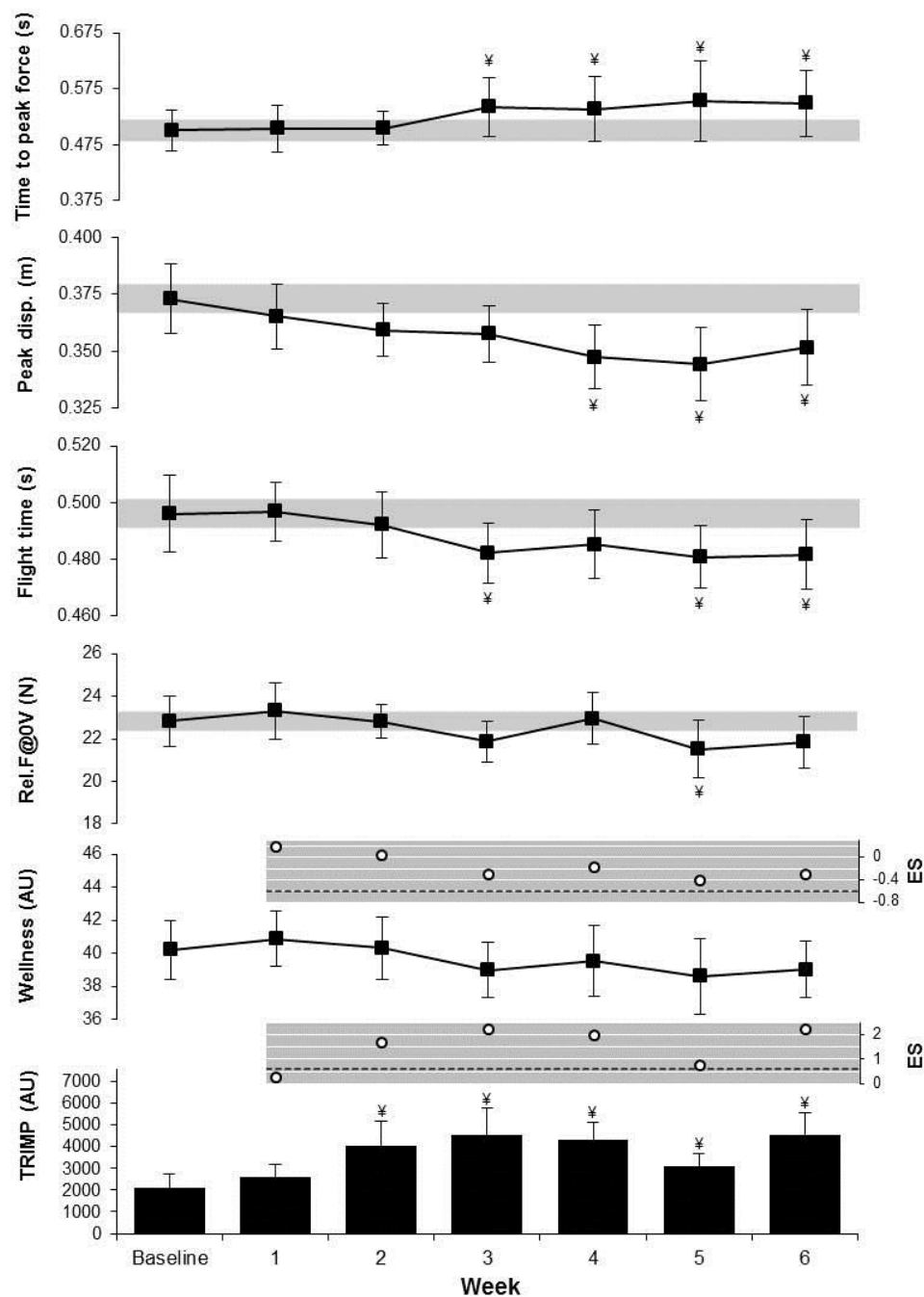


Figure 5-3: Mean and 90% CL for time to peak force, peak displacement (peak disp.), flight time, relative force at zero velocity (Rel.F@0V), wellness and TRIMP for the whole group at each time point. * indicates substantial differences compared to baseline. Shaded areas represent moderate changes in each variable (based on mean group coefficient of variation; CV). Effect sizes (ES; white circles; based on whole group between-subject SD) are shown for wellness and TRIMP, with the dashed lines representing the moderate ES threshold (i.e. ± 0.6).

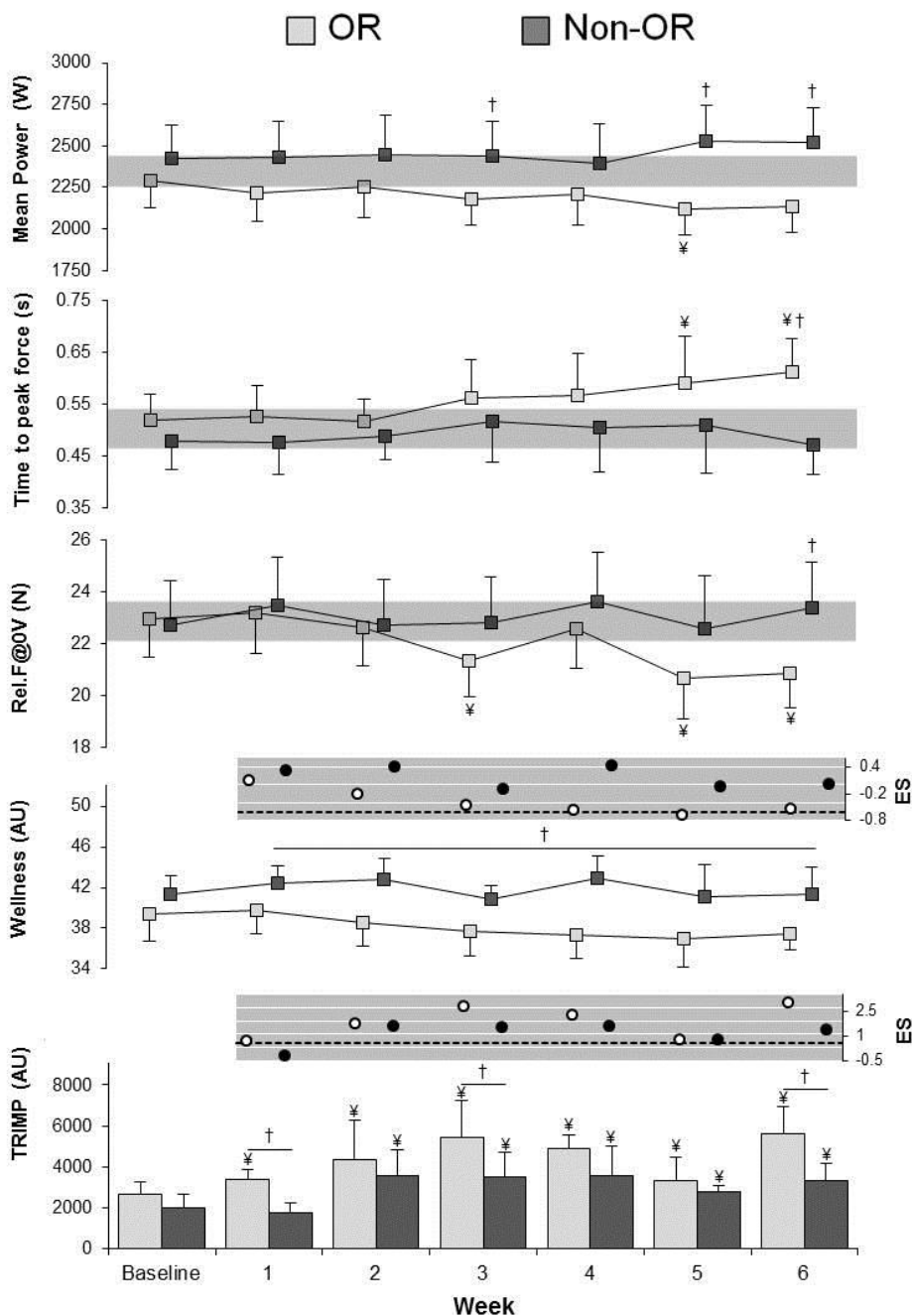


Figure 5-4: Mean and 90% CL for peak power, time to peak force, relative area under the eccentric phase of the force-velocity trace (Rel.F-V AUC), wellness and TRIMP for OR and Non-OR groups at each time point. ‡ indicates substantial differences compared to baseline. † indicates substantial differences between OR and Non-OR groups. Shaded areas represent moderate changes in each variable (based on mean group CV). ES (based on between-subject SD for OR and Non-OR groups separately) are shown for wellness and TRIMP, with dashed lines representing moderate ES threshold (i.e. ± 0.6). OR and Non-OR groups are represented by white and black circles, respectively.

5.5 Discussion

The purpose of this investigation was to utilise CMJ performance to detect accumulated fatigue-induced changes in neuromuscular (NM) function during a high load 6-week training block in elite female rugby players. Through analysis of both common and alternative CMJ variables we believe this to be one of the most comprehensive longitudinal NM fatigue studies in elite team-sport athletes. Throughout the training block, athlete perceptions of wellness decreased alongside increased self-report training load (TRIMP). Several CMJ variables (flight time, peak displacement, TTPF) appeared sensitive to the increased TRIMP scores, indicating diminished NM function; especially in a sub-group of overreached athletes.

5.5.1 TRIMP and Wellness

Group TRIMP scores ranged from 2092AU (baseline) to 4537AU (week 6; Fig. 5.3), corresponding with pre-season training values reported in professional rugby union athletes (Argus, Gill, Keogh, Hopkins, & Beaven, 2009). Weeks 3, 4 and 6 saw TRIMP and wellness trends characteristic of increased training load and decreased tolerance, while at week 5 the reduced TRIMP but diminished wellness suggests lingering fatigue from preceding weeks (Fig. 5.3).

To gain insight into individual responses, we formed two sub-groups based on peak power change from baseline to week 6. As described in methods, non-overreached athletes (Non-OR) were defined as showing a change in peak power (group *mean*±*SD*: $6.1\pm 3.2\%$) greater than the CV (3.3%), with overreached (OR) athletes displaying no change in peak power (less than the CV: $-2.6\pm 3.2\%$). TRIMP and wellness differences were increased in both groups across 6 weeks (Fig. 5.4), and evident between these groups, with OR athletes reporting very large TRIMP increases on weeks 1, 3 and 6 compared to non-OR (Fig. 5.4). The OR group nevertheless progressively decreased in wellness whereas levels were maintained in the Non-OR group. Decreased self-reported mood and wellbeing are established as overreached symptoms (Halson & Jeukendrup, 2004) and may enable discrimination between adapting and non-adapting athletes (Coutts, Slattery, & Wallace, 2007). Accordingly, the differing TRIMP and wellness trends between OR and non-OR groups appear to support our athlete classifications based on peak power changes.

5.5.2 CMJ performance changes over the monitoring period

Logistical realities prevented most athletes from performing CMJ testing until after the first daily training session, thus distinguishing between CMJ responses of acute and/or accumulated NM fatigue is difficult. In contrast, athlete wellness was determined before training, and so should represent accumulated fatigue only. Ideally, combination

of perceptual data with decreased performance are advocated for fatigue monitoring (Twist & Highton, 2013). Accumulated fatigue was therefore determined when wellness was decreased alongside prolonged suppression (i.e. over multiple time-points) of a CMJ variable. In contrast, acute fatigue was inferred when a CMJ variable was temporarily decreased (i.e. a single time-point), irrespective of wellness state.

Peak displacement, TTPF (time to peak force), flight time and, to a lesser extent, F@0V displayed substantial and prolonged diminished values from week 3 (Fig. 5.3). These variables may therefore prove key simple group indicators of accumulated NM fatigue. As minimum displacement demonstrated no marked changes, the decreased peak displacement and flight time likely reflect decreased height attained during the jump. Interestingly, the unchanged velocity variables meant that jump height calculated through peak velocity was likewise unchanged. Similar observations have been made previously (Cormack, Newton, & McGuigan, 2008; Gathercole, Stellingwerff, et al., 2014), thus this method of jump height calculation may be inadequate for fatigue detection.

Given its ease of measurement (e.g. timing mats), flight time would be an appealing accumulated fatigue measure. Post-match decreases in flight time have been observed during a rugby league season (McLean et al., 2010). These changes were considered an acute fatigue response as suspected differences in accumulated fatigue over the season did not alter flight time recovery profiles. Whether decreased flight time reflects acute or accumulated fatigue is difficult to determine. Previously we have observed decreased flight time immediately following fatiguing running activity, but not

24- or 72-hours later (Gathercole, Stellingwerff, et al., 2014). While, in the current study, flight time decreased only in the OR group (Table 5.2), even though Non-OR athletes likely also experienced acute fatigue. Given that flight time reflects the end result of the entire jump movement, we speculate that its decrease could reflect NM deficits accompanying either acute or accumulated fatigue.

A threshold of a greater than 8% decrease in FT:CT is speculated as indicative of low-frequency NM fatigue (Cormack et al., 2013; Cormack, Newton, & McGuigan, 2008; Cormack, Newton, McGuigan, & Cormie, 2008; Mooney et al., 2013). Our group (mean % change: -5.3%) and, specifically, OR results (-8.0%) support the use of FT:CT as a variable in NM fatigue detection; however we question the use of this fatigue threshold as it seems improbable that all individuals will exhibit a >8% decrease when fatigued. This approach is based on a previously reported FT:CT CV (Cormack, Newton, McGuigan, & Doyle, 2008), however here we observed a smaller CV (4.9%), highlighting that FT:CT variability is not set at 8%. Instead, for individually tailored results, we recommend the utilisation of individually standardized changes (e.g. effect size based on individual CV; individual Z-scores). Similarly, as a ratio variable, FT:CT is limited by the fact that responses can be obscured if similar changes occur in both variables, which may explain why substantial decreases in flight time were not replicated in FT:CT. Previously we have reported both increased and decreased jump duration in response to NM fatigue (Gathercole, Sporer, Stellingwerff, et al., 2014; Gathercole, Stellingwerff, et al., 2014) and chronic training (Gathercole, Stellingwerff, et al., 2014),

respectively. Consequently, contraction time does appear susceptible to change, and so to improve interpretation of underlying NM fatigue changes we advocate additional consideration of both flight and contraction time separately.

TTPF substantially increased from week 3 onwards (Fig. 5.3), with these changes appearing specifically due to OR group responses (Fig. 5.4; Table 5.2). As total duration was unchanged, these increases appear the result of differences in when peak force was achieved within the jump. This change is illustrated in Figure's 5.1A and B, with baseline peak force attained alongside a velocity of 0 to $1\text{m}\cdot\text{s}^{-1}$, whereas at week 6 this was delayed until 2 to $3\text{m}\cdot\text{s}^{-1}$, highlighting that peak force occurred at a later stage of the week 6 jump. These results, combined with the $F@0V$ decreases, suggest that diminished eccentric capacity contributed to this shift. In support, we have previously observed diminished eccentric capacity up to 72-hours following an acute fatiguing bout (Gathercole, Sporer, Stellingwerff, et al., 2014). Structural, mechanical and neural factors all contribute to SSC fatigue (Nicol et al., 2006), making it difficult to ascertain underlying mechanisms. Such SSC changes may however alter mechanical efficiency (McBride & Snyder, 2012), thereby increasing the energy expenditure of repeated contractions, and so potentially accelerate further fatigue-induced performance declines (Byrne et al., 2004). Thus these changes are likely of importance to performance.

Changes in CMJ movement strategy can limit fatigue-induced jump height deterioration (Schmitz et al., 2013). Previously, fatigue-induced increases in jump duration at 0- (Gathercole, Sporer, Stellingwerff, et al., 2014; Gathercole, Stellingwerff,

et al., 2014) and 72-hour post (Gathercole, Sporer, Stellingwerff, et al., 2014), have led us to suggest that these increases may reflect altered CMJ mechanics. Here jump duration variables (i.e. eccentric, concentric and total duration) were mostly unchanged despite mean trace data (Fig. 5.1 & 5.2), and TTPF and F@0V results, indicating altered CMJ mechanics. CMJ duration variables may therefore lack sufficient sensitivity to detect NM fatigue over an extended period. This may be because the extent of strategy shift required to alter duration may only be an acute response, or possibly because week-to-week variability is too large for the detection of meaningful changes.

Although group results showed no change, OR group results revealed fatigue-induced declines in a number of concentric variables (mean power, peak/mean force). Peak power is the NM component considered most susceptible to overreaching (Meeusen et al., 2013), with decreases previously observed alongside increased training and competitive demands (Argus et al., 2009; McLean et al., 2010). Here decreased peak power was observed only once (OR group, week 5), which is surprising given that other variables demonstrated changes appearing characteristic of accumulated fatigue. Interestingly, variability in CMJ mechanics has been suggested as a possible fatigue response limiting the concentric impact of diminished eccentric capacity (Byrne et al., 2004), thus the shifts observed in CMJ strategy may have enabled maintenance of peak power. These findings have important implications to fatigue monitoring, suggesting again that CMJ analysis should incorporate assessment of CMJ strategy variables.

The number of first year athletes in OR and Non-OR groups differed (OR: 1 of 7; Non-OR: 3 of 5). Given that these were ‘new’ athletes, it appears likely that training tolerance would be lower than more ‘seasoned’ athletes. However, power development rate is also highest during the first training year (McMaster et al., 2013). Although the first and third largest peak power improvements were demonstrated by third year athletes, the Non-OR group’s greater improvement capacity appears evident in the mostly improved concentric CMJ variables by week 6. Thus, in these individuals, training-induced NM improvement appears to have masked fatigue-induced declines. Consequently, ‘new’ athletes may require special monitoring, with greater emphasis possibly placed on wellness assessment rather than NM measures given their greater capacity to improve.

5.5.3 CMJ Monitoring Considerations

Post-taper CMJ assessment may have enabled exploration of the effects of functional versus non-functional overreaching; however this was not possible as athletes immediately departed immediately following the training block. Although a control group undertaking ‘regular’ training could have partly negated the absence of post-taper assessment, the real-world environment in which the study was performed also negated such possibility.

Although our investigation has examined numerous CMJ variables, many reflect the same mechanisms, and so practitioners need not perform as extensive a CMJ analysis as performed here. However our observations suggest that, in addition to the traditionally-derived concentric CMJ variables (i.e. peak/mean power, force, velocity), NM fatigue monitoring is improved through consideration of eccentric capacity and strategy-related variables (e.g. F@0V, TTPF, total duration), both of which elicit important effects on the energy efficiency of performance (Byrne et al., 2004).

5.5.4 Conclusions

A high intensity, high volume team-sport preparatory training phase elicits a number of changes in CMJ performance, corresponding to increases in TRIMP and decreases in perceptions of wellness in a very individualized manner. The CMJ test provides a simple means of comprehensively examining NM function and can therefore be used to determine various fatigue-induced declines in performance. Accordingly, different individual fatigue responses can be determined using the same test. Here, variables describing the jump output (e.g. flight time, peak displacement) and eccentric function/strategy (TTPF, F@0V) appeared to exhibit the greatest sensitivity to increased training load in elite female rugby players, thus variables reflecting these jump components should be included in CMJ monitoring protocols. To improve the usefulness of CMJ testing, practitioners are therefore advised to adopt a more thorough analytical approach, with the inclusion of CMJ NM strategy variables.

6 Conclusions

6.1 Dissertation: Summary

Monitoring NM fatigue is of considerable interest to applied sport scientists as, through improved information regarding fatigue status, it can facilitate optimal performance and training adaptation (Twist & Highton, 2013). Despite their frequent usage, the suitability of many tests for NM fatigue detection appears unresolved, while the NM constructs most susceptible to NM fatigue (Taylor, 2012) and adaptation remain unclear. Given the complexity of fatigue and its restoration, it seems plausible that NM changes exhibit considerable variability depending on factors such as the phase of the fatigue-recovery cycle, whether the fatigue-induced is acute and/or accumulated, the fatiguing activity performed, and the athlete themselves (e.g. age, sex, training status, genetics). It was the purpose of the series of investigations contained within to explore these questions.

In Chapter 2, four common NM function tests (specifically, CMJ, SJ, DJ and SPRINT) were compared to establish their suitability for the detection of NM fatigue as part of regular athlete monitoring. Evaluation of suitability was based on test repeatability and the sensitivity of the test to NM fatigue (determined by the magnitude and duration of post-exercise NM changes). Although each test typically displayed acceptable intra- and inter-session repeatability (i.e. <10% CV; (Cormack, Newton, McGuigan, & Doyle,

2008)), between-test differences were evident. The greatest repeatability was displayed in SPRINT performance (mean CV: $\leq 2\%$; Table 2.1). Vertical jump test comparisons (Fig. 2.1) revealed DJ performance to be the least repeatable (4.8%), whereas CMJ (3.0%) and SJ (3.5%) test repeatability was very similar. The fatiguing protocol elicited different NM responses between tests (Fig. 2.2). While all four tests displayed pronounced immediate changes, only CMJ and DJ performance showed diminished function following this time-point (i.e. from 24- to 72-hour), and so these tests were determined as most sensitive to prolonged NM fatigue. In light of the observed high repeatability and sensitivity to prolonged NM fatigue, the CMJ test was identified as most suitable for NM fatigue monitoring.

Once the CMJ test was established as most suitable, fatigue-induced NM changes as revealed through CMJ testing were scrutinised further (Chapters 3 to 5). As part of this process, two CMJ analytic methods were adapted from previous investigations and incorporated into a novel alternative CMJ analyses. The first method, based on the work of Taylor et al. (2010), attempted to improve CMJ inter-session repeatability by utilising the most consistent jumps from multiple jump trial data (i.e. the four most consistent CMJ trials from the six collected) as opposed to single or the mean of all CMJ trials. The second method, used to explore mechanical changes associated with NM fatigue, measured a set of infrequently analysed CMJ variables (referred to as 'alternative'; i.e. CMJ-ALT) derived using power-time and force-velocity CMJ traces, and based on the work of Cormie and associates ((2008, 2009; 2010a, 2010b).

Chapter 3 describes a more comprehensive analysis of the CMJ test data collected during the first investigation (i.e. in Chapter 2). CMJ performance was examined following a fatiguing intermittent running protocol in sub-elite team-sport athletes. Results revealed large immediate NM deficits, a temporary restoration at 24-hour, and a secondary reduction at 72-hour (Table 3.3 & 3.4; Fig. 3.4), resembling the biphasic recovery pattern of SSC fatigue, as previously demonstrated in the literature (Komi, 2000; Nicol et al., 2006). The secondary reduction at 72-hour was associated with diminished function in a number of time- and rate-based variables. Combined with the differences apparent in force-velocity and power-time traces (Fig. 3.3A & B), these changes supported previous observations (Schmitz et al., 2013) that NM changes associated with fatigue and the recovery process (i.e. from 24- to 72-hour post) can influence how the CMJ is performed (i.e. CMJ mechanics). In addition to supporting the value of CMJ testing to athlete fatigue monitoring, these results suggested that while acute responses to NM fatigue may influence most NM constructs, NM changes during the recovery phase may exhibit greater effects on CMJ mechanics than actual CMJ performance outputs (e.g. jump height/power, etc).

The next investigation examined the suitability of CMJ testing, and the utilised analytic approaches, in a highly-trained athletic population (Chapter 4). CMJ performance was assessed in elite snowboard-cross athletes following both a fatiguing exercise protocol and a 19-week training block (Fig. 4.1). Following the fatiguing protocol CMJ force production and eccentric function were reduced, while jump duration

was increased (Table 4.1; Fig. 4.2 & 4.3). In direct contrast, the training block was associated with increased CMJ force production and eccentric function, alongside decreased jump duration (Table 4.2; Fig. 4.4 & 4.5). Within each comparison, the largest changes, or greatest sensitivity, were displayed by CMJ-ALT variables, underlining the value in examining mechanical changes in CMJ performance in the detection of both fatigue- and training-induced NM adaptive responses.

The final investigation, described in Chapter 5, examined whether the same methods could be utilised to monitor NM changes associated with increased training loads in elite female Rugby Sevens athletes. Results revealed marked changes in CMJ variables relating to time, eccentric function and the jump outcome (i.e. flight time, peak displacement) (Table 5.2; Fig. 5.3). These results again supported the presence of fatigue-induced mechanical changes (i.e. time to peak force, $F@0V$), which may have contributed to the decreased jump performance outcomes (flight time, peak displacement).

Collectively, these investigations support the use of CMJ testing to detect diminished NM function acutely following a fatiguing exercise protocol (Chapters 3 and 4), during the post-exercise recovery phase (Chapter 3), and in response to increased training loads (Chapters 4 and 5). Moreover, they highlight the value of these techniques in the assessment of positive NM adaptation (i.e. training-induced NM improvement; Chapter 4), and also the complexity of NM changes associated with various exercise

stimuli, in that in most circumstances a comprehensive CMJ analysis is required to adequately evaluate NM change.

To summarise, the series of investigations have:

- 1) Identified CMJ testing as the most suitable NM function test for NM fatigue detection, from both a repeatability, and also acute and prolonged sensitivity perspective.
- 2) Utilised and developed CMJ analytic techniques, providing additional information regarding NM changes resulting from differing stimuli.
- 3) Demonstrated the value of these techniques in the monitoring of NM function and fatigue following acutely fatiguing activity and during the post-exercise recovery phase (Chapter 3), and in elite athletes in response to acute fatigue, a 19-week structured training block (Chapter 4), and in response to accumulated fatigue associated with an intensive training block (Chapter 5).
- 4) Revealed that NM fatigue can manifest as alterations in CMJ movement strategy.

6.2 Dissertation: Practical Applications

Based on the series of investigations performed and described within this dissertation, a number of practical recommendations are made:

1. SPRINT testing appears to offer a simple (i.e. 'yes/no'), repeatable and sensitive means of determining performance decreases immediately following (i.e. ~0-hour post) fatiguing exercise (Chapter 2).
2. The ability to achieve maximal sprint speed appears restored relatively quickly following the fatiguing exercise utilised here (i.e. <24-hour) (Chapter 2). Performance in a fatigue state (>24-hour post-fatiguing activity) during activities with a sprint component may therefore be influenced less so by sprint ability and more so by other factors (e.g. technique execution/production, a desire to achieve maximal sprint speed).
3. Of the NM function tests examined, the high repeatability and capacity to detect fatigue-induced NM changes up to 72-hour post indicates that CMJ testing is suitable for NM function testing as part of a regular athlete monitoring test battery (Chapter 2).
4. Fatigue-induced NM changes can elicit both direct (e.g. decreased concentric performance; decreased timing) and indirect (e.g. decreases in NM efficiency; deteriorations in technique) performance effects (Chapters 3, 4, and 5). As such practitioners should consider each component when making a decision on an

athlete's fatigue state, and how the subsequent changes may affect performance in an athlete's particular sport.

5. The value of CMJ testing for NM fatigue detection can be further enhanced by:
 - a. Determine fatigue state using data collected from more than one CMJ trial. The CMJ is a highly technical movement of short duration (~1-second), and so the movement performed can be quite variable. The variability in obtained results can be decreased through the utilisation of multiple jump trials (Taylor et al., 2010) followed by the standardised selection of the most consistent (i.e. removal of the most dissimilar based on EccConMP) trials for further examination (i.e. Fig. 3.2B). Here we used the mean of four of six (Chapters 2, 3, 4) or two of three trials (Chapter 5) and so the practicality of CMJ testing is not necessarily hampered by this approach.
 - b. For detection of mechanical CMJ changes, athletes should be encouraged to perform the CMJ in a manner familiar to them and without movement restriction (e.g. a pre-determined countermovement depth).
 - c. CMJ analysis should examine a range of NM components of CMJ performance. In addition to common concentrically-focused CMJ variables (e.g. peak power/force, jump height), practitioners should consider the use of power-time and force-velocity CMJ traces, and CMJ-ALT variables, to better describe underlying mechanical changes in CMJ performance.

6. NM fatigue responses should be examined on an individual-by-individual and sport-by-sport basis. Given the complexity of NM fatigue it appears unlikely that the same NM construct (or ‘fatigue marker’) will respond to all fatiguing stimuli, to the same extent, and in all individuals. Consequently, unless ‘familiar’ trends within athletes become evident (i.e. athlete ‘x’ exhibits a predisposition to decreased peak power when fatigued), analysis should always be both comprehensive and individualized. Related to this, utilisation of individualized fatigue thresholds based on z-scores or effect sizes using intra-individual technical error (i.e. Chapters 2, 4, and 5; Fig. 4.3 & 4.5) could be adopted to describe the degree of change in respect of the typical variability associated with that individual.
7. Given their greater capacity for NM development (McMaster et al., 2013), practitioners should remain cognisant that ‘rookie’ and/or younger athletes may require special attention in regards to fatigue monitoring, as NM function may exhibit improvement despite the presence of NM fatigue (Chapter 5).

6.3 Dissertation: Recommendations for Future Research

The series of investigations described herein have contributed to the understanding of NM fatigue analysis through the assessment of NM function and CMJ testing, specifically. Moreover, they have provided insight into the NM responses

associated with fatiguing SSC exercise immediately following, through the accumulation of training stress, and during post-exercise recovery. The following suggestions are provided to build upon this body of research.

1. While this research has revealed a number of NM changes in CMJ performance following different fatiguing stimuli and during different stages of recovery, the extent to which these changes are due to the fatiguing stimuli and/or the individuals involved is unclear. For example, more marked mechanical and smaller concentric changes were observed acutely in highly trained individuals (i.e. Chapter 4) compared to the sub-elite group (i.e. Chapter 3). Were these differences related to the population tested (i.e. training status) or the fatiguing stimuli utilized, or an alternative factor? Future investigations should compare NM responses in both elite and non-elite athletes following the same fatiguing stimuli.
2. Although these described investigations support the value of CMJ testing to detect fatigue following SSC exercise (i.e. Chapters 2-5), it is unclear whether CMJ fatigue monitoring is of value in athletes participating in low-SSC , low-eccentric loading and/or non-jumping sports (e.g. cross-country skiing, swimming). If movement specificity is crucial to the detection of NM fatigue then it would appear of limited use, but if a CMJ is simply a movement model utilized to examine different components of NM function then it may be of value. Similarly,

despite the disparity between a CMJ and these low-SSC sports, many of these athletes perform training with an SSC-component. Consequently, the CMJ test may still be suitable for monitoring training-specific NM responses. Investigation of CMJ performance following non-SSC demanding activities would therefore appear beneficial.

3. Many of the CMJ variables measured in each of these investigations reflect similar NM and/or performance constructs (e.g. peak displacement, flight time). Consequently, as fewer CMJ variables may be required to represent the same NM components, a number are likely superfluous. For a more streamlined analytical process, future investigations should determine which variables can be omitted without a loss in the investigative capacity of CMJ testing.
4. In this research we have repeatedly associated altered CMJ mechanics and decreases in eccentric function with deleterious performance implications (i.e. Chapter 2 – 5). Future investigations should explore how such changes may interact with performance to determine if they are indeed associated with direct (e.g. decreased skill execution, increased movement time requirement, decreased timing) and/or indirect (e.g. accelerated fatigue decline) performance effects. An additional avenue of research is whether these NM adjustments function to maintain performance output (e.g. a longer duration jump to maintain power output) and/or reduce the risk of injury (e.g. reduced eccentric loading in fatigued/damaged motor units)?

Bibliography

- Abbiss, C. R., & Laursen, P. B. (2005). Models to explain fatigue during prolonged endurance cycling. *Sports Med*, 35(10), 865-898.
- Abernethy, P., Wilson, G., & Logan, P. (1995). Strength and power assessment. Issues, controversies and challenges. *Sports Med*, 19(6), 401-417.
- Allen, D. G., Lamb, G. D., & Westerblad, H. (2008). Skeletal muscle fatigue: cellular mechanisms. *Physiol Rev*, 88(1), 287-332.
- Amann, M. (2011). Central and peripheral fatigue: interaction during cycling exercise in humans. *Med Sci Sports Exerc*, 43(11), 2039-2045.
- Amann, M. (2012). Significance of Group III and IV muscle afferents for the endurance exercising human. *Clin Exp Pharmacol Physiol*, 39(9), 831-835.
- Amann, M., Blain, G. M., Proctor, L. T., Sebranek, J. J., Pegelow, D. F., & Dempsey, J. A. (2011). Implications of group III and IV muscle afferents for high-intensity endurance exercise performance in humans. *J Physiol*, 589(Pt 21), 5299-5309.
- Ament, W., & Verkerke, G. J. (2009). Exercise and fatigue. *Sports Medicine*, 39(5), 389-422.
- Andersson, H., Raastad, T., Nilsson, J., Paulsen, G., Garthe, I., & Kadi, F. (2008). Neuromuscular Fatigue and Recovery in Elite Female Soccer: Effects of Active Recovery. *Medicine & Science in Sports & Exercise*, 40(2), 372-380.
- Andersson, H. M., Raastad, T., Nilsson, J., Paulsen, G., Garthe, I., & Kadi, F. (2008). Neuromuscular fatigue and recovery in elite female soccer: effects of active recovery. *Med Sci Sports Exerc*, 40(2), 372-380.
- Argus, C. K., Gill, N. D., Keogh, J. W., Hopkins, W. G., & Beaven, C. M. (2009). Changes in strength, power, and steroid hormones during a professional rugby union competition. *J Strength Cond Res*, 23(5), 1583-1592.
- Argus, C. K., Gill, N. D., Keogh, J. W., McGuigan, M. R., & Hopkins, W. G. (2012). Effects of two contrast training programs on jump performance in rugby union players during a competition phase. *International journal of sports physiology and performance*, 7(1), 68-75.
- Asp, S., Rohde, T., & Richter, E. A. (1997). Impaired muscle glycogen resynthesis after a marathon is not caused by decreased muscle GLUT-4 content. *Journal of Applied Physiology*, 83(5), 1482-1485.

- Avela, J., & Komi, P. V. (1998). Interaction between muscle stiffness and stretch reflex sensitivity after long-term stretch-shortening cycle exercise. *Muscle Nerve*, 21(9), 1224-1227.
- Avela, J., Kyrolainen, H., Komi, P. V., & Rama, D. (1999). Reduced reflex sensitivity persists several days after long-lasting stretch-shortening cycle exercise. *J Appl Physiol*, 86(4), 1292-1300.
- Babault, N., Pousson, M., Ballay, Y., & Van Hoecke, J. (2001). Activation of human quadriceps femoris during isometric, concentric, and eccentric contractions. *Journal of Applied Physiology*, 91(6), 2628-2634.
- Bailey, D. M., Erith, S. J., Griffin, P. J., Dowson, A., Brewer, D. S., Gant, N., & Williams, C. (2007). Influence of cold-water immersion on indices of muscle damage following prolonged intermittent shuttle running. *J Sports Sci*, 25(11), 1163-1170.
- Bakken, A., Bere, T., Bahr, R., Kristianslund, E., & Nordsletten, L. (2011). Mechanisms of injuries in World Cup Snowboard Cross: a systematic video analysis of 19 cases. *Br J Sports Med*, 45(16), 1315-1322.
- Bangsbo, J. (n.d.). The Yo-Yo tests. Retrieved September 9, 2013, from <http://www.soccerfitness.com>
- Bangsbo, J., Iaia, F. M., & Krstrup, P. (2008). The Yo-Yo intermittent recovery test : a useful tool for evaluation of physical performance in intermittent sports. *Sports Med*, 38(1), 37-51.
- Barnett, A. (2006). Using recovery modalities between training sessions in elite athletes: does it help? *Sports Med*, 36(9), 781-796.
- Batterham, A. M., & Hopkins, W. G. (2006). Making meaningful inferences about magnitudes.
- Bigland-Ritchie, B. (1981). EMG/FORCE RELATIONS AND FATIGUE OF HUMAN VOLUNTARY CONTRACTIONS. *Exercise and sport sciences reviews*, 9(1), 75-118.
- Billaut, F., Basset, F. A., & Falgairette, G. (2005). Muscle coordination changes during intermittent cycling sprints. *Neurosci Lett*, 380(3), 265-269.
- Billaut, F., Kerris, J. P., Rodriguez, R. F., Martin, D. T., Gore, C. J., & Bishop, D. J. (2013). Interaction of central and peripheral factors during repeated sprints at different levels of arterial O₂ saturation. *PLoS One*, 8(10), e77297.
- Bishop, P. A., Jones, E., & Woods, A. K. (2008). Recovery from training: a brief review: brief review. *J Strength Cond Res*, 22(3), 1015-1024.
- Blazevich, A. J., Gill, N., & Newton, R. U. (2002). Reliability and validity of two isometric squat tests. *J Strength Cond Res*, 16(2), 298-304.

- Bobbert, M. F. (1990). Drop jumping as a training method for jumping ability. *Sports Med*, 9(1), 7-22.
- Borresen, J., & Lambert, M. I. (2009). The quantification of training load, the training response and the effect on performance. *Sports Medicine*, 39(9), 779-795.
- Boullosa, D. A., Tuimil, J. L., Alegre, L. M., Iglesias, E., & Lusquinos, F. (2011). Concurrent fatigue and potentiation in endurance athletes. *Int J Sports Physiol Perform*, 6(1), 82-93.
- Boyas, S., & Guével, A. (2011). Neuromuscular fatigue in healthy muscle: Underlying factors and adaptation mechanisms. *Annals of Physical and Rehabilitation Medicine*, 54(2), 88-108.
- Bradley, P. S., Mohr, M., Bendiksen, M., Randers, M. B., Flindt, M., Barnes, C., . . . Krstrup, P. (2011). Sub-maximal and maximal Yo-Yo intermittent endurance test level 2: heart rate response, reproducibility and application to elite soccer. *Eur J Appl Physiol*, 111(6), 969-978.
- Bradshaw, E. J., Maulder, P. S., & Keogh, J. W. (2007). Biological movement variability during the sprint start: Performance enhancement or hindrance? *Sports Biomechanics*, 6(3), 246-260.
- Brechue, W. F., Mayhew, J. L., & Piper, F. C. (2010). Characteristics of sprint performance in college football players. *The Journal of Strength & Conditioning Research*, 24(5), 1169-1178.
- Brown, L. E., Whitehurst, M., & Findley, B. W. (2005). Reliability of rate of velocity development and phase measures on an isokinetic device. *J Strength Cond Res*, 19(1), 189-192.
- Buchheit, M., Chivot, A., Parouty, J., Mercier, D., Al Haddad, H., Laursen, P. B., & Ahmaidi, S. (2010). Monitoring endurance running performance using cardiac parasympathetic function. *Eur J Appl Physiol*, 108(6), 1153-1167.
- Byrne, C., & Eston, R. (2002). The effect of exercise-induced muscle damage on isometric and dynamic knee extensor strength and vertical jump performance. *J Sports Sci*, 20(5), 417-425.
- Byrne, C., Twist, C., & Eston, R. (2004). Neuromuscular function after exercise-induced muscle damage: theoretical and applied implications. *Sports Med*, 34(1), 49-69.
- Cairns, S. P., Knicker, A. J., Thompson, M. W., & Sjøgaard, G. (2005). Evaluation of models used to study neuromuscular fatigue. *Exercise and sport sciences reviews*, 33(1), 9-16.
- Cairns, S. P., & Lindinger, M. I. (2008). Do multiple ionic interactions contribute to skeletal muscle fatigue? *J Physiol*, 586(Pt 17), 4039-4054.

- Chambers, C., Noakes, T. D., Lambert, E. V., & Lambert, M. I. (1998). Time course of recovery of vertical jump height and heart rate versus running speed after a 90-km foot race. *Journal of Sports Sciences*, 16(7), 645-651.
- Cone, J. R., Berry, N. T., Goldfarb, A. H., Henson, R. A., Schmitz, R. J., Wideman, L., & Shultz, S. J. (2012). Effects of an individualized soccer match simulation on vertical stiffness and impedance. *J Strength Cond Res*, 26(8), 2027-2036.
- Cook, C. J., & Beaven, C. M. (2013). Individual perception of recovery is related to subsequent sprint performance. *Br J Sports Med*, 47(11), 705-709.
- Cormack, S. J., Money, M., Morgan, W., & McGuigan, M. R. (2012). Influence of Neuromuscular Fatigue on Accelerometer Load in Elite Australian Football Players. *International journal of sports physiology and performance*.
- Cormack, S. J., Mooney, M. G., Morgan, W., & McGuigan, M. R. (2013). Influence of neuromuscular fatigue on accelerometer load in elite Australian football players. *Int J Sports Physiol Perform*, 8(4), 373-378.
- Cormack, S. J., Newton, R. U., & McGuigan, M. R. (2008). Neuromuscular and endocrine responses of elite players to an Australian rules football match. *Int J Sports Physiol Perform*, 3(3), 359-374.
- Cormack, S. J., Newton, R. U., McGuigan, M. R., & Cormie, P. (2008). Neuromuscular and endocrine responses of elite players during an Australian rules football season. *Int J Sports Physiol Perform*, 3(4), 439-453.
- Cormack, S. J., Newton, R. U., McGuigan, M. R., & Doyle, T. L. (2008). Reliability of measures obtained during single and repeated countermovement jumps. *Int J Sports Physiol Perform*, 3(2), 131.
- Cormie, P., McBride, J. M., & McCaulley, G. O. (2008). Power-time, force-time, and velocity-time curve analysis during the jump squat: impact of load. *J Appl Biomech*, 24(2), 112-120.
- Cormie, P., McBride, J. M., & McCaulley, G. O. (2009). Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *J Strength Cond Res*, 23(1), 177-186.
- Cormie, P., McGuigan, M. R., & Newton, R. U. (2010a). Adaptations in athletic performance after ballistic power versus strength training. *Med Sci Sports Exerc*, 42(8), 1582-1598.
- Cormie, P., McGuigan, M. R., & Newton, R. U. (2010b). Changes in the eccentric phase contribute to improved stretch-shorten cycle performance after training. *Med Sci Sports Exerc*, 42(9), 1731-1744.
- Coutts, A. J., Reaburn, P., Piva, T. J., & Rowsell, G. J. (2007). Monitoring for overreaching in rugby league players. *Eur J Appl Physiol*, 99(3), 313-324.

- Coutts, A. J., Slattery, K. M., & Wallace, L. K. (2007). Practical tests for monitoring performance, fatigue and recovery in triathletes. *J Sci Med Sport*, 10(6), 372-381.
- Cronin, J. B., & Hansen, K. T. (2005). Strength and Power Predictors of Sports Speed. *The Journal of Strength & Conditioning Research*, 19(2), 349-357.
- Cronin, J. B., Hing, R. D., & McNair, P. J. (2004). Reliability and validity of a linear position transducer for measuring jump performance. *J Strength Cond Res*, 18(3), 590-593.
- Currell, K., & Jeukendrup, A. (2008). Validity, Reliability and Sensitivity of Measures of Sporting Performance. *Sports Medicine*, 38(4), 297-316.
- Dauids, K., Araújo, D., Vilar, L., Renshaw, I., & Pinder, R. (2013). An ecological dynamics approach to skill acquisition: Implications for development of talent in sport. *Talent Development & Excellence*.
- Dellal, A., Chamari, K., Wong, D. P., Ahmaidi, S., Keller, D., Barros, R., . . . Carling, C. (2011). Comparison of physical and technical performance in European soccer match-play: FA Premier League and La Liga. *European Journal of Sport Science*, 11(1), 51-59.
- Deschenes, M. R., Brewer, R. E., Bush, J. A., McCoy, R. W., Volek, J. S., & Kraemer, W. J. (2000). Neuromuscular disturbance outlasts other symptoms of exercise-induced muscle damage. *J Neurol Sci*, 174(2), 92-99.
- Ditroilo, M., Watsford, M., Fernandez-Pena, E., D'Amen, G., Lucertini, F., & De Vito, G. (2011). Effects of fatigue on muscle stiffness and intermittent sprinting during cycling. *Med Sci Sports Exerc*, 43(5), 837-845.
- Douset, E., Avela, J., Ishikawa, M., Kallio, J., Kuitunen, S., Kyrolainen, H., . . . Komi, P. V. (2007). Bimodal recovery pattern in human skeletal muscle induced by exhaustive stretch-shortening cycle exercise. *Med Sci Sports Exerc*, 39(3), 453-460.
- Duffield, R., Murphy, A., Snape, A., Minett, G. M., & Skein, M. (2012). Post-match changes in neuromuscular function and the relationship to match demands in amateur rugby league matches. *J Sci Med Sport*, 15(3), 238-243.
- Enoka, R. M. (1995). Mechanisms of muscle fatigue: central factors and task dependency. *Journal of Electromyography and Kinesiology*, 5(3), 141-149.
- Enoka, R. M. (2012). Muscle fatigue--from motor units to clinical symptoms. *J Biomech*, 45(3), 427-433.
- Falvo, M. J., Schilling, B. K., & Weiss, L. W. (2006). Techniques and considerations for determining isoinertial upper-body power. *Sports Biomechanics*, 5(2), 293 - 311.

- Farina, D., Holobar, A., Merletti, R., & Enoka, R. M. (2010). Decoding the neural drive to muscles from the surface electromyogram. *Clin Neurophysiol*, *121*(10), 1616-1623.
- Fitts, R. H. (2008). The cross-bridge cycle and skeletal muscle fatigue. *J Appl Physiol (1985)*, *104*(2), 551-558.
- Foster, C., Florhaug, J. A., Franklin, J., Gottschall, L., Hrovatin, L. A., Parker, S., . . . Dodge, C. (2001). A new approach to monitoring exercise training. *J Strength Cond Res*, *15*(1), 109-115.
- Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiol Rev*, *81*(4), 1725-1789.
- Gathercole, R., Sporer, B., & Stellingwerff, T. (2014). Longitudinal countermovement jump performance with increased training loads in elite female rugby players. *Int J Sports Physiol Perform*, *Currently in review at IJSP*.
- Gathercole, R., Sporer, B., Stellingwerff, T., & Sleivert, G. (2014). Alternative Countermovement Jump Analysis to Quantify Acute Neuromuscular Fatigue. *Int J Sports Physiol Perform*, *Epub ahead of print*. doi: 10.1123/ijssp.2013-0413
- Gathercole, R., Stellingwerff, T., & Sporer, B. (2014). Effect of acute fatigue and training adaptation on countermovement jump performance in elite snowboard cross athletes. *Journal of Strength & Conditioning Research*, *Accepted June 2014*.
- Gejl, K. D., Hvid, L. G., Frandsen, U., Jensen, K., Sahlin, K., & Ortenblad, N. (2014). Muscle Glycogen Content Modifies SR Ca²⁺ Release Rate in Elite Endurance Athletes. *Medicine and science in sports and exercise*, *46*(3), 496-505.
- Girard, O., Bishop, D. J., & Racinais, S. (2013). Neuromuscular adjustments of the quadriceps muscle after repeated cycling sprints. *PLoS One*, *8*(5), e61793.
- Girard, O., Lattier, G., Maffiuletti, N. A., Micallef, J. P., & Millet, G. P. (2008). Neuromuscular fatigue during a prolonged intermittent exercise: Application to tennis. *J Electromyogr Kinesiol*, *18*(6), 1038-1046.
- Girard, O., Mendez-Villanueva, A., & Bishop, D. (2011). Repeated-sprint ability - part I: factors contributing to fatigue. *Sports Med*, *41*(8), 673-694.
- Girard, O., Micallef, J. P., & Millet, G. P. (2011). Changes in spring-mass model characteristics during repeated running sprints. *Eur J Appl Physiol*, *111*(1), 125-134.
- Gondin, J., Guette, M., Ballay, Y., & Martin, A. (2005). Electromyostimulation training effects on neural drive and muscle architecture. *Med Sci Sports Exerc*, *37*(8), 1291-1299.

- Gondin, J., Guette, M., Jubeau, M., Ballay, Y., & Martin, A. (2006). Central and peripheral contributions to fatigue after electrostimulation training. *Med Sci Sports Exerc*, 38(6), 1147-1156.
- Goodall, S., Ross, E. Z., & Romer, L. M. (2010). Effect of graded hypoxia on supraspinal contributions to fatigue with unilateral knee-extensor contractions. *Journal of Applied Physiology*, 109(6), 1842-1851.
- Halson, S. L., Bridge, M. W., Meeusen, R., Busschaert, B., Gleeson, M., Jones, D. A., & Jeukendrup, A. E. (2002). Time course of performance changes and fatigue markers during intensified training in trained cyclists. *J Appl Physiol* (1985), 93(3), 947-956.
- Halson, S. L., & Jeukendrup, A. E. (2004). Does overtraining exist? An analysis of overreaching and overtraining research. *Sports Med*, 34(14), 967-981.
- Hargreaves, M. (2008). Fatigue mechanisms determining exercise performance: integrative physiology is systems biology. *J Appl Physiol* (1985), 104(5), 1541-1542.
- Harris, N., Cronin, J., & Keogh, J. (2007). Contraction force specificity and its relationship to functional performance. *J Sports Sci*, 25(2), 201-212.
- Haugen, T. A., Tonnessen, E., & Seiler, S. K. (2012). The difference is in the start: impact of timing and start procedure on sprint running performance. *J Strength Cond Res*, 26(2), 473-479.
- Hoffman, J. R., Maresh, C. M., Newton, R. U., Rubin, M. R., French, D. N., Volek, J. S., . . . Ratamess, N. A. (2002). Performance, biochemical, and endocrine changes during a competitive football game. *Med Sci Sports Exerc*, 34(11), 1845-1853.
- Hoffman, J. R., Nusse, V., & Kang, J. (2003). The Effect of an Intercollegiate Soccer Game on Maximal Power Performance. *Canadian Journal of Applied Physiology*, 28(6), 807-817.
- Hooper, S. L., & Mackinnon, L. T. (1995). Monitoring overtraining in athletes. *Sports Medicine*, 20(5), 321-327.
- Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Med*, 30(1), 1-15.
- Hopkins, W. G. (2004). How to interpret changes in an athletic performance test. *Sportscience*, 8, 1-7.
- Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*, 41(1), 3-13.
- Hopkins, W. G., Schabort, E. J., & Hawley, J. A. (2001). Reliability of power in physical performance tests. *Sports Med*, 31(3), 211-234.

- Horita, T., Komi, P. V., Nicol, C., & Kyrolainen, H. (1996). Stretch shortening cycle fatigue: interactions among joint stiffness, reflex, and muscle mechanical performance in the drop jump [corrected]. *Eur J Appl Physiol Occup Physiol*, 73(5), 393-403.
- Howatson, G., & Milak, A. (2009). Exercise-induced muscle damage following a bout of sport specific repeated sprints. *J Strength Cond Res*, 23(8), 2419-2424.
- Howatson, G., & van Someren, K. A. (2008). The prevention and treatment of exercise-induced muscle damage. *Sports Med*, 38(6), 483-503.
- Hubal, M. J., Rubinstein, S. R., & Clarkson, P. M. (2007). Mechanisms of variability in strength loss after muscle-lengthening actions. *Med Sci Sports Exerc*, 39(3), 461-468.
- Jakobsen, M. D., Sundstrup, E., Randers, M. B., Kjaer, M., Andersen, L. L., Krstrup, P., & Aagaard, P. (2012). The effect of strength training, recreational soccer and running exercise on stretch-shortening cycle muscle performance during countermovement jumping. *Hum Mov Sci*, 31(4), 970-986.
- Jidovtseff, B., Croisier, J. L., Lhermerout, C., Serre, L., Sac, D., & Crielaard, J. M. (2006). The concept of iso-inertial assessment: Reproducibility analysis and descriptive data. *Isokinetics and Exercise Science*, 14(1), 53-62.
- Johnston, R. D., Gibson, N. V., Twist, C., Gabbett, T. J., MacNay, S. A., & MacFarlane, N. G. (2013). Physiological responses to an intensified period of rugby league competition. *J Strength Cond Res*, 27(3), 643-654.
- Jones, D. A. (1996). High-and low-frequency fatigue revisited. *Acta Physiol Scand*, 156(3), 265-270.
- Jones, D. A. (2010). Changes in the force-velocity relationship of fatigued muscle: implications for power production and possible causes. *J Physiol*, 588(Pt 16), 2977-2986.
- Jubeau, M., Rupp, T., Perrey, S., Temesi, J., Wuyam, B., Levy, P., . . . Millet, G. Y. (2014). Changes in voluntary activation assessed by transcranial magnetic stimulation during prolonged cycling exercise. *PLoS One*, 9(2), e89157.
- Kallerud, H., & Gleeson, N. (2013). Effects of stretching on performances involving stretch-shortening cycles. *Sports Med*, 43(8), 733-750.
- Kellmann, M. (2010). Preventing overtraining in athletes in high-intensity sports and stress/recovery monitoring. *Scandinavian journal of medicine & science in sports*, 20(s2), 95-102.
- Khamoui, A. V., Brown, L. E., Nguyen, D., Uribe, B. P., Coburn, J. W., Noffal, G. J., & Tran, T. (2009). Relationship Between Force-Time and Velocity-Time Characteristics of Dynamic and Isometric Muscle Actions. *J Strength Cond Res*.

- Knicker, A. J., Renshaw, I., Oldham, A. R., & Cairns, S. P. (2011). Interactive processes link the multiple symptoms of fatigue in sport competition. *Sports Med*, 41(4), 307-328.
- Komi, P. V. (2000). Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *J Biomech*, 33(10), 1197-1206.
- Krustrup, P., Mohr, M., Amstrup, T., Rysgaard, T., Johansen, J., Steensberg, A., . . . Bangsbo, J. (2003). The yo-yo intermittent recovery test: physiological response, reliability, and validity. *Med Sci Sports Exerc*, 35(4), 697-705.
- Krustrup, P., Mohr, M., Steensberg, A., Bencke, J., Kjaer, M., & Bangsbo, J. (2006). Muscle and blood metabolites during a soccer game: implications for sprint performance. *Med Sci Sports Exerc*, 38(6), 1165-1174.
- Krustrup, P., Zebis, M., Jensen, J. M., & Mohr, M. (2010). Game-induced fatigue patterns in elite female soccer. *J Strength Cond Res*, 24(2), 437-441.
- Kufel, T. J., Pineda, L. A., & Mador, M. J. (2002). Comparison of potentiated and unpotentiated twitches as an index of muscle fatigue. *Muscle Nerve*, 25(3), 438-444.
- Kuitunen, S., Avela, J., Kyrolainen, H., Nicol, C., & Komi, P. V. (2002). Acute and prolonged reduction in joint stiffness in humans after exhausting stretch-shortening cycle exercise. *Eur J Appl Physiol*, 88(1-2), 107-116.
- Lepers, R., Hausswirth, C., Maffiuletti, N., Brisswalter, J., & van Hoecke, J. (2000). Evidence of neuromuscular fatigue after prolonged cycling exercise. *Med Sci Sports Exerc*, 32(11), 1880-1886.
- Lockie, R. G., Murphy, A. J., Schultz, A. B., Jeffriess, M. D., & Callaghan, S. J. (2013). Influence of sprint acceleration stance kinetics on velocity and step kinematics in field sport athletes. *J Strength Cond Res*, 27(9), 2494-2503.
- Macintosh, B. R., Robillard, M. E., & Tomaras, E. K. (2012). Should postactivation potentiation be the goal of your warm-up? *Appl Physiol Nutr Metab*, 37(3), 546-550.
- Marcora, S. M., & Staiano, W. (2010). The limit to exercise tolerance in humans: mind over muscle? *Eur J Appl Physiol*, 109(4), 763-770.
- Markovic, G., Dizdar, D., Jukic, I., & Cardinale, M. (2004). Reliability and factorial validity of squat and countermovement jump tests. *J Strength Cond Res*, 18(3), 551-555.
- McBride, J. M., & Snyder, J. G. (2012). Mechanical efficiency and force-time curve variation during repetitive jumping in trained and untrained jumpers. *Eur J Appl Physiol*, 112(10), 3469-3477.

- McGuigan, M. R., Doyle, T. L., Newton, M., Edwards, D. J., Nimphius, S., & Newton, R. U. (2006). Eccentric utilization ratio: effect of sport and phase of training. *J Strength Cond Res*, 20(4), 992-995.
- McGuigan, M. R., Newton, M. J., Winchester, J. B., & Nelson, A. G. (2010). Relationship between isometric and dynamic strength in recreationally trained men. *J Strength Cond Res*, 24(9), 2570-2573.
- McLean, B. D., Coutts, A. J., Kelly, V., McGuigan, M. R., & Cormack, S. J. (2010). Neuromuscular, endocrine, and perceptual fatigue responses during different length between-match microcycles in professional rugby league players. *Int J Sports Physiol Perform*, 5(3), 367-383.
- McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011a). Markers of postmatch fatigue in professional Rugby League players. *J Strength Cond Res*, 25(4), 1030-1039.
- McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011b). Performance analysis of elite Rugby League match play using global positioning systems. *J Strength Cond Res*, 25(6), 1703-1710.
- McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011c). The role of rate of force development on vertical jump performance. *J Strength Cond Res*, 25(2), 379-385.
- McMaster, D. T., Gill, N., Cronin, J., & McGuigan, M. (2013). The development, retention and decay rates of strength and power in elite rugby union, rugby league and American football: a systematic review. *Sports Med*, 43(5), 367-384.
- McMaster, D. T., Gill, N., Cronin, J., & McGuigan, M. (2014). A brief review of strength and ballistic assessment methodologies in sport. *Sports Med*, 44(5), 603-623.
- Meeusen, R., Duclos, M., Foster, C., Fry, A., Gleeson, M., Nieman, D., . . . Urhausen, A. (2013). Prevention, diagnosis, and treatment of the overtraining syndrome: joint consensus statement of the European College of Sport Science and the American College of Sports Medicine. *Med Sci Sports Exerc*, 45(1), 186-205.
- Meeusen, R., Watson, P., Hasegawa, H., Roelands, B., & Piacentini, M. F. (2006). Central fatigue: the serotonin hypothesis and beyond. *Sports Med*, 36(10), 881-909.
- Meeusen, R., Watson, P., Hasegawa, H., Roelands, B., & Piacentini, M. F. (2007). Brain neurotransmitters in fatigue and overtraining. *Appl Physiol Nutr Metab*, 32(5), 857-864.
- Mendez-Villanueva, A., Edge, J., Suriano, R., Hamer, P., & Bishop, D. (2012). The recovery of repeated-sprint exercise is associated with PCr resynthesis, while muscle pH and EMG amplitude remain depressed. *PLoS One*, 7(12), e51977.

- Mendez-Villanueva, A., Hamer, P., & Bishop, D. (2008). Fatigue in repeated-sprint exercise is related to muscle power factors and reduced neuromuscular activity. *Eur J Appl Physiol*, *103*(4), 411-419.
- Mero, A. (1988). Force-Time Characteristics and Running Velocity of Male Sprinters during the Acceleration Phase of Sprinting. *Research Quarterly for Exercise and Sport*, *59*(2), 94-98.
- Meylan, C., Cronin, J., & Nosaka, K. (2008). Isoinertial Assessment of Eccentric Muscular Strength. *Strength & Conditioning Journal*, *30*(2), 56-64
10.1519/SSC.1510b1013e31816a37037.
- Meylan, C., McMaster, T., Cronin, J., Mohammad, N. I., & Rogers, C. (2009). Single-leg lateral, horizontal, and vertical jump assessment: reliability, interrelationships, and ability to predict sprint and change-of-direction performance. *The Journal of Strength & Conditioning Research*, *23*(4), 1140-1147.
- Meylan, C., Nosaka, K., Green, J., & Cronin, J. (2011). The effect of three different start thresholds on the kinematics and kinetics of a countermovement jump. *J Strength Cond Res*, *25*(4), 1164-1167.
- Miller, P. C., Bailey, S. P., Barnes, M. E., Derr, S. J., & Hall, E. E. (2004). The effects of protease supplementation on skeletal muscle function and DOMS following downhill running. *J Sports Sci*, *22*(4), 365-372.
- Millet, G. Y. (2011). Can neuromuscular fatigue explain running strategies and performance in ultra-marathons? *Sports Medicine*, *41*(6), 489-506.
- Millet, G. Y., & Lepers, R. (2004). Alterations of neuromuscular function after prolonged running, cycling and skiing exercises. *Sports Med*, *34*(2), 105-116.
- Millet, G. Y., Martin, V., Martin, A., & Verges, S. (2011). Electrical stimulation for testing neuromuscular function: from sport to pathology. *Eur J Appl Physiol*, *111*(10), 2489-2500.
- Millet, G. Y., Morin, J. B., Degache, F., Edouard, P., Feasson, L., Verney, J., & Oullion, R. (2009). Running from Paris to Beijing: biomechanical and physiological consequences. *Eur J Appl Physiol*, *107*(6), 731-738.
- Minett, G. M., & Duffield, R. (2014). Is recovery driven by central or peripheral factors? A role for the brain in recovery following intermittent-sprint exercise. *Front Physiol*, *5*, 24.
- Mirkov, D. M., Nedeljkovic, A., Milanovic, S., & Jaric, S. (2004). Muscle strength testing: evaluation of tests of explosive force production. *Eur J Appl Physiol*, *91*(2-3), 147-154.
- Moir, G., Button, C., Glaister, M., & Stone, M. H. (2004). Influence of familiarization on the reliability of vertical jump and acceleration sprinting performance in

- physically active men. *The Journal of Strength & Conditioning Research*, 18(2), 276-280.
- Mooney, M. G., Cormack, S., O'Brien B, J., Morgan, W. M., & McGuigan, M. (2013). Impact of neuromuscular fatigue on match exercise intensity and performance in elite Australian football. *J Strength Cond Res*, 27(1), 166-173.
- Morin, J. B., Jeannin, T., Chevallier, B., & Belli, A. (2006). Spring-mass model characteristics during sprint running: correlation with performance and fatigue-induced changes. *Int J Sports Med*, 27(2), 158-165.
- Morin, J. B., Tomazin, K., Samozino, P., Edouard, P., & Millet, G. Y. (2012). High-intensity sprint fatigue does not alter constant-submaximal velocity running mechanics and spring-mass behavior. *Eur J Appl Physiol*, 112(4), 1419-1428.
- Morio, C., Chavet, P., Androuet, P., Foissac, M., Berton, E., & Nicol, C. (2011). Time course of neuro-mechanical changes underlying stretch-shortening cycle during intermittent exhaustive rebound exercise. *Eur J Appl Physiol*, 111(9), 2295-2305.
- Murphy, A. J., & Wilson, G. J. (1996). Poor correlations between isometric tests and dynamic performance: relationship to muscle activation. *Eur J Appl Physiol Occup Physiol*, 73(3-4), 353-357.
- Murphy, A. J., & Wilson, G. J. (1997). The ability of tests of muscular function to reflect training-induced changes in performance. *J Sports Sci*, 15(2), 191-200.
- Nedelec, M., McCall, A., Carling, C., Legall, F., Berthoin, S., & Dupont, G. (2012). Recovery in soccer: part I - post-match fatigue and time course of recovery. *Sports Med*, 42(12), 997-1015.
- Nicol, C., Avela, J., & Komi, P. V. (2006). The stretch-shortening cycle : a model to study naturally occurring neuromuscular fatigue. *Sports Med*, 36(11), 977-999.
- Nicol, C., Komi, P. V., & Marconnet, P. (1991). Fatigue effects of marathon running on neuromuscular performance. *Scandinavian journal of medicine & science in sports*, 1(1), 18-24.
- Nielsen, J., Schrøder, H. D., Rix, C. G., & Ørtenblad, N. (2009). Distinct effects of subcellular glycogen localization on tetanic relaxation time and endurance in mechanically skinned rat skeletal muscle fibres. *J Physiol*, 587(14), 3679-3690.
- Nimphius, S., Mcguigan, M. R., & Newton, R. U. (2010). Relationship between strength, power, speed, and change of direction performance of female softball players. *The Journal of Strength & Conditioning Research*, 24(4), 885-895.
- Nuzzo, J. L., McBride, J. M., Cormie, P., & McCaulley, G. O. (2008). Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. *J Strength Cond Res*, 22(3), 699-707.

- Oliver, J., Armstrong, N., & Williams, C. (2008). Changes in jump performance and muscle activity following soccer-specific exercise. *Journal of Sports Sciences*, 26(2), 141-148.
- Osgnach, C., Poser, S., Bernardini, R., Rinaldo, R., & di Prampero, P. E. (2010). Energy cost and metabolic power in elite soccer: a new match analysis approach. *Med Sci Sports Exerc*, 42(1), 170-178.
- Pallares, J. G., Sanchez-Medina, L., Perez, C. E., De La Cruz-Sanchez, E., & Mora-Rodriguez, R. (2014). Imposing a pause between the eccentric and concentric phases increases the reliability of isoinertial strength assessments. *J Sports Sci*, 32(12), 1165-1175.
- Perrey, S., Racinais, S., Saimouaa, K., & Girard, O. (2010). Neural and muscular adjustments following repeated running sprints. *Eur J Appl Physiol*, 109(6), 1027-1036.
- Place, N., Lepers, R., Deley, G. L., & Millet, G. Y. (2004). Time Course of Neuromuscular Alterations during a Prolonged Running Exercise. *Medicine & Science in Sports & Exercise*, 36(8), 1347-1356.
- Place, N., Maffiuletti, N. A., Martin, A., & Lepers, R. (2007). Assessment of the reliability of central and peripheral fatigue after sustained maximal voluntary contraction of the quadriceps muscle. *Muscle Nerve*, 35(4), 486-495.
- Platzer, H. P., Raschner, C., Patterson, C., & Lember, S. (2009). Comparison of physical characteristics and performance among elite snowboarders. *J Strength Cond Res*, 23(5), 1427-1432.
- Prasartwuth, O., Taylor, J. L., & Gandevia, S. C. (2005). Maximal force, voluntary activation and muscle soreness after eccentric damage to human elbow flexor muscles. *J Physiol*, 567(Pt 1), 337-348.
- Pruyn, E. C., Watsford, M. L., Murphy, A. J., Pine, M. J., Spurrs, R. W., Cameron, M. L., & Johnston, R. J. (2012). Relationship between leg stiffness and lower body injuries in professional Australian football. *J Sports Sci*, 30(1), 71-78.
- Pua, Y. H., Koh, M. T., & Teo, Y. Y. (2006). Effects of allometric scaling and isokinetic testing methods on the relationship between countermovement jump and quadriceps torque and power. *J Sports Sci*, 24(4), 423-432.
- Rampinini, E., Bosio, A., Ferraresi, I., Petruolo, A., Morelli, A., & Sassi, A. (2011). Match-related fatigue in soccer players. *Med Sci Sports Exerc*, 43(11), 2161-2170.
- Ratamess, N. A., Kraemer, W. J., Volek, J. S., Rubin, M. R., Gomez, A. L., French, D. N., . . . Dioguardi, F. (2003). The effects of amino acid supplementation on muscular performance during resistance training overreaching. *J Strength Cond Res*, 17(2), 250-258.

- Reilly, T., Morris, T., & Whyte, G. (2009). The specificity of training prescription and physiological assessment: a review. *J Sports Sci*, 27(6), 575-589.
- Requena, B., González-Badillo, J. J., Villareal, E. S. S. d., & Erelina, J. (2009). Functional Performance, Maximal Strength, and Power Characteristics in Isometric and Dynamic Actions of Lower Extremities in Soccer Players. *Journal of Strength and Conditioning Research*, 23(5), 1391-1401.
- Rhea, M. R. (2004). Determining the magnitude of treatment effects in strength training research through the use of the effect size. *J Strength Cond Res*, 18(4), 918-920.
- Robson-Ansley, P. J., Gleeson, M., & Ansley, L. (2009). Fatigue management in the preparation of Olympic athletes. *J Sports Sci*, 27(13), 1409-1420.
- Rodacki, A. L., Fowler, N. E., & Bennett, S. J. (2002). Vertical jump coordination: fatigue effects. *Med Sci Sports Exerc*, 34(1), 105-116.
- Ross, A., Gill, N., & Cronin, J. (2013). Match Analysis and Player Characteristics in Rugby Sevens. *Sports Med*.
- Ross, E. Z., Middleton, N., Shave, R., George, K., & Nowicky, A. (2007). Corticomotor excitability contributes to neuromuscular fatigue following marathon running in man. *Exp Physiol*, 92(2), 417-426.
- Ruotsalainen, I., Ahtiainen, J. P., Kidgell, D. J., & Avela, J. (2014). Changes in corticospinal excitability during an acute bout of resistance exercise in the elbow flexors. *Eur J Appl Physiol*.
- Sanchez-Medina, L., & Gonzalez-Badillo, J. J. (2011). Velocity loss as an indicator of neuromuscular fatigue during resistance training. *Med Sci Sports Exerc*, 43(9), 1725-1734.
- Schmikli, S. L., de Vries, W. R., Brink, M. S., & Backx, F. J. (2012). Monitoring performance, pituitary-adrenal hormones and mood profiles: how to diagnose non-functional over-reaching in male elite junior soccer players. *Br J Sports Med*, 46(14), 1019-1023.
- Schmitz, R. J., Cone, J. C., Copple, T. J., Henson, R. A., & Shultz, S. J. (2013). Lower Extremity Biomechanics and Maintenance of Vertical Jump Height during Prolonged Intermittent Exercise. *J Sport Rehabil*.
- Seiler, S., & Sjørnsen, J. E. (2004). Effect of work duration on physiological and rating scale of perceived exertion responses during self-paced interval training. *Scand J Med Sci Sports*, 14(5), 318-325.
- Sheppard, J. M., Cormack, S., Taylor, K. L., McGuigan, M. R., & Newton, R. U. (2008). Assessing the force-velocity characteristics of the leg extensors in well-trained athletes: the incremental load power profile. *J Strength Cond Res*, 22(4), 1320-1326.

- Sidhu, S. K., Bentley, D. J., & Carroll, T. J. (2009). Locomotor exercise induces long-lasting impairments in the capacity of the human motor cortex to voluntarily activate knee extensor muscles. *J Appl Physiol*, *106*(2), 556-565.
- Sidhu, S. K., Cresswell, A. G., & Carroll, T. J. (2012). Motor cortex excitability does not increase during sustained cycling exercise to volitional exhaustion. *J Appl Physiol*, *113*(3), 401-409.
- Sidhu, S. K., Cresswell, A. G., & Carroll, T. J. (2013). Corticospinal responses to sustained locomotor exercises: moving beyond single-joint studies of central fatigue. *Sports Med*, *43*(6), 437-449.
- Sidhu, S. K., Lauber, B., Cresswell, A. G., & Carroll, T. J. (2013). Sustained cycling exercise increases intracortical inhibition. *Med Sci Sports Exerc*, *45*(4), 654-662.
- Sleivert, G., & Taingahue, M. (2004). The relationship between maximal jump-squat power and sprint acceleration in athletes. *European journal of applied physiology*, *91*(1), 46-52.
- St Clair Gibson, A., Schabert, E., & Noakes, T. (2001). Reduced neuromuscular activity and force generation during prolonged cycling. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *281*(1), R187-R196.
- St Gibson, A. C., Lambert, E. V., Rauch, L. H., Tucker, R., Baden, D. A., Foster, C., & Noakes, T. D. (2006). The role of information processing between the brain and peripheral physiological systems in pacing and perception of effort. *Sports Medicine*, *36*(8), 705-722.
- Stone, M. H., Sands, W. A., Carlock, J., Callan, S., Dickie, D., Daigle, K., . . . Hartman, M. (2004). The importance of isometric maximum strength and peak rate-of-force development in sprint cycling. *J Strength Cond Res*, *18*(4), 878-884.
- Symons, T. B., Clasey, J. L., Gater, D. R., & Yates, J. W. (2004). Effects of Deep Heat As A Preventative Mechanism on Delayed Onset Muscle Soreness. *The Journal of Strength & Conditioning Research*, *18*(1), 155-161.
- Takashima, W., Ishii, K., Takizawa, K., Yamaguchi, T., & Nosaka, K. (2007). Muscle damage and soreness following a 50-km cross-country ski race. *European Journal of Sport Science*, *7*(1), 27 - 33.
- Taylor, J. L., Butler, J. E., & Gandevia, S. (2000). Changes in muscle afferents, motoneurons and motor drive during muscle fatigue. *European journal of applied physiology*, *83*(2-3), 106-115.
- Taylor, K. L. (2012). Fatigue monitoring in high performance sport: a survey of current trends. *Journal of Australian Strength and Conditioning*, *20*(1).

- Taylor, K. L., Cronin, J., Gill, N. D., Chapman, D. W., & Sheppard, J. (2010). Sources of variability in iso-inertial jump assessments. *Int J Sports Physiol Perform*, 5(4), 546-558.
- Tee, J. C., Bosch, A. N., & Lambert, M. I. (2007). Metabolic consequences of exercise-induced muscle damage. *Sports Medicine*, 37(10), 827-836.
- Thorlund, J. B., Michalsik, L. B., Madsen, K., & Aagaard, P. (2008). Acute fatigue-induced changes in muscle mechanical properties and neuromuscular activity in elite handball players following a handball match. *Scand J Med Sci Sports*, 18(4), 462-472.
- Tod, D. A., Iredale, K. F., McGuigan, M. R., Strange, D. E., & Gill, N. (2005). "Psyching-up" enhances force production during the bench press exercise. *The Journal of Strength & Conditioning Research*, 19(3), 599-603.
- Twist, C., & Highton, J. (2013). Monitoring fatigue and recovery in rugby league players. *Int J Sports Physiol Perform*, 8(5), 467-474.
- Twist, C., Waldron, M., Highton, J., Burt, D., & Daniels, M. (2011). Neuromuscular, biochemical and perceptual post-match fatigue in professional rugby league forwards and backs. *Journal of Sports Sciences*, 30(4), 359-367.
- Urhausen, A., & Kindermann, W. (2002). Diagnosis of overtraining: what tools do we have? *Sports Med*, 32(2), 95-102.
- Vollaard, N. B., Constantin-Teodosiu, D., Fredriksson, K., Rooyackers, O., Jansson, E., Greenhaff, P. L., . . . Sundberg, C. J. (2009). Systematic analysis of adaptations in aerobic capacity and submaximal energy metabolism provides a unique insight into determinants of human aerobic performance. *J Appl Physiol (1985)*, 106(5), 1479-1486.
- Wadden, K. P., Button, D. C., Kibele, A., & Behm, D. G. (2012). Neuromuscular fatigue recovery following rapid and slow stretch-shortening cycle movements. *Appl Physiol Nutr Metab*, 37(3), 437-447.
- Watsford, M. L., Murphy, A. J., McLachlan, K. A., Bryant, A. L., Cameron, M. L., Crossley, K. M., & Makdissi, M. (2010). A prospective study of the relationship between lower body stiffness and hamstring injury in professional Australian rules footballers. *Am J Sports Med*, 38(10), 2058-2064.
- Watson, P., Hasegawa, H., Roelands, B., Piacentini, M. F., Looverie, R., & Meeusen, R. (2005). Acute dopamine/noradrenaline reuptake inhibition enhances human exercise performance in warm, but not temperate conditions. *J Physiol*, 565(Pt 3), 873-883.

- Webb, N., Harris, N., Cronin, J., & Walker, C. (2012). The Relative Efficacy of Three Recovery Modalities Following Professional Rugby League Matches. *J Strength Cond Res*, 27(9), 2449-2455.
- Wilson, G. J., & Murphy, A. J. (1996). The use of isometric tests of muscular function in athletic assessment. *Sports Med*, 22(1), 19-37.
- Wilson, G. J., Walshe, A. D., & Fisher, M. R. (1997). The development of an isokinetic squat device: reliability and relationship to functional performance. *Eur J Appl Physiol Occup Physiol*, 75(5), 455-461.
- Wisløff, U., Castagna, C., Helgerud, J., Jones, R., & Hoff, J. (2004). Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *British Journal of Sports Medicine*, 38(3), 285-288.