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Monitoring neuromuscular fatigue in high performance athletes

Kristie-Lee Taylor
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Monitoring Neuromuscular Fatigue in High Performance Athletes

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This thesis is submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy (Sports Science)

AUGUST 2012

DECLARATION

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ABSTRACT

With improving professionalism of sports around the world, the volume and frequency of training required for competitive performances at the elite level has increased concurrently. With this amplification in training load comes an increased need to closely monitor the associated fatigue responses, since maximising the adaptive response to training is also reliant on avoiding the negative consequences of excessive fatigue. The rationale for the experimental chapters in this thesis was established after considering survey responses regarding current best practice for monitoring fatigue in high performance sporting environments (Chapter 3). On the basis of the results, vertical jump assessments were selected for further investigation regarding their utility in determining neuromuscular fatigue responses. Outcomes from the subsequent series of studies aimed to provide practitioners working in high performance sport with guidelines for using vertical jumps to monitor athletic fatigue.

The results from Chapter 4 indicate using the mean value of at least six jumps enhances the ability to detect small but practically important changes in performance from week to week. This study also highlighted large differences (4-6%) in morning and afternoon performance, indicating that the time of day performance is assessed needs to be accounted for when monitoring changes in jump performance. Chapter 5 explored the theory that the time of day effect observed in Chapter 4 can be explained by internal temperature differences. This theory was supported by demonstrating that an extended warm-up period can negate differences in jump performance in the morning and the afternoon. Researchers who are unable to standardise the time of day that assessment occurs are able, therefore, to control for performance differences by manipulating the warm-up protocols.

The third study examined changes in vertical jump performance over a three month training period and produced several novel outcomes. A major finding was that unloaded jumps were more sensitive to neuromuscular fatigue during intensive training than loaded jumps (Chapter 6). Furthermore, this set of results showed that all subjects changed their jump technique via a reduction in the amplitude of the countermovement when they were highly fatigued. Using the same data, an analysis was performed to quantify individual differences in within-subject variation (Chapter 7) during normal and intensive training. These results provided the first

indication that within-subject variability in vertical jump performance is substantially different between individuals and between different training phases, an important consideration for interpreting the practical importance of performance changes.

In Chapter 8 the relationship between vertical jump performance and electrically elicited force of the knee extensors was examined to better understand the mechanism(s) of changes in jump performance associated with neuromuscular fatigue during intensive overload training. The results showed that the fatigue assessed by vertical jump performance was likely not only peripheral in origin as previously suggested by other authors. Further research is required to further understand the mechanisms of reduced performance during overload training, although the preliminary evidence presented implicates central mechanisms. To conclude the thesis, the findings presented in the experimental chapters are summarised, with a series of practical recommendations for using vertical jumps to monitor athletic fatigue presented.

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PUBLICATIONS ARISING FROM THIS THESIS

Refereed Journal Articles

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Taylor KL, Cronin JB, Gill ND, Chapman DW and Sheppard JM. (2011) Sources of variability in iso-inertial jump assessments. *International Journal of Sports Physiology and Performance*, 5(4): 546-558.

Taylor KL, Cronin J, Gill N, Chapman D and Sheppard J. (2011) Warm-up affects diurnal variation in power output. *International Journal of Sports Medicine*, 32: 185-189.

Taylor KL, Hopkins WG, Chapman DW, Cronin JB, Newton MJ, Cormack SJ, and Gill ND. (In review) Monitoring neuromuscular fatigue using vertical jumps. *International Journal of Sports Medicine*.

Taylor KL, Hopkins WG, Chapman DW and Newton MJ. (In review) Error of measurement in jump performance is influenced by training phase. *International Journal of Sports Physiology and Performance*.

Taylor KL, Chapman DW, Newton MJ, Cronin JB and Hopkins WG. (In review) Relationship between changes in jump performance and laboratory measures of low frequency fatigue. *Journal of Sports Medicine and Physical Fitness*.

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A statement of contribution of others is provided for each publication in Appendix B.

Peer-Reviewed Conference Proceedings

Taylor KL, Mitchell J, Cronin JB, (2008). Diurnal variation associated with dynamic power output and variability in performance. New Zealand Sports Medicine and Science Conference. Dunedin, New Zealand.

Taylor KL, Barker M, Cronin JB, Gill ND, Chapman DW, and Sheppard JM. (2009). The effect of an extended warm-up on diurnal performance differences in loaded counter-movement jumps. NSCA National Conference. Las Vegas, USA.

Taylor KL, Cronin JB, Newton MJ, Gill, ND, and Chapman, DW. (2010). Validation of a practical test for measuring neuromuscular fatigue in athletes. European Congress of Sport Science Congress. Antalya, Turkey.

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CHAPTER ONE

Introduction and Overview

1.1. THESIS RATIONALE

With improving professionalism of sports around the world, the volume and frequency of training required for competitive performances at the elite level has increased concurrently, with this phenomenon also evident at the sub-elite levels of sports performance [200]. Along with this amplification in training load comes an increase in the need to closely monitor the associated fatigue responses, since maximising the adaptive response to training is also reliant on avoiding the negative consequences of excessive fatigue. Athlete fatigue however, is a difficult concept to define, making its measurement equally problematic. In much of the scientific literature the definition of ‘fatigue’ is limited to a reduction in force producing capabilities of an isolated muscle group, often measured in an isometric condition. The rationale for this type of assessment is that it affords researchers the scope to investigate mechanisms associated with central and/or peripheral neuromuscular fatigue. Mechanisms investigated can include reduced central activation, excitation-contraction coupling failure, or limitations in energy supply and/or the accumulation of metabolites within the muscle fibre. There are various commonly accepted methods for understanding short-term fatigue within the elite sporting environment. However there is some debate as to how to best quantify longer lasting neuromuscular fatigue within this elite sporting context. Laboratory methods for the assessment of neuromuscular fatigue are relatively standardised however, they are also invasive, time consuming and costly. This differs to the methods used in applied sport science research and the day to day training environment of high performance sports, where tests of performance employing complex multi-joint movements, such as vertical jumping, are preferred and may provide insight into neuromuscular fatigue. This method is more convenient, has greater ecological validity and is easier to implement, allowing for regular assessment of large groups of athletes.

While vertical jumps provide many advantages, there are a number of important methodological considerations still to be addressed when using changes in performance to influence training prescription. For example, practitioners require information regarding the magnitude of changes in jump outcomes that affect training and competition performance, and an indication of which kinetic and kinematic variables are most useful for monitoring these changes. Another limitation in using tests of this nature as a measure of neuromuscular fatigue is that it is not possible to elucidate any information regarding the aetiology of

reductions in performance. More information about the relationship between changes in these parameters and what is happening at the muscular level is needed.

The purpose of this thesis is to investigate a variety of practical methods for monitoring fatigue in athletes in order to effectively ascertain readiness for continued training and evaluating training responses in the regular training environment of the high performing athlete. Along with establishing the relationship between laboratory and practical measures of neuromuscular fatigue, this series of studies investigates a range of methods for monitoring changes in neuromuscular fatigue during periods of high training stress, providing recommendations about the best analytical model for confidently detecting changes that are practically important for athletes on an individual basis.

1.2. SIGNIFICANCE OF THE RESEARCH

The research studies that comprise this thesis aimed to develop a practical system for measuring neuromuscular fatigue in athletes involved in intensive training and competition. This body of work builds on previous research [60, 62, 65, 66] by expanding the analysis to include a more comprehensive set of dependent variables and using innovative statistical approaches to quantify and interpret changes in performance. It also includes comparative analyses of practical field-based measures of performance with previously established clinical measures of neuromuscular fatigue, which has not been comprehensively documented previously.

Along with information gathered from the scientific literature, the rationale for the experimental chapters in this thesis was developed by surveying 100 participants involved in coaching or sport science support roles in a variety of high performance sports programs to devise a list of current best practice methods for monitoring athlete fatigue and recovery (Chapter 3), ensuring that the research outcomes are relevant to the high performance sports environment.

The findings from the research studies undertaken during the doctoral studies have the potential to provide coaches of high performance athletes with an objective measurement tool for monitoring the neuromuscular and fatigue responses to varied training and competition loads. Such an objective measurement can assist coaches in decision-making

regarding an athlete's readiness for continued high intensity training and/or competition; and may bring us closer to mastering the task of ensuring optimal physical performance at crucial competitive events.

1.3. AIMS OF THE THESIS

The aims of this thesis are to:

1. Describe the current methods employed in monitoring fatigue in high performance training environments (Chapter 3).
2. Understand the thresholds currently used for determining practically important changes in functional performance capacity (Chapter 3).
3. Establish the normal variation associated with kinetic and kinematic variables measured during non-consecutive vertical jumps via a linear position transducer (Chapter 4).
4. Examine how this variation can be reduced such that small but practical changes in performance are discernible (Chapters 4 and 5).
5. Investigate if alterations in body temperature (via an active warm-up) reduce performance differences due to diurnal variation, ensuring that valid maximal performance results can be obtained independent of the time of day that assessment occurs (Chapter 5).
6. Examine differences in sensitivity of kinetic and kinematic variables to high levels of neuromuscular fatigue (Chapter 6).
7. Examine the relationship between changes in laboratory-based measures of peripheral neuromuscular fatigue and performance-based measures of force and power in a counter-movement jump (Chapter 8).
8. Provide recommendations for the measurement and analysis of changes in performance capacity when athletes are exposed to a variety of training stimuli (Chapters 7 and 9).

1.4. THESIS STRUCTURE

This thesis is submitted in the form of a series of published papers. The current chapter, along with the review of literature in Chapter 2 form the theoretical basis and rationale for this thesis, while Chapter 3 investigates anecdotal evidence that the methods for monitoring fatigue popularly presented in the scientific literature do not accurately reflect what is currently practiced in the high performance training environment. Given the high popularity of vertical jumps for monitoring neuromuscular fatigue in applied sport science research and the high performance training environment, the experimental chapters (4,5,6,7 and 8) investigate their utility. Chapter 9 concludes the thesis by integrating the results from the experimental chapters and providing recommendations for the use of vertical jumps as a fatigue monitoring tool.

The papers comprising Chapters 3, 4 and 5 have all been published within the period of candidacy, with post-print versions of the manuscripts included in Appendix A. Chapters 6, 7 and 8 have been submitted for publication and are currently in the review process. Those chapters are presented herewith in the format of the journal to which they have been submitted. An overall reference list from the entire thesis has been collated at the end of the thesis.

CHAPTER TWO

Methods for monitoring fatigue in athletes: a review

2.1. SYNOPSIS

This review of literature begins by examining the role of fatigue in inducing training adaptations, along with the short and long-term consequences of insufficient recovery between training bouts. The definition of fatigue and the use of the term in the scientific literature is considered by discussing how differences in definitions may influence the methods used to investigate accumulated training-induced fatigue. The following section aims to bring together the relevant areas of physiological investigations into the fatigue and recovery responses of athletes to single exercise bouts, which is most commonly investigated, and consider responses to successive sessions, where empirical data is lacking. Finally, current systems for monitoring fatigue are reviewed, with methodological considerations for each method evaluated in reference to the regular use for monitoring in the high performance training environment.

2.2. THE INFLUENCE OF PROGRAM DESIGN ON FATIGUE

The supercompensation model is the most straightforward representation of the training adaptation process [104]. It is a concept that is ingrained in the philosophy of almost all sports coaches and sports scientists responsible for the planning and management of training programs for elite athletes. The concept holds that whenever an athlete is subjected to an overloading training stimulus that causes fatigue (strain), the body will re-organise its capacities such that the next exposure to the same stimulus will produce less strain, given that sufficient recovery has occurred between exposures. In this process the length of time required for recovery or regeneration depends primarily upon the magnitude of the initial overload and the subsequent displacement in homeostasis. In order to achieve supercompensation in performance, traditional training theory advises that each new training stimulus should not begin until the perturbations from the previous training bout has been fully restored or over-restored [34, 173, 201, 262]. Figure 2.1 illustrates this process, showing sufficient recovery between successive exposures to a training stimulus. Since the exposure to the next training stimulus occurs when the maximum training effect from the previous session has been gained, continual improvements are achieved. This is replicated with each session so that repeated exposures result in an accumulated positive training effect.

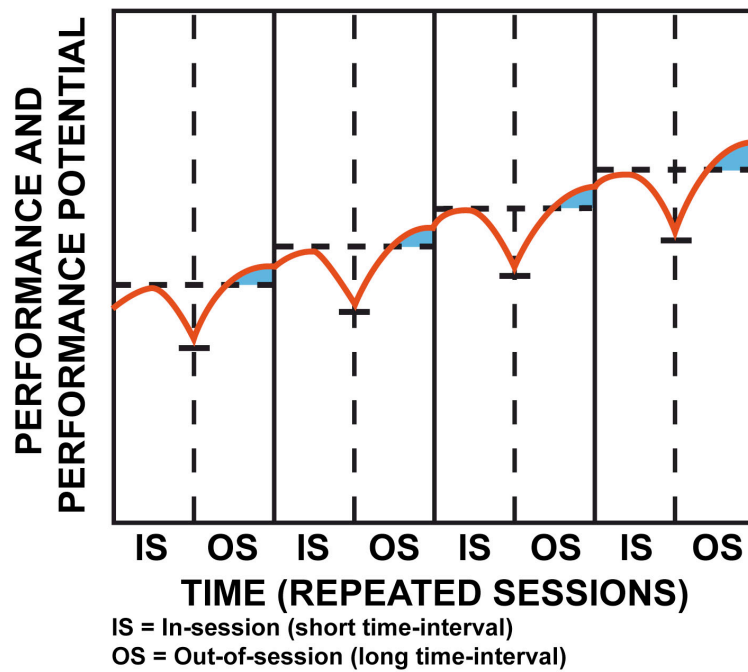


Figure 2.1 Stylized presentation of the responses to successive training stimuli when sufficient recovery between exposures is provided (Adapted from Rushall & Pyke 1990, p33).

There is however a limit to how much athletes can improve using this approach. More recent theories and recommendations advocate that physical loads should be systematically repeated without allowing for full restoration of homeostasis [272]. This leads to an accumulation of the immediate training effects whereby the additional fatigue-after effects superimpose existing ones, intensifying inadequate adaptation [26]. This process of inducing a “valley of fatigue”, where stress accumulates over periods of days or weeks, requires careful planning of the training program. Continual monitoring of individual responses to the load becomes even more important, since there is a critical point or threshold for each athlete where their reserve capacities cannot cope with the accumulated fatigue [173]. If this threshold is surpassed, maladaptation to training can occur, resulting in continual performance decrements and a state of overtraining (Figure 2.2). To avoid the occurrence of maladaptation, an optimal training program needs to monitor/assess the individual athlete’s current tolerance of stress or fatigue [298]. The remainder of this review will explore current methods available for monitoring fatigue and responses to training stressors with the aim of maximising performance and minimising the risk over overtraining.

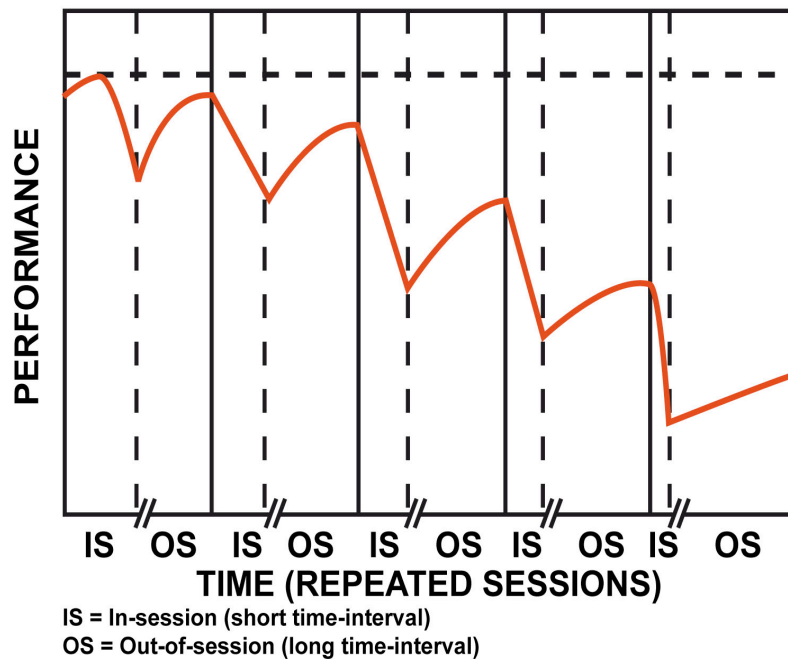


Figure 2.2 Stylized presentation of the responses to successive training stimuli when insufficient recovery between exposures is provided (Adapted from Rushall & Pyke 1990, p34).

2.3. AETIOLOGIES OF FATIGUE AND ASSOCIATED RECOVERY PROFILES

In coaching texts on training theory and program design the term fatigue is often not explicitly defined, but rather referred to generally as a reduced performance capacity following training. In the scientific literature, fatigue is used in a variety of contexts. Abiss and Laursen [1] suggested that the definition of fatigue in scientific investigations has typically been manipulated to answer diverse research questions in different sports science disciplines, resulting in multiple interpretations of the term. They give the following examples of how fatigue may be defined depending on the discipline being studied:

- Biomechanics: a reduction in force output of a muscle, or a reduction in efficiency
- Psychology: the sensation or perception of tiredness, or a decrease in cognitive function
- Physiology: a limitation of a specific physiological system, such as the inability of the heart to supply ample blood flow to working tissues or failure in the muscle excitation-contraction coupling process
- Neurology: reduced motor drive or neural activation

In addition, people may present clinically as being ‘fatigued’ based on subjective feelings of general tiredness [192]. This review will be mostly limited to physiological fatigue responses to exercise, however even within this realm, differences are still apparent in the way that fatigue is described and subsequently investigated. Throughout the remainder of this treatise fatigue is discussed in the context of a reduction in overall performance capacity; however, there are still a number of perspectives from which this reduction should be considered [176].

2.3.1. Task failure and acute muscle fatigue

Physiological fatigue is often defined as the failure to maintain a required or expected force output [81], or the inability to continue working at a given intensity [35]. The mechanisms responsible for fatigue have been extensively reviewed [7, 85, 91, 107], however the aetiologies have yet to be clearly established since multiple factors such as fibre type composition of the contracting muscle(s), the intensity, type, and duration of contractile activity, and the individual degree of fitness all influence the manifestation of fatigue in varying situations [91].

Task failure specifically denotes fatigue that develops during sustained activity and results in the inability to continue working at a given intensity. Enoka [84] outlined nine processes within the neuromuscular system that can be impaired during exercise, leading to a reduction in force production capabilities. These include; (1) activation of the primary motor cortex, (2) central nervous system drive to the motor neurons, (3) the muscles or motor units that are activated, (4) neuromuscular propagation, (5) excitation-contraction coupling, (6) the availability of metabolic substrates, (7) the intracellular milieu, (8) the contractile apparatus, and (9) muscle blood flow (Figure 2.3).

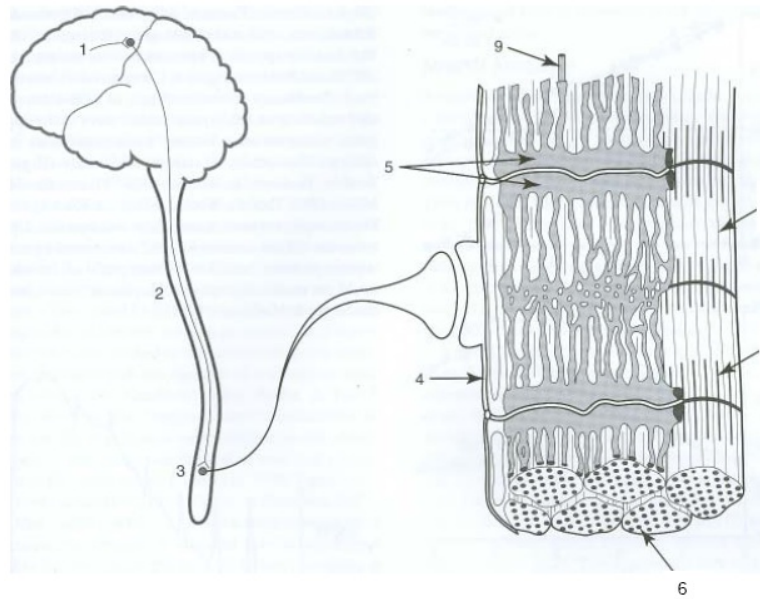


Figure 2.3 Locations of the nine processes that may contribute to fatigue during physical activity (Enoka, 2002; p.375)

Within this collection of processes there are a number of both central and peripheral factors. The functional importance of central processes in the manifestation of fatigue have been dismissed by many authors, with modern reviews of muscle physiology proceeding on the premise that the reduction in force production by volition occurs within the muscle itself [7, 91, 312]. These authors argue that the influence of central mechanisms on fatigue is minimal and can therefore be ignored. Other experts disagree arguing that efferent neural commands produce change in the output of motor cortical cells, the spinal interneuronal input to motoneurons and the discharge frequencies of motoneurons [105, 285, 290]. The popular central governor theory [184, 226, 286] contends that the reduction in efferent neural commands are a response to afferent feedback that enables the athlete to subconsciously ‘anticipate’ the demands of the exercise task, and select the best pacing strategy to accomplish it most effectively. More specifically, sensory information from the periphery is integrated by the brain to determine appropriate exercise behaviours that ensure bodily homeostasis [225]. This theory is dismissed by Marcora who advocates that exercise performance is not influenced by afferent feedback [194, 195]. Instead, in his psychobiological model of fatigue he proposes conscious self-regulation of exercise intensity is determined primarily by cognitive/motivational factors [195]. Whilst much of the literature makes a distinction between peripheral and central fatigue, most authors agree that both pathways are likely integrated [256]. The complexity of this integration, as well as

the interplay between centrally regulated (subconscious) and cognitive/motivational (conscious) fatigue models, has sparked intense debate in the scientific community [9, 10, 195, 234], although most authors agree that fatigue is a complex process and its understanding should not be reduced to a single isolated phenomenon [235].

The occurrence of central fatigue is predominantly indicated by an increase in the increment in force evoked by electrical or magnetic stimulation of the motor nerve or musculature during a maximal voluntary effort. While excitation provided by supraspinal centres is generally not impaired during brief high-force contractions, it can be during prolonged maximal and submaximal contractions [84, 290]. During such prolonged contractions the progressive decline in force is generally accompanied by a progressive increase in the absolute force increment obtained by electrical or magnetic stimulation (e.g. [190, 259]) with the decline referred to as central fatigue. In a sports performance context, reductions in central activation have been observed during and after numerous forms of exercise, including squash match-play [112], tennis match-play [111], prolonged cycling [181], downhill running [199], and marathon [259] and ultramarathon running [213]. The underlying causes of central fatigue mechanisms are complex and still not fully understood, however Taylor and Gandevia [290] presented three actions involving the motoneuron pool that might lead to motoneuron slowing. These include a decrease in excitatory input, an increase in inhibitory input (e.g. firing of Type III and IV afferent fibres commensurate with metabolite build-up or muscle damage), and a decrease in the responsiveness of the motoneurons through a change in their intrinsic properties (late adaptation). It is further suggested that all three actions are likely to occur during prolonged fatiguing activities.

The division of centrally and peripherally mediated fatigue responses is generally drawn at the level of the neuromuscular junction. A much greater volume of work has examined fatigue induced changes in the neuromuscular landscape at the peripheral level, perhaps due to the predominance of peripheral factors in intense exercise [153, 284]. In Figure 2.3 it is shown that numerous post-synaptic sites within the muscle fibre can contribute to muscle fatigue. Neuromuscular propagation, excitation-contraction coupling, the availability of metabolic substrates, metabolic changes within the intracellular milieu, and muscle blood flow can all influence the effectiveness of muscular contractions and the resultant force output.

Excitation-contraction (E-C) coupling describes a complex sequence of events necessary for converting an action potential to cross-bridge formation in muscle cells [239]. Within this sequence of events are a number of potential sites for muscle fatigue, however the entire pathway is still not fully understood [114, 310], making the identification of the mechanisms of E-C coupling failure difficult. The sequence begins with the initiation and propagation of an action potential along the sarcolemma and transverse-tubular system. Effective neuromuscular propagation is assessed via changes in the compound muscle action potential (M-wave) amplitude, with reduced amplitude indicating impairment in the conversion of axonal action potential into a sarcolemmal action potential. Several processes are involved in this conversion, including branch-point failure (failure of the axonal action potential to invade all the branches of the axon), a failure of excitation-secretion coupling in the pre-synaptic terminal, a depletion of neurotransmitter, a reduction in the quantal release of neurotransmitter, and a decrease in the sensitivity of the post-synaptic receptors and membrane [84]. In addition to changes in M-wave amplitude, impairments in action potential propagation over the sarcolemma can be assessed via changes in high frequency stimulated force output. Reductions in force output in response to high frequency stimulation indicates an inability to generate action potentials repeatedly at the high frequencies required for maximal or near maximal force generation by the fibre, which may result in a failure to translate fully the neural signal to the interior of the fibre. This form of fatigue, often referred to as high frequency fatigue, appears to occur because of an inability to restore Na^+ and K^+ gradients across the sarcolemma before the next neural impulse [57]. Reductions in M-wave amplitude tend to occur in long-duration, low-intensity contractions and less frequently in short-duration, high-intensity contractions [28, 92], whereas changes in high frequency stimulated force output have been observed after maximal stretch-shortening cycle (SSC) exercise of short duration [289, 295].

Along with alterations in excitability and action potential conduction, excitation-contraction coupling involves changes in the contractile apparatus, where cross-bridge formation is impaired during fatiguing exercise. The most likely ionic cause of altered cross-bridge kinetics are elevated intracellular Ca^{2+} levels [41, 310], which reduces the release of Ca^{2+} from the sarcoplasmic reticulum [8], consequently reducing the number of activated cross-bridges [84, 163, 312]. In addition to limiting cross-bridge activation, this failure of calcium regulation at the level of the contractile elements can also lead to slowing of relaxation [7, 8,

91, 305] which can limit performance during dynamic exercise where rapidly alternating movements are performed.

Along with ionic changes in the muscle cell, disturbances in E-C coupling may also be a result of damage to the structure of the muscle fibre [91, 162, 222, 310] or an indication of the remodelling process of muscle during adaptation [69, 94, 318]. Injury to skeletal muscle fibres may occur during shortening, isometric or lengthening contractions, although the probability of injury is greatest during lengthening contractions [88]. Certainly in high-intensity exercise the degree of muscle injury has been shown to increase at long fibre lengths [164, 222], most likely due to the higher force that can be generated [114]. A number of underlying mechanisms are proposed to be responsible, including structural damage [95] and dislocation of long or weak sarcomeres due to overstretching [41] as well as disruptions to the muscle membrane itself. The magnitude of the injury and the recovery process can be assessed directly with measures of cellular and ultrastructural damage, or indirectly with various imaging techniques (MRI, ultrasonography), changes in enzyme efflux, calcium efflux, measures of isometric and dynamic strength loss, and in humans via reports of muscle soreness [88].

Following intense muscular contractions metabolic changes are closely correlated with observed decreases in force capacity. At high intensities fatigue is characterised by marked depletion of high energy phosphate stores in the active muscle. Complete restoration of these stores requires 2-5 mins [264, 296], which has been shown to coincide with the restoration of contractile force after short duration, high-intensity exercise [264]. During these exercise conditions (short duration, high intensity exercise), glycogen levels remain high, whereas glycogen depletion has frequently been associated with fatigue during prolonged, submaximal exercise [91, 114, 263] where endurance capacity is closely related to the pre-exercise level of muscle glycogen [136]. It is thought that glycogen depletion may also trigger functional changes in the sarcoplasmic reticulum or other cell organelles, suggesting its causative role in muscle fatigue may be independent of its role in energy production [91].

In addition to the depletion of energy stores, the accumulation of metabolites resulting from energy conversion also affects the ability of the muscle to produce force. The accumulation of ADP, inorganic phosphate and H^+ serves not only to reduce the free energy liberated by

ATPase hydrolysis, but also to cause a profound down-regulation in ATPase activity [114] and slowing of the actin-myosin interaction and the rate of cross-bridge dissociation [30, 45, 73]. However, while good temporal correlations have been observed between the reduction of force and pH, more recent studies have challenged the force depressing role of H^+ at physiological temperatures [233, 246, 313]. Experimental studies have also shown that although H^+ remains elevated, contraction force is completely restored after ~2 mins of recovery, [264]. Similarly, after maximal cycling, peak power output is restored with a similar time course as phosphocreatine [221], while inorganic phosphate and muscle force followed similar time courses, recovering within 5 minutes of short duration exercise [24]. Such evidence suggests this accumulation of hydrogen ions and lactate is probably of limited importance in causing fatigue in mammals [7, 312].

2.3.3. Long-lasting muscle fatigue and dysfunction

The time course of recovery from centrally mediated fatigue following exercise has been documented to take 2-3 minutes after high intensity or maximal contractions and greater than 10 minutes after long-lasting submaximal efforts [290]. Other authors have shown central activation to be near maximal both before and after fatiguing dynamic contractions [175, 188] and running protocols [273]. Indications from studies assessing central activation during and subsequent to prolonged running and cycling suggest that recovery of centrally mediated responses exceeds 30 minutes [238]. It is unclear whether these longer lasting effects are due to central sensitisation or continuing afferent activity, though it is feasible that continued (or de novo) afferent firing may be particularly relevant after exercise which results in significant muscle damage [212, 290]. It is suggested that some of these ‘central’ features may disrupt performance more than the reduction in maximal muscle force [106]. However apart from acute laboratory fatiguing tasks and one off performances of long lasting cyclic exercise, few studies have reported the instances of such fatigue after a typical training bout. Nor have many, if any, attempts been made to quantify centrally mediated responses after multiple or successive training sessions. It is therefore apparent that more data is needed to map the recovery profile of centrally mediated fatigue mechanisms in order to understand the implications in the regular high performance training environment.

At the peripheral level a number of the identified processes proposed to be responsible for acute muscular fatigue recover soon after cessation of activity. It is widely accepted that the

involvement of metabolic factors in the slow recovery of force is unlikely given the different time courses of reversal of the metabolic changes and recovery of force [7, 41, 91, 264]. Similarly, alterations in muscle blood flow return to normal almost immediately [265, 308]. The impairment of action potential propagation following high-intensity, short duration exercise has been shown to recover within 5 to 10 minutes of cessation of activity, with authors advocating that this mechanism is unlikely to explain the slow recovery of force after fatigue [28, 32, 41, 103]. In contrast, contractions repeated for longer durations appear to induce greater alterations, with studies showing depressed M-wave amplitudes for a minimum of 15 minutes following supramaximal cycling [13] and progressive cycling to fatigue [159]. Additionally, reduced sarcolemmal excitability persisted for two days following 22 days of endurance cycling [258]. Such findings suggest that high frequency fatigue may persist longer than traditionally reported, especially following longer duration activity or repetitive exercise on consecutive days.

The most likely and accepted peripheral mechanism responsible for delayed recovery after a single exercise bout lies within the excitation-contraction-relaxation processes. A large volume of scientific investigations have focused on describing the time course of force recovery from acute fatiguing interventions using high- and low-frequency stimulated contractions. It has been shown that low frequency force is often selectively affected in the hours and days after a fatiguing intervention. This phenomenon has been termed low frequency fatigue (LFF) and was first described by Edwards and colleagues [82] who observed that the contractile responses to low frequency stimulation were diminished to a greater extent than responses to high frequency stimulations in the hours or days after fatiguing exercise. Along with affecting performance via reduced force production capabilities, the occurrence of LFF may also affect central drive and sense of effort experienced during voluntary contractions, as well as the activation pattern needed to produce targeted levels of force [169]. It is suggested that these alterations are perceived by athletes as heavy legs, which is especially apparent during low exercise intensities and daily activities [93, 301]. Table 2.1 highlights selected in-vivo studies reporting the recovery profile of high and low frequency stimulated force of the leg extensor muscles following a variety of acute dynamic fatiguing interventions. While most of these studies confirm prolonged recovery of force measured at low stimulation frequencies due to impairments in excitation-contraction coupling, it is interesting to note that there are also many observations of depressed high frequency stimulated force at concurrent time points. This is in contrast to

much of the literature suggesting high frequency fatigue generally develops to its maximum 1-2 h after the end of the fatiguing contraction and then dissipates well before low frequency force is restored [82].

Along with controlled studies measuring changes in neuromuscular function in the laboratory, numerous studies have tracked changes in “neuromuscular performance” via tests of functional performance following a variety of exercise bouts (Table 2.2). It is thought that such investigations are useful in establishing the minimum recovery period necessary for repeating maximal performance in competitive periods. In these studies there is no scope to investigate the mechanism/s responsible for slow recovery of performance, and often the authors assume a relationship between neuromuscular fatigue measured at the muscular level and functional performance tests. The relationship between neuromuscular fatigue measured at the muscular level and functional performance tests have not been investigated extensively. However support for the use of functional performance tests such as a countermovement jump (CMJ) to represent neuromuscular fatigue was presented by Raastad and Hallen, [241]. Raastad and Hallen observed similar patterns of change in low frequency twitch force and jump height during recovery from a bout of heavy resistance exercise strength trained athletes. Conversely Petersen et al., [236] observed a decrease in muscle power during a CMJ, without concomitant changes in muscle twitch characteristics following a marathon, suggesting peripheral fatigue was not responsible for the changes in CMJ performance. Skurvydas and colleagues concluded that that relationship between functional performance tests and LFF following 100 maximal intensity drop jumps was unclear, with decreases in low frequency twitch force larger than the observed decreases in jump height [275, 278]. While these studies together provide some indication of a relationship between LFF and jump performance after a variety of acute fatiguing protocols, the mechanisms responsible for reduced performance following exercise remain unknown if the time course of recovery is mapped solely using tests of functional performance.

Table 2.1 Studies showing delayed recovery of maximal voluntary force and force in response to high- and low-frequency stimulation of leg extensor muscles in-vivo after acute dynamic fatiguing interventions.

FATIGUING EXERCISE	SUBJECTS	MEASURED PARAMETERS	PRE-POST DECREASE	RECOVERY TIME
SSC EXERCISE TASKS				
60 mins box-stepping at a fixed rate of 20 steps/min [72]	Males (n=5)	Peak twitch torque	25%	> 20 h
		Tetanic torque (20Hz)	55%	> 20 h
		20-50Hz ratio	not reported	> 20 h
100 drop jumps performed intermittently (every 20s) [276]	Healthy untrained males (n=12)	MVC	23%	> 24 h
		Tetanic torque (20Hz)	72%	> 24 h
		Tetanic torque (50Hz)	37%	> 24 h
		20-50Hz ratio	52%	> 24 h
		CMJ height	not reported	> 24 h
100 drop jumps performed continuously (5 bouts of 20 jumps with 10s between bouts) [276]	Healthy untrained males (n=12)	MVC	19%	> 24 h
		Tetanic torque (20Hz)	50%	> 24 h
		Tetanic torque (50Hz)	23%	> 24 h
		20-50Hz ratio	37%	> 24 h
		CMJ height	44%	> 24 h
100 drop jumps [278]	Healthy untrained males (n=11)	MVC	17%	> 72 h
		Tetanic torque (20Hz)	70%	> 72 h
		Tetanic torque (100Hz)	50%	> 72 h
		Drop jump height	10%	> 72 h
RESISTANCE EXERCISE PROTOCOLS				
10 x 10 back squats 70% 1RM [118]	Strength athletes males (n=10) females (n=9)	MVC (males)	47%	48 h
		MVC (females)	29%	24 h
20 x 1 back squat 100& 1RM [117]	Strength athletes males (n=10) females (n=9)	MVC (males)	24%	2-24 h
		MVC (females)	21%	2-24 h
Isotonic RE protocol consisting of 3x3 back squat +front squat; 3x6 knee extensions using 100% RM [241]	Male strength athletes (n=8)	Isokinetic knee extension	~13%	30-33 h
		Tetanic torque (20Hz)	~40%	30-33 h
		Tetanic torque (50Hz)	~22%	26-33 h
		SJ height	12%	30-33 h
Isotonic RE protocol consisting of 3x3 back squat +front squat; 3x6 knee extensions using 70% RM [241]	Male strength athletes (n=8)	Isokinetic knee extension	~7%	<3 h
		Tetanic torque (20Hz)	~21%	26-33 h
		Tetanic torque (50Hz)	~12%	26-33 h
		SJ height	ns Δ	<3 h
PROLONGED CYCLIC EXERCISE				
Cycling at ~60% VO ₂ peak or for a maximum of 2 h (repeated over 2 days) [287]	Active, untrained students males (n=6) females (n=6)	MVC	~13%	> 3 d
		Tetanic torque (10Hz)	35-40%	> 3 d
		Tetanic torque (100Hz)	ns Δ*	> 3 d

* non-significant decreases immediately following exercises were followed by a reduction at subsequent time points.
Abbreviations: CMJ; countermovement jump, SSC; Stretch-shortening cycle, MVC; maximal voluntary contraction, ns Δ; non-significant change

Table 2.2 Studies showing delayed recovery after acute fatiguing interventions using tests of functional performance.

FATIGUING EXERCISE	SUBJECTS	MEASURED PARAMETERS	PRE-POST DECREASE	RECOVERY TIME
10 x 10 back squats 70% 1RM [43]	Healthy males (n=5) and females (n=3)	MVC CMJ height SJ height DJ height	~ 20% ~ 9% ~ 14% ~ 10%	4-7 days 3-4 days 3-4 days 3-4 days
Australian Rules Football (ARF) match [60]	Professional ARF players (n=22)	CMJ flight time CMJ mean power	4% 9%	> 24 h > 24 h
Plyometric exercise [51]	Healthy recreationally trained men (n=24)	MVC CMJ height SJ height	ns Δ 8% 8%	na 72-96h 72-96h
Ironman Triathlon [227]	Experienced, well-trained triathlete (n=1)	MVC CMJ and SJ height	50% 50%	≤ 24 h ≤ 8 d
Rugby league match [204]	Professional rugby league players (n=12)	CMJ height CMJ power	not reported not reported	4-48h 4-48h
Rugby league match [205]	Professional rugby league players (n=17)	CMJ peak force CMJ peak power CMJ PRFD	19% 30% 36%	< 24 h 24-48 h 24-48 h
Intercollegiate soccer match [139]	Female soccer players (n=19)	CMJ peak power CMJ peak force SJ peak power SJ peak force	ns Δ ns Δ ns Δ ns Δ	16% reduction at 24 h 9% reduction at 24 h 12% reduction at 24 h 9% reduction at 24 h
High intensity strength training session [110]	Club standard rowers (n=8)	CMJ height SJ height	18% at 2h 10% at 2h	> 48 h > 48 h
International football match [11]	Elite female soccer players (n=22)	20 m sprint CMJ height	3% 5%	< 5 h > 69 h
Friendly soccer match [16]	Junior male soccer players (n=22)	CMJ height SJ height 20 m sprint	not reported not reported ns Δ	> 48 h > 48 h na

Key: BM – body mass; KE – knee extensor; CMJ – countermovement jump; SJ – squat jump; DJ – drop jump; ns Δ – non-significant change from baseline

2.3.4. Fatigue accumulated during repetitive exercise bouts: neuromuscular properties

Much effort has been devoted to understanding the factors that limit human performance in competition (or one off, maximal efforts) whereas much less is understood about the mechanisms responsible for reduced force production capacities during periods of heavy physical loading. Despite evidence that LFF and/or performance decrements can persist for up to 4 days following an exercise session e.g [43, 241, 278], athletes training in high performance environments are generally required to train or compete subsequently, before full recovery is achieved. Limited studies have focused on alterations in muscle contractile function in response to repeated bouts of exercise in highly trained competitive athletes.

To our knowledge few studies have reported the time-course of recovery and/or alterations in LFF or central fatigue using established laboratory methods during training consisting of multiple training sessions or competitive bouts. Following two consecutive days of cycling, Stewart et al., [287] observed that voluntary and stimulated force recovered by the third day, whereas three days of consecutive exercise resulted in force decrements that persists for several days. Similarly, repetitive endurance cycling resulted in depressed maximal force, M-wave amplitude and central activation measured on days nine and 17 of a 22 day simulated Tour de France race [258]. These measurements were taken after at least 18 h of recovery from the previous exercise bout attesting to persistent neuromuscular alterations throughout the race. The authors of this study concluded that the acute transient losses in muscle strength demonstrated in the hours after single prolonged bouts of whole-body exercise become chronic changes in the ability to produce voluntary force after consecutive prolonged exercise bouts.

It seems reasonable to assume that incomplete recovery prior to a subsequent exercise bout will intensify the fatigue response to the second bout of exercise. In contrast to this belief, findings from Skurvydas and colleagues have indicated that although force did not recover prior to a subsequent exercise bout, similar decrements in performance were noted following a second bout of 50 maximal drop jumps [277, 278]. Similarly, drop jump training consisting of 3 sessions per week for 3 weeks only induced transient changes in maximal voluntary force, with full recovery observed after each individual training session

[166]. This was despite plasma creatine kinase remaining elevated throughout the training period. During 2 weeks of daily resistance training Fry et al., [100] also failed to observe a progressive decline in strength with continued intensified training. In instances involving large amounts of eccentric work resulting in muscle damage, this phenomenon is referred to as the repeated bout effect, whereby protective mechanisms appear to limit further damage to the muscle [55, 228]. This effect has been observed in repeated exercise bouts as little as 5 d apart. Ebbeling and colleagues [80] reported significantly smaller changes in dependent variables produced by an identical bout of exercise repeated 5 d following the first. In this study the recovery time required from the second bout was also faster whether or not muscles were fully restored. The repeated bout did not exacerbate soreness, performance decrements, and elevation of serum creatine kinase when performed by affected muscles that had not fully recovered from the first bout. Thus, the results suggest that an adaptation response had taken place prior to full recovery and restoration of muscle function following the initial eccentric exercise bout. It is unknown if this phenomenon is restricted to muscle damaging exercise protocols, or in fact whether this protective mechanism also exists for other aspects of neuromuscular fatigue.

Whilst a dearth of information is available describing muscle contractile function following repetitive exercise bouts using established laboratory methods, numerous studies have tracked changes in neuromuscular function via tests of functional performance. For example incomplete restoration of 20 m sprint time and countermovement jump performance was observed during an international handball tournament [257 251]. Kramer et al., [180] showed that 24 hours was insufficient for restoring maximal isometric strength following 3 matches on the first day of a wrestling tournament. The utility of functional tests for monitoring neuromuscular fatigue and training responses will be discussed in more detail in section 2.4.

2.3.5. Fatigue accumulated during repetitive exercise bouts: Over-training Syndrome and hypothalamic dysfunction

As previously discussed acute fatigue from a single fatiguing bout can result in both short-term and long-lasting neuromuscular fatigue. The time required for recovery from an acute training stress varies widely depending on the type and magnitude of the training stimulus;

however general consensus is that recovery from “normal” training fatigue should be less than 24 hours [34, 280] or up to 72 hours [173]. This minimum recovery period has been shown to be insufficient following high-intensity competition matches in Australian Rules Football [60], Rugby League [204] and following a plyometric training session [51]. With such lengthy recovery periods needed for full restoration between successive exercise bouts, it is often logistically difficult to ensure that athletes are exposed to the appropriate training stimuli, whilst avoiding the negative consequences of prolonged or excessive fatigue. It is when such an imbalance exists between the overall strain of training and the individual’s tolerance of stress that long-term performance decrements can occur [209].

Overtraining is the term that has generally been used to describe long-term performance decrements due to an imbalance in stress and recovery in athletes. However, rather than overtraining existing as an objective condition, it is said to lie at the end of a continuum, which begins with acute fatigue and can progress to an overtrained state if training is not adjusted to meet the recovery requirements of the athlete. There have been differences in the literature regarding the definitions and stages of overtraining. In a recent position statement from the European Congress of Sport Science and the American College of sports Medicine [209] it is stated that rather than overtraining being a condition experienced as a consequence of training, it is a process involving intensified training which has a range of possible outcomes. These outcomes include short-term overreaching (functional overreaching), extreme overreaching (non-functional overreaching), or the Over-training Syndrome (OTS). Functional overreaching (OR) is another term used to describe the “valley of fatigue” referred to in section 2.2, and is considered to be part of the normal training process for elite or high performance athletes. Reductions in training allowing complete recovery following functional OR usually results in supercompensation of performance within 1 to 2 weeks [179][209]. However if this intensified training continues without sufficient recovery the athlete can evolve into a state of non-functional OR, where the decrease in performance may not recover for several weeks or months [209]. In addition to sustained performance decrements, several confounding factors such as inadequate nutrition (energy and/or carbohydrate intake), illness (most commonly upper respiratory tract infections, URTI), psychosocial stressors (work-, team-, coach-, family-related) and sleep disorders may be present [209]. If this condition is not resolved with months of rest, the athlete is said to have progressed to a state of OTS. In OTS the athlete will often show the same clinical, hormonal and other signs and symptoms as in non-functional OR.

Therefore, the diagnosis of OTS can often only be made retrospectively when the time course of recovery can be overseen.

Muscle contractile capacities and central nervous system functioning of athletes diagnosed with NFOR or OTS have not been extensively explored. More often symptoms of NFOR and OTS have been associated with hypothalamic dysfunction that affects the neuroendocrine and autonomic nervous system responses to exercise. Two forms of OTS have been identified according to the effect it has on the autonomic nervous system. In 1958, Israel [156] distinguished between a sympathetic and a parasympathetic form of overtraining, although there exists little empirical evidence to support this classification [38]. Within this division, sympathetic overtraining is characterised by an increase in sympathetic activity in the resting state, while parasympathetic overtraining results from an inhibition of the sympathetic system, with parasympathetic activity predominating at rest. It is commonly believed that the sympathetic type of overtraining is preferentially found in explosive, non-endurance type sports, while the parasympathetic type occurs most frequently in endurance athletes.

Common symptoms of the two forms of overtraining are presented in Table 2.3. As can be seen in this table the common item in both forms of OTS is a decrease in sports performance. At an early stage, all forms of overreaching/overtraining may only be reflected by increased perceptions of fatigue by the athlete. Athletes suffering typical OTS symptoms also commonly complain about the feeling of heavy muscles in the lower limbs at unusually modest exercise intensities [299], with mood disturbances another common observation.

A multitude of tools have been suggested as being useful in the identification and diagnosis of overreaching and OTS. Numerous reviews are available discussing the interesting diagnostic information resulting from maximal and sub-maximal fitness tests (e.g. heart rate and lactate concentration during and subsequent to exercise), deteriorations in mood state and other psychophysiological complaints, and a wide variety of biochemical markers [101, 182, 253, 300, 301]. The relevance of each of these markers of overtraining will be discussed in the following sections.

Table 2.3 Signs and symptoms of sympathetic and parasympathetic forms of overtraining (from Stone et al., [276]).

Sympathetic	Parasympathetic
<ul style="list-style-type: none"> • Decreased sports performance • Increased resting heart rate • Increased resting blood pressure • Decreased maximal power output • Decreased maximal blood lactate concentrations • Slower recovery after exercise • Weight loss • Decreased appetite • Decreased desire to exercise • Increased irritability and depression • Increased incidence of injury • Increased incidence of infection 	<ul style="list-style-type: none"> • Decreased sports performance • Decreased resting heart rate • Faster return of heart rate to resting value after exercise • Decreased blood lactate concentrations during submaximal and maximal exercise • Unemotional behaviour

2.3.6. Summary

The acute fatigue after-effects of a training stimulus can be neural, mechanical and metabolic in nature. Metabolic fatigue is generally short-lasting with full recovery coinciding with cessation of activity and normalisation of cellular energy potential [114]. Conversely neuromuscular fatigue, which is a complex phenomenon that impairs central and peripheral mechanisms, can have much longer lasting effects [82, 93]. In addition to the neuromuscular after-effects of training, periods of intensified training without adequate recovery can lead to dysfunction of the neuroendocrine system, resulting in maladaptation to training and prolonged reductions in performance capacity.

Fatigue response to a single exercise bout and the fatigue associated with periods of intensified training are not often discussed collectively. In the basic sciences, decades of research has focused on elucidating the mechanisms responsible for fatigue that limits force production during exercise. These mechanisms are generally well understood; though debate exists as to whether changes in skeletal muscle metabolism (i.e. peripheral fatigue) or changes in efferent neural command is the primary limiting factor [107, 285]. Many basic and applied research questions regarding changes in physiological capacities subsequent to fatiguing exercise have also been investigated, with the time course of recovery examined via serial measurements in the minutes, hours and days after the fatiguing protocol. Much less empirical data are available demonstrating the fatigue and recovery profiles during

periods of intensive training, where fatigue accumulates during successive training bouts. It is likely that understanding the mechanisms responsible for fatigue under these circumstances requires a different methodological approach.

2.4. METHODS FOR MONITORING ACCUMULATED TRAINING FATIGUE

Ideally fluctuations in performance capacities throughout a training cycle would be measured directly via a maximal test of performance in the athlete's competitive event. However there are a number of difficulties associated with this approach. Most significantly repeated maximal performance efforts are likely to contribute to a fatiguing effect, which is impractical, especially during the competitive season. Secondly, accurately defining maximal performance in a number of sporting pursuits, particularly field and court sports, is challenging if not impossible at this point in time. As well, such a "blunt force" approach to monitoring performance does not indicate the underlying physiological changes associated with performance fluctuations [33]. Therefore monitoring performance and functional capacity during athletic training is reliant on indirect markers of maximal performance or relevant physiological and/or psychological characteristics.

A plethora of physiological, biochemical, psychological and performance markers are available to assist in informing coaching staff when an athlete is in a state of fatigue or recovery. Research regarding the utility of these markers is generally divided into two categories. The first involves descriptive studies in which overtrained athletes are screened for abnormal biochemistry, autonomic function (via heart rate) and/or responses to exercise (e.g. [178, 283]). The second category of research studies includes those where intensified training is prescribed for study participants while a range of markers are monitored for the study period (e.g. [39, 65, 68, 96, 121, 160]). In this type of study it is hypothesised that changes in the selected physiological, biochemical, psychological and performance markers will reflect the increased training load and/or training intensity. A subcategory of these investigations include descriptive studies where a range of markers are monitored in response to a competitive match [60] or successive matches [62, 179, 204], during tournament play [126, 180, 216, 257] and intensive short-term training camps [135], or throughout extended training periods [140, 266]. Researchers have suggested that a variety of these methods may be useful for monitoring early signs of overtraining, or in monitoring the recovery process during successive bouts of training and competition. The following

sections describe these methods for monitoring training and competition fatigue, with particular emphasis placed on their practical utility in the daily high performance training environment.

2.4.1. Performance tests

While it is difficult to regularly measure maximal performance in an athlete's competitive event, an indication of their underlying physiological capacities can be gained via a range of functional performance tests. In such tests the measured outcome is referred to as a performance indicator, due to close relationships to actual performance. This method is frequently used for the assessment of neuromuscular function, where authors use tests such as vertical jumps, maximal strength assessment, and sprints (overground and ergometer) to assess levels of neuromuscular fatigue. Other forms of performance tests may include maximal aerobic running or cycling tests, however due to the maximal nature of these tests which may induce significant amounts of fatigue, such assessments will not be discussed in this section.

Maximal strength assessment

Historically laboratory assessment of neuromuscular function during or after a fatiguing protocol consisted of the measurement of maximal strength during an isometric contraction (voluntary or evoked). Research has however shown poor relationships between fatigue-induced changes in isometric strength and strength in dynamic contractions [53, 74], leading researchers to suggest that this form of assessment is invalid for assessing fatigue relevant to dynamic movements [46]. In some sporting events however maximal dynamic strength may be an important performance indicator, and as such it has been monitored during periods of deliberate overreaching. In rugby league players, minimal clinically important reductions in 3RM squat and bench press have been observed following 6 weeks of deliberate overreaching [65]. Similarly, statistically significant changes in 1RM squat have been observed in weight-trained males training daily for 2 weeks [100]. The limitation with this form of assessment is the high technical ability needed to perform maximal dynamic strength testing. Additionally, regular assessment may be unduly fatiguing, adding to the overall fatiguing effect. Hence, regular assessment of maximal strength may provide relevant information regarding the levels of neuromuscular fatigue in sports where

performance is dependent on maximum strength, however the practicality of repeated maximal strength testing might be problematic.

Vertical jump assessments

Vertical jumping is a convenient model to study neuromuscular function and has been used in a multitude of studies investigating the time course of recovery from fatiguing interventions [60, 99, 111, 137, 180, 223, 257, 311]. Isoinertial SSC actions like the vertical jump have been suggested as a suitable tool for monitoring long-lasting low frequency fatigue that is caused by E-C coupling impairments subsequent to fatiguing activity [93], though limited evidence exists confirming the validity of this approach.

Vertical jump performance during periods of heavy loading has been monitored using vane jump and reach apparatus [48, 65, 66, 96, 216], contact or switch mats [126, 311], and force platforms [62, 180, 204, 223, 257]. Results from single and repetitive jumps have demonstrated the ability to reflect fatigue in military populations, with significant performance reductions observed following prolonged work and limited food intake and sleep [223, 311]. Ronglan et al., [257] also demonstrated a significant decrement in CMJ height over 3 days of elite handball competition. Coutts and colleagues [65, 66] however found conflicting results when using a vertical jump to monitor responses of rugby league players to a 6 week overreaching training block, with one group demonstrating no changes in jump height and the other displaying clinically important reductions. Cormack et al., [60] monitored changes in vertical jump performance measured on a force platform following an Australian Rules Football match and reported that only 6 of the 18 force-time variables analysed during single and 5-repetition jumps had declined substantially following the match. In particular there was a lack of sensitivity of jump height to fatigue which supported the earlier work of Coutts et al., [66]. Furthermore the pattern of response in these parameters varied greatly during the recovery period (from 24 h to 120 h post match) [60]. This research highlights the considerable differences in changes in vertical jump performance based on the performance variable of interest.

Taken together the above results indicate that vertical jumping may be a valuable tool in monitoring fatigue and recovery during training, however varied responses of vertical jump parameters suggest that further research is needed to elucidate the most appropriate

variables to use when using the vertical jump to assess fatigue. In particular, it is important that the reliability associated with each assessment method be thoroughly assessed, since numerous investigations have reported a large range of typical error values [60, 71, 149, 270]. Given the relatively high values reported in some of these studies (e.g. > 8-12% for some variables) it is critical that they be compared with the magnitude of change that is considered important in the context of fatigue assessment before they can be used to confidently assess such changes. To date only Cormack and colleagues [61] have reported such relationships, showing that the error associated with a large number of force-time variables was in excess of the smallest worthwhile change in performance (calculated as 0.2 times the between-subject standard deviation). It is likely that more work is needed in this area to firstly establish more reliable assessment protocols, and then secondly to determine the smallest important change necessary for determining the presence of neuromuscular fatigue.

Over-ground sprint assessments

Changes in over-ground sprint performance have been monitored in running based sports during tournament play, throughout competitive seasons, and following periods of deliberate overreaching. Studies have confirmed performance decrements with increasing training or competition demands [257], however non-significant changes in 10 and 40 m sprint times have been reported following 6 weeks of deliberate overreaching in rugby league players [65]. Interestingly, 20 yard (18.3m) sprint performance decreased in starters but not in non-starters during 11 weeks of regular soccer competition, while changes in 40 yard (36.7 m) sprint time did not change significantly in either group [179] suggesting that sprint distance may influence the outcome and the utility of sprint tests in monitoring neuromuscular fatigue responses.

Methodological considerations for functional performance tests

Monitoring fatigue and recovery responses to training and competition using functional performance tests are popular in applied research studies as well as in the daily training environment. The following factors may be important when considering the use of such assessments:

- Assessments can be easily implemented regularly throughout different training phases to assess individual training responses since minimal equipment and time are needed to carry out the assessments.
- Large numbers of athletes can be tested in minimal time.
- Results from the assessments provide coaches with relevant information even when no negative adaptations are apparent.
- Changes in dynamic performance measures are likely more relevant to sports performance than the isometric force measurements obtained in laboratory assessments of neuromuscular fatigue.
- The major disadvantage is that limited information is obtained regarding the cause of performance reductions.
- While many studies have reported “good” reliability of many of the performance indicators discussed above, the relationship between the typical error and expected changes due to fatigue, or the smallest worthwhile change in performance, have not been reported.
- There is no consensus as to which vertical jump parameters are most informative when monitoring fatigue. It has been suggested that not all parameters respond to fatiguing exercise in the same manner and therefore more work is needed before recommendations can be articulated on the most appropriate parameters to measure. Such recommendations will enable greater comparisons of research in this area, which is presently problematic given the diversity of parameters reported.

Summary of functional performance tests for monitoring fatigue and recovery

Regular maximal performance testing may be unduly fatiguing and impractical for most athletic settings. Functional performance tests are a popular method for monitoring changes in performance capacities in response to heavy loading in training and/or competition. Whilst such assessments do not indicate the underlying physiological changes associated with performance fluctuations, regular monitoring of an athlete's performance capacities can provide relevant information concerning their recovery status. In the applied sports science research vertical jump tests are most commonly used, with numerous assessment methods and outcome variables available for the analysis of neuromuscular function. It has been postulated that reductions in such measures are an indication of neuromuscular fatigue; however minimal data exists confirming this approach [93].

2.4.2. Biochemical markers

Since physical training and competition elicits a range of acute neuroendocrine responses, it is thought that changes in hormonal concentrations during recovery may have important implications for the rate of recovery processes, and the duration of the recovery phase [182]. Hormonal concentrations measured in serum, plasma and saliva such as cortisol, testosterone, adrenocorticotrophic hormone (ACTH), β -Endorphins, prolactin and others have been investigated during heavy periods of training with various responses observed. While the acute neuroendocrine response to an exercise session is generally well documented, the data on these hormonal responses to long-term training and the resulting fatigue state are controversial [21, 60, 90, 120]. A variety of other biochemical markers have been examined for their response to intensive training also with varied results. For example, serum and plasma concentrations of enzymes suggestive of muscle damage (e.g. creatine kinase, myoglobin and fatty-acid binding protein) have been investigated heavily, as well as a variety of cytokines that play an important role in the inflammatory processes. Free amino acid concentrations (e.g. glutamine, glutamate) and brain neurotransmitters have also received attention and will be discussed in the following sections.

Hormones

Testosterone and cortisol appear to be among the most frequently investigated biochemical markers of training stress and recovery. Cortisol is a catabolic (stress) hormone and its presence is suggested as an indicator of the endocrine systems response to exercise. Acute cortisol responses have varied with reports that cortisol levels return to pre-exercise levels within 2 to 3 hours after exercise cessation [197], however increased levels have been observed for up to 24h after an Australian Rules Football match [60]. However, evidence also exists that the doubling of training volume results in a decrease in cortisol levels [98, 99] making interpretation of acute responses difficult. It is suggested that the presence of increased resting levels of cortisol contribute to an exhaustion of the hypothalamic-pituitary-adrenal axis, thus preventing an adequate cortisol response to acute stress [102].

Testosterone is an anabolic hormone and is important in muscle hypertrophy and muscle glycogen synthesis. Acute bouts of heavy resistance training result in greater levels of total testosterone [98, 99, 119]. Chronically, resting testosterone levels are negatively related to increases in training volume [119], while other longitudinal studies have reported no

changes in resting levels [6, 120]. In addition to investigating cortisol and testosterone responses independently, changes in the anabolic-catabolic balance (or testosterone: cortisol ratio) are often monitored. Since testosterone and cortisol vary in opposite directions in response to exercise (and are competitive agonists at the receptor level of muscular cells), it is theorised that an increase in training load will result in a decrease in the testosterone: cortisol ratio, representing an imbalance in the anabolic and catabolic response [83]. The relationship between testosterone and cortisol has therefore been used as a marker of catabolic and anabolic activity during periods of elevated training loads [25, 65, 90, 97, 108, 120, 217, 250, 302], with early observations indicating that a decrease of 30% or more is a good maker of overtraining [4]. This finding is supported by a range of studies in which significant relationships between changes in the testosterone: cortisol ratio and performance have been observed [25, 120]; though evidence has also been presented showing non-significant relationships in team sports [89]. Similarly the hormonal profile of overreached or overtrained athletes has been shown to be unaltered [108]. Together these results suggest that it is likely that the testosterone: cortisol ratio indicates the short-term physiological strain in training, rather than having utility to be an early marker of overtraining syndrome [208, 298].

Plasma catecholamine concentrations appear to be the next most common hormone used for indicating overall stress and recovery levels in athletes involved in heavy training, since many of the known signs and symptoms of overtraining involve many systems which are under adrenergic control [102]. Circulating adrenaline may modify skeletal muscle force production and substrate availability, thus influencing both maximal strength and local muscular endurance [102]. It is suggested that inappropriate physical loading can increase plasma concentrations of catecholamines and cortisol due to an over-secretion of adrenocorticotrophic hormone (ACTH) as a response to the increased sensitivity of the hypothalamic axis (HPA) response to stress. It is also suggested that the increased resting levels of cortisol contribute to an exhaustion of the hypothalamic-pituitary-adrenal axis, thus preventing an adequate cortisol response to acute stress [102, 315], particularly in response to a secondary exercise bout [210]. Numerous other blood hormones have been investigated in relation to their response to single and repeated bouts of exercise in athletes with OTS; including but not limited to gonadotrophins (luteinising hormone and follicle stimulating hormone), β -Endorphins, prolactin, thyroid stimulating hormone, insulin and insulin-like growth factors. While many scientific investigations exist supporting the monitoring of such

hormones for early indications of overreaching or OTS, these hormones are less commonly assessed in the regular high performance environment and therefore have not been individually discussed in the current review. Interested readers are referred to Urhuasen and colleagues [298, 300], Viru and Viru [304] and Meeusen and colleagues [210] for further information.

Amino acids and other enzymes

Plasma concentrations of glutamine and glutamate have been suggested as useful markers of overreaching and OTS in endurance athletes. Periods of overtraining have been associated with reductions in glutamine concentration in the blood plasma, however this finding is not consistent. For example, Smith and Norris [281] reported unchanged resting plasma glutamine concentrations in athletes who were classified as having OTS. In contrast to reductions in glutamine concentrations with intensified training, there is evidence supporting elevated plasma glutamate levels in overreached [123] and overtrained athletes [232, 281], although the role of glutamate in the mechanisms of overreaching and overtraining is questionable [123]. Rather than relying on changes in glutamine or glutamate concentrations in isolation, the ratio of glutamine/glutamate has been suggested as a more useful indicator of overreaching or overtraining. Reductions in the glutamine/glutamate ratio have been associated with training intolerance in rugby league players during deliberate overreaching [65], following intensified training in cyclists [123] and after heavy training which induced OTS in five endurance athletes [281]. Based on their data Smith and Norris suggested a threshold value of <3.58 in the glutamine/glutamate ratio be used to indicate overreaching [281]. The use of this threshold was supported by Halson and colleagues [123] who observed values <3.58 during intensified training. Importantly however, the ratio normalised in these athletes after two weeks of recovery, confirming that the threshold supports the classification of overreaching rather than OTS. To the authors knowledge this is one of the only biochemical markers for which an agreed threshold for overreaching exists, distinguishing it as possibly the most useful.

A variety of blood markers have also been used to investigate the effects of muscle damage following exercise. Resting levels of creatine kinase (CK), myoglobin and fatty-acid binding protein are used, however CK is most commonly monitored. Similar to hormonal markers of exercise stress and tolerance, the acute response of CK and other enzymes is well

documented, with much less known about the resting levels during periods of intensified training or regular competition. For example short-term increases in CK have been observed following three days of tournament play in basketball [216] and seven days of intensive training in female judokas [297]. Increases have also been reported during six weeks of progressive endurance training [167], following six weeks deliberate overreaching in rugby league players [65] and throughout two weeks of daily high-intensity resistance exercise [100]. Whilst the use of CK as a marker of reduced performance due to muscle damage appears appealing based on the above evidence, Hartmann and Metser [133] investigated resting CK levels in rowers and reported ‘enormous’ individual variability, making the ability to accurately measure training induced changes problematic.

Methodological considerations of biochemical markers

From the available evidence numerous methodological considerations are highlighted that would influence the usefulness of biochemical monitoring within a training-monitoring program. These include:

- Most measures exhibit low reliability and large intra-individual differences making accurate measurements difficult to obtain.
- The time, cost, and expertise required for data collection and analysis are all high.
- Daily monitoring is generally not feasible [253].
- Diurnal fluctuations can confound results [294].
- Chronic versus acute effects are not clear [294]
- Details on female hormone responses are lacking.
- Analysis is time consuming and there is generally a relatively long lag time for feedback.
- Reference values indicating a “normal” exercise tolerance in trained athletes are lacking [298], with the exception of the glutamine/glutamate ratio.
- The relevance of changes in biochemical markers to changes in sports performance is mostly unknown.

Summary of biochemical markers for monitoring training stress and recovery

While a large amount of research has been devoted to finding a biochemical marker(s) to indicate early stages of training maladaptation, the reported responses to high training loads

and competition have varied greatly and therefore the usefulness of these measures for monitoring training stress and adaptive capacities remains unclear. It still remains to be established whether a transient drop in hormone levels below initial values reflects physiological overstrain and does indeed influence the recovery processes [182]. Additionally, the methodological limitations for use in the high performance training environment are great and potentially limit the utility of such markers in a routine fatigue monitoring system. The measures are at best only modestly related to training loads, and there is considerable variation within and between individuals. Precise control of prior exercise, time of day, diet, presence of injury along with the inconvenience of taking venepuncture blood samples, and the relatively high cost associated with laboratory analysis make this method difficult to implement in a practical training environment. If however cost is not prohibitive and staff are available to analyse the samples relatively quickly, there could be value in further investigation in specific athletic populations, but care must be taken to account for the large intra-individual variation.

2.4.3. Heart rate

Negative adaptation to training stress potentially involves the autonomic nervous system, and may result in a concomitant alteration in heart rate [2, 38]. It is thought autonomic nervous system changes due to overtraining may be reflected in resting heart rate, heart rate variability measures and heart rate responses to exercise. Two comprehensive reviews are available on the use of heart rate indices for monitoring responses to increased training loads [2, 38].

Resting and sleeping heart rate

Increased resting heart rate is probably one of the first signs of overtraining reported in the literature [38], where it was suggested that overreaching is likely accompanied by an increase in resting heart rate, reflecting an increased sympathetic tone [182]. While some early studies have supported increased resting heart rates in individuals with OTS [76, 174, 316], most studies reported no differences in resting heart rate between normal and overreached states [100, 121, 160, 189, 283, 299]. In their meta-analysis of 34 studies investigating the effect of training load on heart rate indices, Bosquet et al., [38] calculated only trivial increases in resting heart rate, and suggested therefore that it cannot be considered a valid sign of functional OR, non-functional OR or OTS. They did however

observe greater increases after short-term training interventions (≤ 2 weeks), and suggested that resting heart rate may possibly be useful as a valid indicator of short-term fatigue. While the evidence for using resting heart rate measures as an early detection of overtraining responses is unclear, there is support that sleeping heart rate may be a more accurate indicator since many of the extraneous factors affecting heart rate are reduced [160, 288, 307]; however few studies have confirmed this finding.

Heart rate variability

Some authors have suggested that nocturnal heart rate variability (HRV) may be more a more useful indicator of overtraining, and as such there has been a spike in research activity in recent years evaluating changes in HRV in athletes involved in heavy training. Even when the resting heart is relatively stable, the time between beats can differ substantially [2]. The variation in this time, known as the R-R interval, is often used as an index of autonomic nervous system responsiveness, or cardiac vagal control. Along with the time domain indices such as the R-R interval, there are a number of variables that can be examined which may provide information on sympathetic versus parasympathetic predominance in overtrained athletes.

While some authors have reported no changes in HRV after intensive training which induced significant performance changes [135], support for HRV as a sign of overreaching or overtraining has been provided across a variety of sports. For example, it was observed in weightlifters, that parallel changes in HRV and weightlifting performance occurred in the 72 hours following a fatiguing training session [52]. Similarly, indices of sympathetic activity were inversely related to performance in elite swimmers [22] and in severely over-trained Finnish athletes from a variety of sports [154]. Changes in HRV also correlated with increases in training load in elite endurance athletes [155], middle-distance runners [237] and with perceived tiredness during a world cup hockey tournament [231]. Despite what appears to be abundance of evidence supporting the use of heart rate variability for monitoring overreaching, the results from the meta-analysis of Bosquet and colleagues [38] revealed only small effects of overreaching on HRV indices, which were also limited to short-term overload less than 2 weeks in duration.

Maximal and submaximal heart rate during standardised tests

Maximal heart rate appears to be decreased in almost all ‘overreaching’ studies [2]. Results from the meta-analysis of Bosquet and colleagues [38] confirmed that it was the only heart rate measure to be altered after both short-term and long-term increases in training load, emphasising its potential usefulness as a sign of functional and non-functional overreaching and overtraining syndrome.

A number of variations of sub-maximal fitness tests have been used in the literature to monitor changes in the physiological state of athletes during periods of heavy loading. While no measure of performance per se is available from this type of test, changes in heart rate, oxygen uptake and plasma lactate can be monitored. In cases of sympathetic overtraining heart rate and oxygen uptake are often increased at submaximal workloads. In cases of parasympathetic type overtraining syndrome, both heart rate and plasma lactate levels may be lower at all workloads [182]. One of the most commonly published sub-maximal performance tests used to monitor training responses is the Heart Rate Interval Monitoring System (HIMS)[186]. The HIMS test is a submaximal shuttle running test 13 minutes in duration (consisting of 4 x 2 minute stages with progressively increasing speeds). After each 2-minute stage, the subjects rest by standing upright for 1 minute. During the HIMS, and for 2 minutes after the end of the test, heart rate is recorded. Using the HIMS test Borresen and Lambert [36] observed a significantly slower heart rate recovery following a 55% increase in training load over 2 weeks. Using a similar test, Coutts et al., [66] reported that changes in sub maximal heart rate after 6 weeks of deliberate overreaching did not relate to changes in 3km time trial performance or training load, indicating that a clear diagnostic pattern for the detection of overreaching was not apparent. This is similar to a number of other findings of unchanged HR during submaximal tests during deliberate overreaching [121].

Methodological considerations for using resting heart rate, heart rate variability and heart rate responses to exercise

- Heart rate is probably one of the most accessible physiological measures available [38]. Heart rate monitors are generally affordable and necessitate minimal interference to training.

- While reductions in heart rate response to overreaching have been suggested as a good marker of overreaching and/or overtraining, a reduction in heart rate during or after exercise may also occur as a positive training response due to improvements in cardiovascular efficiency [66, 187], possibly compromising the accuracy of measuring changes in heart rate and heart rate recovery (i.e. similar changes are observed in adapting and non-adapting athletes).
- Nocturnal HRV requires monitoring heart rate during sleep which may prove uncomfortable and impractical for athletes in the long term [253].
- Most evidence for using heart rate shows elevations in already overtrained individuals. To date minimal evidence exists supporting its use as an early indicator of maladaptation to training.
- The day-to-day variability in heart rate is relatively high [185]. From test to test, a change in heart rate recovery of more than 6 beats per minute or the change in submaximal heart rate of more than 3 beats per minute can be regarded as a meaningful change under controlled conditions [185]. If changes in heart rate and heart rate recovery are to be monitored in athletes, a submaximal protocol should elicit a heart rate between 85 and 90% of maximum heart rate, because this intensity is associated with the least day-to-day variation [185].
- The smallest meaningful change in sub-maximal heart rate and HRV indices during regular training has so far only been established for youth (adolescent) soccer players [42]. More work is needed to quantify to quantify these values in other populations.
- Most studies have investigated responses to increases in endurance training only, although some investigations have been conducted with team sport athletes.
- Variations in muscle glycogen and diet can affect lactate concentration, so conditions prior to submaximal tests require strict standardisation for repeatable measures [253].

Summary of heart rate monitoring for assessing fatigue and recovery

Since the autonomic nervous system is interlinked with many other physiological systems, the responsiveness of the autonomic nervous system in maintaining homeostasis may provide useful information about the functional adaptations of the body. The continued use of HR and HRV measures is in contrast to reported opinion in that although there are significant modifications after short-term fatigue (in resting heart rate and HRV), long-term fatigue (HR during a submaximal workloads) or both (maximal HR), the moderate

amplitude of those alterations limits their clinical usefulness since the expected differences fall within the day-to-day variability of those measures [38].

2.4.4. Perceptual ratings of stress and recovery

Apart from training and competition, additional stressors such as fear of failure, competitive failure, excessive expectations from coach or public, and demands of competition as well as the professional and social areas of an athlete's life can affect an athlete's tolerance and adaptive capacities [171]. Numerous studies have shown mood disturbance coinciding with increased training loads and it has therefore been suggested that self-reporting of fatigue and associated psychological indices may allow fatigue and/or overtraining to be successfully monitored. Research studies have utilised a range of published questionnaires, most popularly the Profile of Mood States [207], the Recovery-Stress Questionnaire for Athletes [172] and the Daily Analysis of Life Demands [261].

Profile of Mood States

The Profile of Mood States (POMS) is a 65-item questionnaire originally developed for the assessment of clinical depression. Using the POMS, changes in total mood disturbance can be calculated by summing the five negative mood scores (fatigue, anger, depression, confusion, tension), adding 100, and subtracting the one positive mood score, vigour [207]. This global score has been shown to have strong positive correlations with changes in training load [87, 121, 191, 218] and changes in blood biochemical variables [297] but it has been criticised for not being sport specific. A shortened version of the POMS was developed by Grove et al., [115], which has been shown to also correlate with changes in training loads [121], however [252] suggested that its sensitivity may be diminished. Minimal data exists linking changes in POMS scores with changes in performance, although Raglin et al., [244] reported a moderate negative correlation ($r = -0.34$) between total mood disturbance and mean swimming power during a competitive swim season. Unfavourable mood states were also observed in soccer players and middle-long distance runners with measured performance decrements lasting greater than one month [268].

Recovery Stress Questionnaire for Athletes

It has been argued that recovery cannot merely be characterized as a lack of stress [170] but also as an active individualized process to reestablish physical and psychological homeostasis [171]. The Recovery Stress Questionnaire for Athletes (RESTQ-Sport; [172]) was designed with the purpose of capturing information about the stress and recovery processes in a sporting context, and indicates the extent to which someone is physically and/or mentally stressed as well as whether or not the person is capable of using individual strategies for recovery. This is achieved by measuring the frequency of current stress and recovery-associated activities via a 77-item questionnaire; where high scores in the stress-associated activity scales reflect intense subjective stress, and high scores in the recovery-oriented scales indicate good recovery activities. Similar to the POMS, a dose-response relationship between RESTQ-Sport scores and training load has been demonstrated [170, 171], although not in all situations [134]. Additionally, evidence exists suggesting that physical stress measured by the RESTQ-Sport correlates with injury occurrence, while indices of psychosocial stress and recovery are related to the occurrence of illness [40]. Moderate associations have also been reported between increases in stress and reductions in performance indicators during a season of professional football [86].

Daily Analysis of Life Demands

The Daily Analysis of Life Demands (DALDA)[261] is divided into two parts: Part A (sources of life stress) and Part B (symptoms of stress) and is normally completed on a daily basis or on alternate days. Peaks in the sum of “worse-than-normal” responses that remain elevated for several days may indicate an athlete who is overreached [261]; which is supported by a significant relationship between changes in 3km time trial performance and DALDA scores during intensified training in triathletes [68], and performance changes during 2 weeks of intensified cycling training [121].

Other questionnaires

Along with established questionnaires numerous authors have gathered data on stress and recovery using customised forms. For example, Halson et al., [124] and Rowsell et al., [260] measured perceived physical and mental recovery, leg soreness and general fatigue on a 1-10 likert scale for the assessment of recovery after one-off fatiguing interventions and

during tournament play respectively. Jeukendrup and colleagues [160, 283] determined that 5 or more positive responses on a 14 item custom designed questionnaire was a positive indicator of overtraining. When investigating ergometric and psychological parameters during overtraining in endurance athletes, Urhausen et al., [299] confirmed the sensitivity of self-reported measures using a standardised scale of self-condition [224], whereby 40 items were used to assess fatigue, recovery, strain, sleepiness and satisfaction. It appears that while published inventories such as the RESTQ-Sport, POMS and DALDA are popularly examined; researchers also commonly create situation specific questionnaires to investigate perceptual ratings of fatigue and recovery.

Methodological considerations for the use perceptual ratings of fatigue and recovery

- Easy to administer.
- Minimal cost, time or expertise is required for data collection and analysis.
- Daily use can provide good longitudinal data.
- Evidence exists suggesting that perceptual ratings of fatigue and recovery may be valid for detecting changes in training load, however less evidence is available regarding relationship with changes in performance.
- Athletes can become habituated or anticipate the responses that will lead to favourable outcomes [253].
- Maintenance of a high compliance to the regular completion of questionnaires would depend on factors such as the length and nature of the questionnaire, type of response required (tick box or sentences), and incidence of feedback to athlete [253].

Summary of perceptual ratings of fatigue and recovery

The popularity of self-report questionnaires for monitoring training in high performance athletic settings is largely due to the simplicity of data collection and analysis. Both the POMS and the RESTQ-Sport have been suggested as valid monitoring instruments, with a dose-response relationship between observed scores and training load. However, it appears difficult to delineate normal changes in perceived fatigue and recovery occurring during regular training from abnormal changes associated with non-functional overreaching overtraining [140].

2.5. SUMMARY AND IMPLICATIONS FROM LITERATURE REVIEW

Fatigue is an integral part of the training process and without it, supercompensation and adaptation would not occur. Current training theory suggests it necessary to plan successions of small training stressors, which when summed produce a seriously disruptive major stress, for the elite athlete to continually improve in performance. Obviously this major disruptive stress needs to be carefully tailored so that recovery and regeneration are possible and that it does not cause maladaptation by exceeding the athlete's physiological and psychological capacities to cope with the stressor. Therefore monitoring the magnitude in the displacement of homeostasis throughout this period is crucial. Numerous modalities are available for monitoring training stress and fatigue, with limited scientific investigations confirming the validity of each.

It is clear that the choice of an appropriate fatigue measure needs to be made in relation to the situation being monitored. While the study of overtraining syndrome has greatly enhanced our understanding of the fatigue states that result in long-term performance decrements; in the regular training environment it may be more useful to find tools that allow the monitoring of regular daily fatigue and recovery in order to better understand the short term fluctuations in performance capacities that result from successive training bouts. Such an understanding would not only assist in preventing maladaptive states, but would greatly improve our ability to monitor individual responses to training stressors and may assist in knowing when further intensive training is contraindicated. More work is needed in mapping changes in individual performance parameters in response to regular training. The selected assessment methods for this purpose requires that the performance test be easily implemented and have minimal effect on training. It is also critical that an understanding of the type of fatigue present is delineated. Such assessments carried out on a regular basis will allow sports coaches and support staff to monitor individual variation in response to normal training and during periods of high physical loading.

CHAPTER THREE

Fatigue monitoring in high performance sport:

A survey of current trends

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3.1. ABSTRACT

Research has identified a plethora of physiological, biochemical, psychological and performance markers that help inform coaching staff about when an athlete is in a state of fatigue or recovery. However use of such markers in the regular high performance training environment remains undocumented. To establish current best practice methods for training monitoring, 100 participants involved in coaching or sport science support roles in a variety of high performance sports programs were invited to participate in an online survey. The response rate was 55% with results indicating 91% of respondents implemented some form of training monitoring system. A majority of respondents (70%) indicated there was an equal focus between load quantification and the monitoring of fatigue and recovery within their training monitoring system. Interestingly, 20% of participants indicated the focus was solely on load quantification, while 10% solely monitored the fatigue/recovery process. Respondents reported that the aims of their monitoring systems were to prevent overtraining (22%), reduce injuries (29%), monitor the effectiveness of training programs (27%), and ensure maintenance of performance throughout competitive periods (22%). A variety of methods were used to achieve this, based mainly on experiential evidence rather than replication of methods used in scientific publications. Of the methods identified for monitoring fatigue and recovery responses, self-report questionnaires (84%) and practical tests of maximal neuromuscular performance (61%) were the most commonly utilised.

3.2. INTRODUCTION

Athlete fatigue is a difficult concept to define, making its measurement equally problematical [1, 85]. Muscle physiologists often describe fatigue simply as an acute exercise-induced decline in muscle force [81]. Within applied exercise science research, fatigue is most commonly referred to as a reduced capacity for maximal performance [176]. Given this characterisation, it would seem that the most relevant way to measure fatigue would be directly, via a maximal test of performance in the athlete's competitive event. There are of course a number of difficulties associated with this approach. Most significantly, repeated maximal performance efforts are likely to contribute to a fatiguing effect, which is impractical, especially during a competitive season. Additionally, accurately defining maximal performance in a number of sporting pursuits, particularly team sports, is challenging if not impossible at this point in time. As well, such a "blunt force" approach to

monitoring performance does not indicate the underlying physiological changes associated with performance fluctuations [33]. Therefore, monitoring performance and functional capacity during athletic training is generally reliant on indirect markers of maximal performance or relevant physiological and/or psychological characteristics [138, 176, 253].

A multitude of such markers are available to assist in informing coaching staff when an athlete is in a state of fatigue or recovery, and while the research in this area is plentiful, no single, reliable diagnostic marker has yet been identified [33, 176]. Also, while numerous markers of fatigue have been identified and studied in relation to the diagnosis of overreaching and overtraining syndromes (see [122, 182, 301] for reviews), less work has been published using such markers during regular training and competition in high performing athletes. Despite a lack of scientific confirmation in the use of such markers for fatigue monitoring and predicting non-functional overreaching in athletes involved in regular training and competition schedules, anecdotal evidence suggests that most coaches and support staff involved in high performance sport programs have adopted monitoring systems that rely on a range of these markers to provide insight into their athlete's state of fatigue and readiness for training and/or competition.

As there is a paucity of information in the scientific literature on the current training monitoring methods being employed in high performance sports programs, the purpose of the current research was to gather information on the type of training monitoring systems that are considered current best practice. Specifically, information pertaining to the purpose of the monitoring systems, data collection methods, and their perceived effectiveness were examined via an online survey sent to a variety of coaching and support staff within the Australian and New Zealand high performance sport sector.

3.3. METHODS

3.3.1. Subjects

This descriptive study utilised an online survey electronically mailed to 100 individuals identified via their employment within high performance programs across a variety of sports. The survey response rate was 55%. The majority of respondents who affirmed their use of training monitoring systems were employed as the head strength and conditioning coach

within their program (n=30), with other respondents identifying themselves as sports scientists (n=12), high performance managers/sports science co-ordinators (n=9), head coach (n=3) or other (n=1). Of the 55 respondents, five indicated that they do not use any form of training monitoring and were thereafter excluded from the analyses. The respondents all worked with elite/non-professional athletes or professional athletes across a variety of sports (Figure 3.1). Ethical approval was granted by the Institutional Human Research Ethics Committee.

3.3.2. Survey

The survey divided the topic of ‘training monitoring’ into two distinct areas; a) the quantification of training load, and b) monitoring of the fatigue/recovery responses to training or competition loads. The results presented herewith primarily relate to methods employed for monitoring athlete fatigue. Participants completed the online survey in three parts; (A) demographic questions including whether or not a training monitoring system was utilised, (B) items assessing the purpose and perceived value of the training monitoring system and how the data was collected and analysed, and (C) details of which methods are used for quantifying training load and for monitoring fatigue. Questions were based on methods identified within the scientific literature surrounding fatigue monitoring, training load quantification and the modelling of fitness-fatigue responses. In addition personal communications with coaches in the high performance sport arena about their current practices provided a further basis for the construction of the questionnaire.

3.3.3. Procedures

Subjects were contacted electronically whereby the purpose of the survey was explained and a link to the online survey provided. They were informed that by completing and returning the survey that their consent to use the information was assumed. Upon completion of the survey all respondents were asked to indicate their availability for providing greater detail on selected responses if required by the principal researcher. Of the 50 respondents who indicated the use of a training monitoring system, 39 indicated their willingness to participate in follow-up questioning. Of these 39 participants, 28 were successfully reached via email correspondence with 17 responses received, permitting a subset of responses to be collated. Follow up questions included details concerning; the protocols used for performance testing, items included in custom designed self-report forms, the performance

indicators used for tracking performance changes in training/competition, reasons for the (non) use of hormonal profiling, and the magnitude of change typically considered important for each of the parameters monitored.

3.3.4. Statistical Analysis

Frequency analysis for each question was conducted with results presented as absolute frequency counts or percentages of those in agreement or disagreement. Only one question used a Likert scale, where respondents were asked to rate the value of their training monitoring system to the overall performance of their athletes on a 5 point scale (1=minimal value; 5=extremely valuable). In addition to a frequency analysis, the mean response \pm standard deviation is presented for this item.

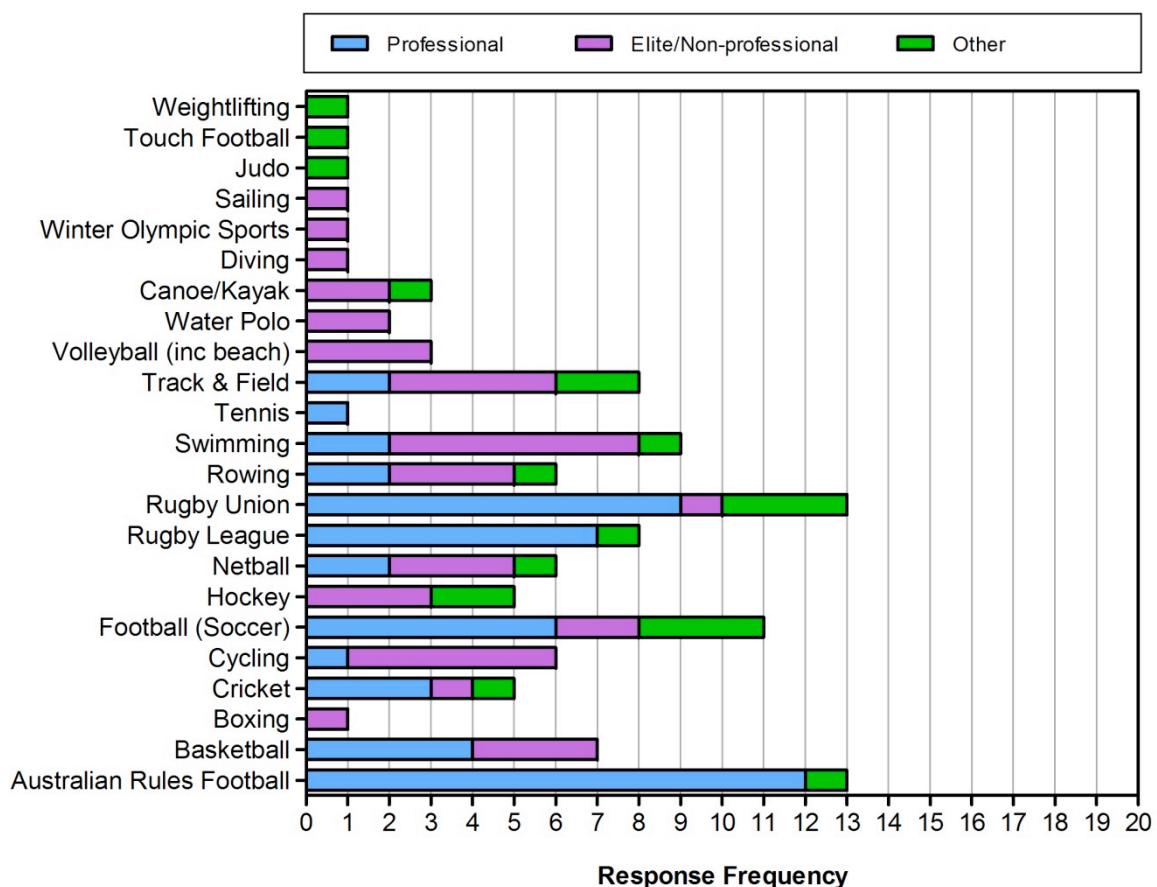


Figure 3.1 Number of respondents representing various sports, with colours differentiating the level of performance. This figure represents the 55 respondents, 53% of whom reported being involved with multiple sports.

3.4. RESULTS

When asked to rate the value of their training monitoring system to the overall performance of their athletes, 38% rated it extremely valuable, with a mean response of 3.9 ± 1.1 . Respondents indicated that the most important purpose of their training monitoring systems were injury prevention (29%), monitoring the effectiveness of a training program (27%), maintaining performance (22%) and preventing overtraining (22%). The majority of respondents indicated that there was an equal focus on load quantification and the monitoring of fatigue and recovery within the training monitoring system (70%), while others indicated the focus was solely on load quantification (20%) or solely the monitoring of fatigue/recovery (10%).

Most respondents spend between 0-4 hours per week collecting training monitoring data, while approximately 30% require 4 hours or more per week to collect their data. Approximately 75% of respondents indicated that the analysis of their data generally takes between 1-6 hours per week, while approximately 20% of respondents spent greater than 6 hours weekly on data analysis. Generally, results are fed-back to the athletes and/or other staff on the day of assessment, with 50% of respondents requiring less than 1 hour and 42% getting results processed in less than one day.

Of the methods identified for monitoring fatigue responses to training and competition, self-report questionnaires were most common (84%), with 11 respondents relying solely on self-reported measures in their monitoring systems. Fifty-five per cent of respondents indicated that they collected self-report information on a daily basis (22% every session; 33% once per day), while others used the forms multiple times per week (24%), weekly (18%), or monthly (2%) (Figure 3.2A). The type of self-report forms most commonly used were custom designed forms (80%), with the Recovery-Stress Questionnaire for Athletes [172] (13%), Profile of Mood States [207] (2%) and Daily Analysis of Life Demands (2%) in minor use. Follow-up responses from 14 respondents who indicated the use of custom designed forms revealed their forms typically included 4-12 items measured on Likert point scales typically ranging from either 1-5 or 1-10. Perceived muscle soreness was most frequently signified as an important indicator of an athlete's recovery state. Sleep duration and quality, and perceptions of fatigue and wellness were also identified as highly important components of the custom designed forms. When asked their reasons for not employing one of the self-

report questionnaires frequently reported in the scientific literature, a common theme in the responses was that they were too extensive, requiring too much time for athletes to complete (influencing compliance and adherence) and for support staff to analyse, and that they lacked sport specificity.

After the use of questionnaires for the monitoring of fatigue, 61% of respondents indicated the use of some form of performance test within their monitoring system. Practical tests of performance included, maximal jump and/or strength assessments, overground sprints, submaximal cycling or running tests, and sports specific performance tests (Figure 3.3). These tests were commonly implemented on a weekly or monthly basis (33% and 30%, respectively), although more frequent testing was performed by 36% of respondents (Figure 3.2B). Within this category of performance tests, jump tests were most popular, used by 54% of respondents. Follow up questioning revealed a variety of equipment used by respondents in the assessment of jump performance, including linear position transducers, force plates, contact mats, and vertical jumping apparatus (e.g. Vertec or Yardstick). Of the 11 follow-up respondents who reported using jump assessments, all used a counter-movement jump (CMJ) for maximum height, with one respondent also using a broad jump, and another using a concentric-only squat jump in addition to the CMJ. Six practitioners assessed CMJ performance in an unloaded condition (hands on hips or holding a broomstick across the shoulders), and five assessed loaded CMJ performance using a 20kg Olympic bar.

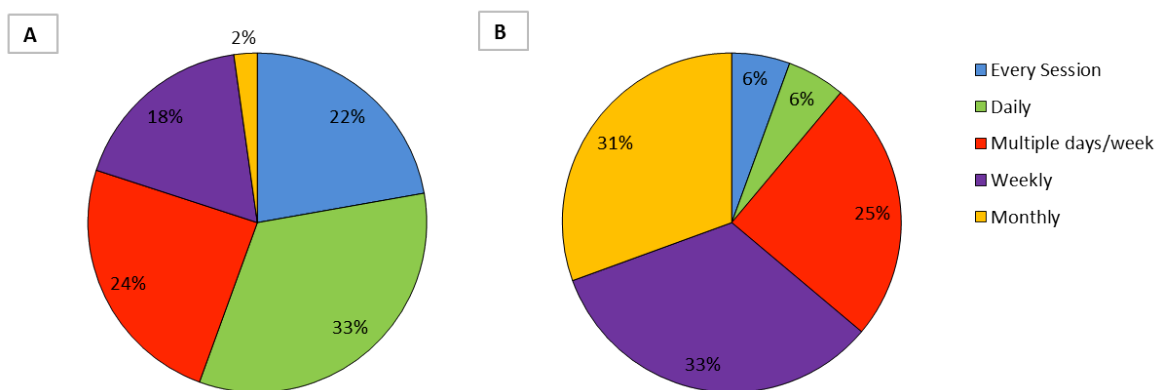


Figure 3.2 Frequency of administration of (A) self-report questionnaires and (B) performance tests

In the performance test category, the next most popular performance tests were sport specific test protocols (20%), strength tests (16%), and submaximal running or cycling tests (14%), with a range of other tests identified that didn't fit into any of the above categories.

Other than self-report questionnaires and performance tests, tracking performance in sporting activity was another popular method for monitoring fatigue and recovery, with 43% of respondents indicating this as a component of their fatigue monitoring system. This method is most popular in Australian Rules Football (n=9), Football (Soccer) (n=4), Rugby League (n=4), Rugby Union (n=3), Swimming (n=3) and Cycling, Rowing and Track and Field (n=2 each). Follow-up responses were received from seven survey respondents. Those involved in field based sports (n=6) all indicated the use of global positioning system (GPS) units to measure a large range of performance indicators from their athletes both in training and competition. Most common were measures of work rate (e.g. metres covered per minute), time spent in high intensity work ranges, and total distance, although numerous other variables were mentioned including the coaches rating of performance, number of tackles performed and other game statistics. One respondent also indicated the use of a measure of "body load", based on data obtained from an accelerometer.

A variety of other forms of fatigue monitoring were suggested by survey respondents. Four participants indicated that they use hormonal profiling as a component of their training monitoring system, and other respondents reported the use of musculoskeletal screenings (n=1), resting heart rate (n=1), and a commercially available athlete monitoring system (restwise.com) (n=1). Two other respondents indicated they relied on asking the athlete how they felt, either at rest or during high intensity training efforts.

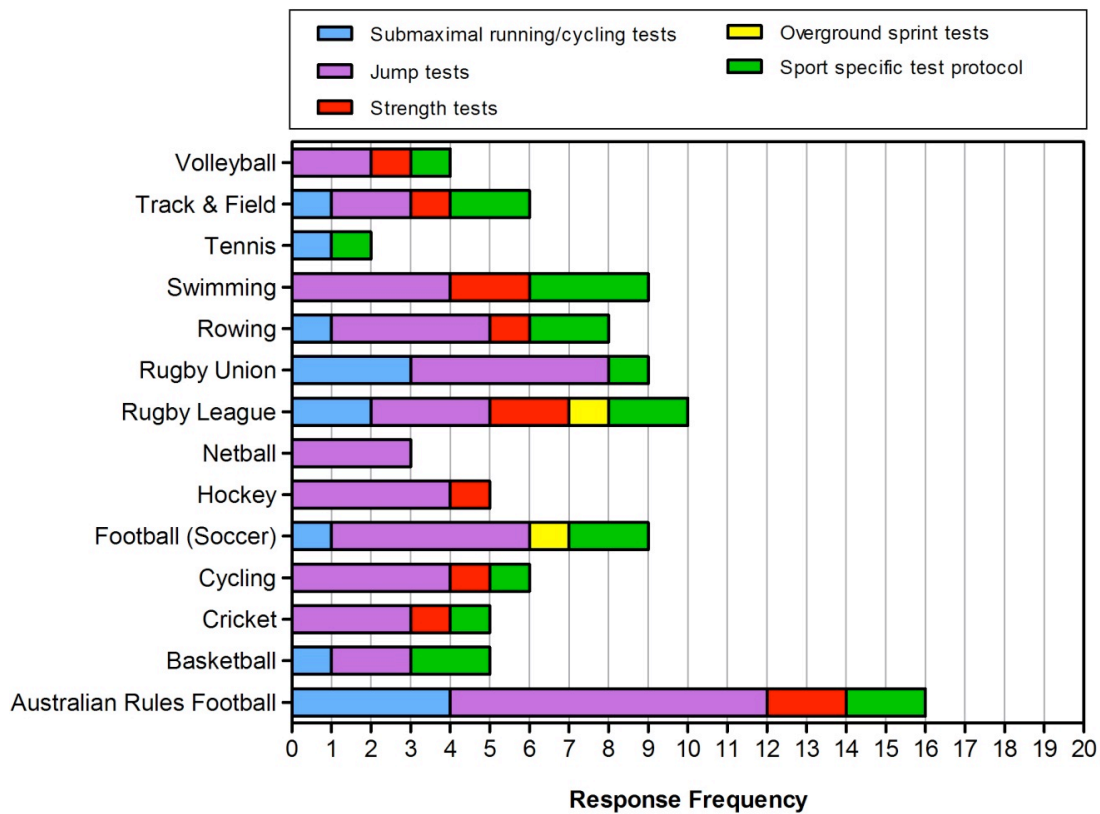


Figure 3.3 Frequency of use of performance tests by sport.

3.5. DISCUSSION

The cumulative fatigue associated with successive overload training and/or frequent competition is an accepted part of modern coaching practice. While anecdotal evidence suggests that a wide variety of methods for monitoring fatigue are practiced in high performance sports programs, the details of what is considered best practice in these environments is not yet detailed in the literature. The results from this survey describe this landscape, and present evidence that a number of methods historically investigated in the scientific literature, such as resting heart rate indices and biochemical monitoring, are not popularly employed at the coalface of high performance sport.

In the population surveyed a high usage of self-report questionnaires for monitoring fatigue was indicated across a wide variety of sports and levels of performance. Support for such

instruments and methods for monitoring fatigue and/or overtraining is provided by a large body of scientific investigations showing mood disturbances coinciding with increased training loads [39, 87, 121, 165, 171, 191, 218] and reduced performance [67, 244]. It is likely that the popularity of self-report questionnaires for monitoring fatigue in high performance athletic settings is largely due to the simplicity of data collection and analysis which is then reflected in the regularity of the data collection, with 55% of respondents collecting this information on a daily basis. A large percentage of those surveyed opted to rely on their own custom designed self-report forms rather than those that have been used in scientific investigations. Further questioning highlighted the need for self-report forms to be concise and targeted to the monitoring situation, which the established versions reported in the literature are not. Accordingly respondents have designed their own forms, generally consisting of 5-12 items using 1-5 or 1-10 point Likert scales, or by modifying existing questionnaires by placing greater emphasis on ratings of muscle soreness, physical fatigue and general wellness. A dearth of experimental data exists investigating the effectiveness of such self-designed forms for monitoring fatigue, with few published reports available questioning the effectiveness of modified versions of existing questionnaires. Despite this lack of empirical evidence validating the modified forms, follow up respondents indicated they were confident that their modified self-report items provided them valid information, and that in their opinion scientific confirmation is unnecessary.

When asked what types of changes prompt the coaching or support staff to adjust an athlete's training or competition load based on their responses to the self-report questionnaires, a number of methods were identified. The majority of respondents indicated a reliance on visually identifying trends in individual data (decline for successive days/sessions); however another common method involved the use of individual "red flags" to identify meaningful changes in responses. The determination of a "red flag" was often based on arbitrary cut-off values or thresholds considered important by the coaching or support staff. One respondent provided a value for this arbitrary cut-off value (5% below the mean value); with others only stating that a "significant" drop below the athletes mean score is flagged as important. In relation to muscle soreness scores in particular, multiple respondents reported the use of the intra-individual standard deviation (SD) values to highlight changes outside of the individual's normal variation. Respondents utilising this quantitative approach for identifying "red flags" typically used values of ± 1 SD in relation to the mean, although the magnitude of these values were not reported. To our knowledge such methods for identifying

unusual changes in regular performance due to fatigue are yet to be reported in the scientific literature.

Fatigue was also commonly assessed by respondents via tests of functional performance, with maximal jump assessments most popular within this category. Vertical jumping in particular has been touted as a convenient model to study neuromuscular function and has been used in a multitude of studies investigating the time course of recovery from fatiguing training or competition [11, 43, 62, 66, 111, 151, 180, 204, 227, 257, 293, 311]. The utility of vertical jumps as a practical measure of neuromuscular fatigue is reflected by the adoption of such testing procedures in the high performance sporting environment. However, a wide variety of protocols and equipment are available for measuring a range of outcome variables associated with vertical jumping performance, and little consensus exists as to the optimal methods or variables of interest for accurately measuring the state of fatigue or recovery in individual athletes. Vertical jump performance during periods of heavy loading has been monitored using vane jump and reach apparatus [48, 65, 66, 96, 216], contact or switch mats [126, 311], and force platforms [62, 180, 204, 223, 257]. Within the population surveyed respondents also indicated the use of the above equipment; with the most popular being linear position transducers, or force plates in combination with linear position transducers. The use of force plates in combination with linear position transducers is not a regularly reported method for monitoring changes in performance due to fatigue in overreaching or overtraining studies, but is used widely for the assessment of vertical jump performance in numerous other settings and interventions (e.g. [63, 78, 270, 271]). Cormack et al., [60] monitored changes in vertical jump performance performed on a force plate following an Australian Rules Football match and reported that only six of the 18 force-time variables analysed during single and 5-repetition jumps had declined substantially following the match. In particular there was a lack of sensitivity of jump height to fatigue which supported the earlier work of Coutts and colleagues [66]. Of further interest was that the pattern of response in these parameters varied greatly during the recovery period (from 24 h to 120 h post match) [60]. This research highlights the considerable differences in changes in vertical jump performance based on the performance variable of interest. The responses to further questions regarding jump assessment protocols indicated that jump height remained popular among the variables being assessed in fatigue monitoring systems, however numerous other kinetic and kinematic variables, such as peak and mean velocity, peak and mean power, and peak force were also monitored. Many of the respondents indicated that they were still

unsure of which parameter(s) are most useful, and thus continued to monitor numerous variables in the hope of gaining a better understanding of how they changed in relation to each other, as well as attempting to establish their relationship with changes in performance. Similar to the self-report questionnaires, the magnitude of change in these variables considered important was often based on visual analysis of trends or arbitrary threshold values ($\pm 5\text{-}10\%$), with two respondents indicating the use of individual SD values (± 1 SD) to identify changes outside of normal intra-individual trends.

Longer-term negative adaptations to training stress often involve changes in the autonomic nervous system which may be reflected in concomitant alterations in resting heart rate (HR), heart rate variability (HRV) measures and heart rate responses to maximal or submaximal exercise [2, 37]. Results from the current survey indicated that heart rate monitoring during submaximal tests are popular, while resting heart rate indices, including heart rate variability, are less commonly monitored. Follow-up questioning regarding custom designed self-report forms did however reveal that resting heart rate was commonly included as an item on these self-report forms, suggesting that its popularity may not have been truly represented in responses during the initial survey. The continued use of HR and HRV measures is in contrast to reported opinion in that although there are significant modifications after short-term fatigue (in resting heart rate and HRV), long-term fatigue (HR during a submaximal workloads) or both (maximal HR), the moderate amplitude of those alterations limits their clinical usefulness since the expected differences fall within the day-to-day variability of those measures [38].

It is interesting that although a large number of scientific investigations have explored the effectiveness of biochemical monitoring for assessing fatigue and/or adaptive states (for extensive reviews see [298, 300, 304]), only four survey participants indicated that this is a component of their training monitoring system. Follow-up questioning suggested that the limited popularity is likely due to the large time, cost and expertise required for the analysis, as well as perceived difficulties in linking changes in biochemical parameters to performance outcomes. In addition, time of day, diet, and presence of injury influence biochemical concentrations, requiring well standardised sampling conditions which are often difficult to realise in the training environment [294, 298]. There also exists considerable variation within and between individuals, influencing the reliability of measures and the availability of reference values indicating a “normal” exercise tolerance

[298]. These methodological issues, along with the inconvenience of collecting samples make this method difficult to implement on a regular basis, which is supported by the findings of the current study.

For all types of assessment, where decisions about an athlete's state of fatigue or recovery are made on the basis of changes in an outcome variable that isn't the performance itself, there is a need to identify a threshold at which negative changes in performance are considered large enough to be meaningful. Commonly this threshold value referred to as the smallest worthwhile change (SWC) in performance. These SWC values for each test parameter change from population to population. However, the reporting of these values in the literature by the people implementing such tests is not widespread. If this reporting practice can be encouraged it will add greatly to the knowledge base and assist in gaining an understanding of what changes are practically important based on the type of sporting performance involved. It is also important that these values fall outside of the typical error of the assessed variable in order for changes to be confidently interpreted [146]. Currently data on the relationship between SWC and typical error has been presented for vertical jumps on a force platform [60] and heart rate values during submaximal running tests [185]. To our knowledge few data exist describing the practically important changes associated with item analyses on self-report questionnaires, limiting the ability to make decisions using critical thresholds based on changes in these parameters. Instead coaches and practitioners rely on these self-report questionnaires as a tool to highlight possible problems in an athlete's fatigue or recovery state, with only a few employing statistical methods to quantify what they consider practically important changes within an individual. To date, changes in these values have only anecdotally been linked with reductions in performance.

Based on the current findings that significant time investment is allocated to training monitoring and that the respondents place a high value on their systems for ensuring maximal performance of their athletes, it seems that more research in this popular area will assist in enhancing current best practice. While there appears to be plentiful research focused on the development of training monitoring systems and their validation in high performance sports environments, the current results suggest that the protocols adopted by coaches and support staff at the coalface of elite sport do not entirely reflect the most current evidence available in the scientific literature. A more focused research approach on the development and validation of methods for monitoring fatigue and recovery via practical

tests of maximal neuromuscular performance is warranted, given the wide variety of methods and protocols currently employed.

3.6. PRACTICAL APPLICATIONS

It is critical for coaches of high performing athletes to have a training plan, yet it is also highly important to be able to adjust the plan based on how the athlete is adapting or coping with the imposed training and competition demands. To do this effectively the coach requires information based on each individual athlete's recovery abilities in response to various training stressors. In high performance sporting environments, self-report questionnaires identifying perceived changes in muscle soreness, feelings of fatigue and wellness, sleep quality and quantity and a variety of other psychosocial factors are relied upon for "flagging" athletes in a state of fatigue. Results from the survey indicate that custom-designed forms are preferred to those existing in the scientific literature because of the time required for completion. This concern is understandable given the time pressures in high performance environments, however shortened versions of the REST-Q are available. Use of a shortened REST-Q would provide a more scientifically valid method for collecting such information and provide support staff with a more reliable cross-reference to broader exercise applications.

Vertical jump tests are also frequently used to assess neuromuscular function, using a variety of equipment and assessment protocols. While limited data are available, unpublished observations from our research group suggest that unloaded jumps are more useful for monitoring fatigue than loaded variations. Similarly we have observed that eccentric displacement in a CMJ is most sensitive to fatigue induced by periods of high loading. Jump height, mean power and peak velocity are also useful variables to monitor. Within the population surveyed CMJs are most popularly employed, however there may also be value in monitoring a variety of different types of jumps (e.g. static-, countermovement- and drop- jumps), since experimental evidence suggests differential responses depending on the fatiguing stimulus.

While only a few practitioners reported using physiological parameters measured during submaximal exercise tasks to monitor training responses, feedback from these respondents along with recent research suggests that such tasks may provide a useful monitoring tool. In

contrast, limited evidence exists supporting the use resting heart rate indices for these purposes due to large day-to-day variability.

Biochemical monitoring is not a popular form of athlete monitoring in the population surveyed, mostly due to the high costs associated as well as the extended time required to process results. There is however plentiful research supporting its use in monitoring athletes susceptible to non-functional overreaching or overtraining, and therefore may be useful in circumstances where the practical limitations can be worked around.

Lastly, when deciding on any assessment method, careful consideration should be given to the magnitude of change considered important for each of the measurement variables. Respondents indicated arbitrary thresholds of 5-10% or $\pm 1SD$, but the consequence of changes beyond these thresholds is unknown. The reporting of typical variation in these values during normal training and periods of high stress may assist practitioners in determining the most appropriate monitoring protocols and threshold levels. With this concept at the forefront of decision making, the authors believe that practitioners seeking to effectively monitor the fatigue state of their athletes should at least be using a shortened version of the REST-Q while monitoring changes in eccentric displacement, jump height, mean power and peak velocity in unloaded CMJs. Each of these variables should be consistently monitored during a period of low intensity training determine an individual's normal variation so as to effectively determine "red flag" thresholds.

CHAPTER FOUR

Sources of variability in iso-inertial jump assessments

Full reference for published manuscript:

Taylor, K., Cronin, J., Gill, N., Chapman, D., and Sheppard, J. (2010). Sources of variability in iso-inertial jump assessments. *International Journal of Sports Physiology and Performance*, 5(4): 546-558.

4.1. ABSTRACT

This investigation aimed to quantify the typical variation for kinetic and kinematic variables measured during loaded jump squats. Thirteen professional athletes performed six maximal effort countermovement jumps on four occasions. Testing occurred over 2 d, twice per day (8 AM and 2 PM) separated by 7 d, with the same procedures replicated on each occasion. Jump height, peak power (PP), relative peak power (RPP), mean power (MP), peak velocity (PV), peak force (PF), mean force (MF), and peak rate of force development (RFD) measurements were obtained from a linear optical encoder attached to a 40 kg barbell. A diurnal variation in performance was observed with afternoon values displaying an average increase of 1.5–5.6% for PP, RPP, MP, PV, PF, and MF when compared with morning values (effect sizes ranging from 0.2-0.5). Day to day reliability was estimated by comparing the morning trials (AM reliability) and the afternoon trials (PM reliability). In both AM and PM conditions, all variables except RFD demonstrated coefficients of variations ranging between 0.8-6.2%. However, for a number of variables (RPP, MP, PV and height), AM reliability was substantially better than PM. PF and MF were the only variables to exhibit a coefficient of variation less than the smallest worthwhile change in both conditions. Results suggest that power output and associated variables exhibit a diurnal rhythm, with improved performance in the afternoon. Morning testing may be preferable when practitioners are seeking to conduct regular monitoring of an athlete's performance due to smaller variability.

4.2. INTRODUCTION

The measurement of kinetic and kinematic variables during instrumented vertical jumps have commonly been used to examine training effects after various short-term interventions [3, 203] and, more recently, to gain insight into an athlete's state of neuromuscular fatigue via monitoring of performance during intensified training or competition [60, 257, 311]. In the regular training environment, especially in high performance sport where training loads are characteristically high, such tests may be useful for coaches and support staff by providing an objective method to assess an athlete's response to training and their recovery between sessions or competitions. However, in order to make informed decisions regarding changes in performance, it is critical that the typical variation or the repeatability of the test be known [143]. In this regard, the observation of meaningful changes in performance is

reliant on knowing whether the observed change is outside of the variation that can be expected to occur by chance, or due to normal variation in the outcome variable. It follows that the more reliable the measurement is, the easier it will be to quantify real changes in performance [18, 143].

To enable the estimation of such values, it is necessary to conduct a reliability study using test-retest procedures, where repeated measures are taken from a group of subjects over a time period that is similar to the planned duration between testing sessions [143]. While a number of authors have established acceptable reliability of loaded and unloaded jump squats and associated kinetic and kinematic variables, comprehensive analyses of variability in athletic populations are limited. Cronin et al. [71] and Hori et al. [149] have reported trial-to-trial reliability, analysing the change in performance between two consecutive trials, using unloaded and loaded (40 kg) counter-movement jumps (CMJ) respectively. Cronin et al. [71] reported acceptable reliability for force related measures (mean force, peak force and time to peak force), using a linear position transducer (LPT) and a force plate with coefficient of variation (CV) values ranging between 2.1 and 7.4%. Hori et al. [149] also reported acceptable trial-to-trial reliability for peak velocity, peak force, peak power and mean power using a variety of measurement devices (LPT, force plate and LPT + force plate), with CVs ranging from 1.2 to 11.1%. Sheppard et al. [270] and Cormack et al. [61] have evaluated the short-term (week-to-week) reproducibility of the CMJ and reported acceptable reliability for a range of variables, with CV values ranging from 2.8 to 9.5 %. These studies have presented reliability statistics based on either a single CMJ trial repeated one week apart [61], or three single trials performed seven days apart, where the best trial from each testing session was used in the analysis [270]. While previous work has provided useful information to practitioners in regard to equipment and dependent variable selection, a comprehensive understanding of the typical variation of each of the variables available during instrumented jumps, and the appropriate testing methodologies, requires further investigation.

Cormack et al. [61], have been the only researchers to consider the reliability statistics in relation to what is considered to be the smallest worthwhile effect on performance. The smallest worthwhile change (SWC), which is analogous to the minimum clinically important difference in the clinical sciences, is described as the smallest effect or change in performance that is considered practically meaningful [145]. For tests or measurements of

athletic performance to be useful in detecting the SWC, the error associated with the measurement needs to be minimal, and ideally less than the SWC [240]. Hence for the valid interpretation of reliability outcomes, an in-depth analysis of typical variation needs to take into account the relationship between the typical variation of a measurement and the smallest effect that is considered important, or practically meaningful. Previous research has not addressed this in relation to kinetic and kinematic variables measured via instrumented jumps.

The final consideration is differences between measurements performed on the same day. It has been previously shown that a diurnal variation in maximal neuromuscular performance exists, with findings generally exhibiting morning nadirs and afternoon maximum values [59, 109, 198, 243, 269, 317] indicating that neuromuscular capabilities are influenced by time of day. While authors have typically ensured that time of day was standardised within subjects, the potential differences in typical variation when testing is conducted at differing times of day has not been examined (i.e. time of day was generally not standardised between subjects). Hence, along with examining time of day differences in neuromuscular performance, it may also be appropriate to examine the loaded CMJ for differences in variability, or reproducibility, between morning and afternoon testing sessions. The specific aims of the present study were therefore to (i) evaluate the time of day effect on jump performance and associated kinetic and kinematic variables, (ii) to comprehensively evaluate the reproducibility/variability in performance of highly trained athletes that were familiar with the testing procedures and (iii) to establish which variables are useful in detecting the smallest worthwhile change in performance.

4.3. METHODS

4.3.1. Design

To examine the effect of time of day on jump performance, subjects performed six loaded CMJs in the morning (AM; 0800-0900) and in the afternoon (PM; 1400-1500) after a standardised warm-up. The six jumps were divided into two sets of three jumps, where athletes rested for 2-3 minutes between sets. Differences in performance between AM and PM sessions were compared using within-subject statistical procedures. All subjects then

repeated the same procedures seven days later, to examine any differences in inter-session reliability between testing conditions (AM and PM).

4.3.2. Subjects

Thirteen professional male rugby union players (mean \pm SD: age 23.7 ± 2.7 years, height 1.86 ± 0.1 m, weight 103.8 ± 10.7 kg) participated in this study as a part of their regular pre-season training regime. All subjects were free from injury and were highly familiar with the requirements of the performance test. Written informed consent was obtained from all participants and the ethics committee of the Australian Institute of Sport approved testing procedures.

4.3.3. Procedures

Prior to each testing session subjects performed a 10 minute dynamic warm-up consisting of general whole body movements emphasising an increase in range of movement, and a variety of running patterns. Subjects were required to progressively increase the intensity of the exercises until the end of the warm-up period until they felt they were capable of maximal performance. Jump assessments consisted of each subject performing a CMJ with a load of 20 kg on an Olympic lifting bar (i.e. total load of 40 kg), a protocol that has been used extensively with this, and similar populations. The subject stood erect with the bar positioned across his shoulders and was instructed to jump for maximal height while keeping constant downward pressure on the barbell to prevent the bar moving independently of the body. Each subject performed three repetitions, pausing for ~ 3 -5 s between each jump. Subjects then rested for 2-3 minutes before repeating a second set of three jumps. No attempts were made to standardise the starting position, amplitude, or rate of the countermovement. A displacement-time curve for each jump was obtained by attaching a digital optical encoder via a cable (GymAware. Kinetic Performance Technologies, Canberra, Australia) to one side of the barbell. This system recorded displacement-time data at a sampling rate of 50 Hz, which was transmitted via Bluetooth to a hand held palm pilot and downloaded on to a desktop computer for later analysis. An analysis program (GymAware Version 3.13, Kinetic Performance Technologies) was used to calculate jump height, peak power (PP), relative peak power (RPP), mean power (MP), peak velocity (PV), peak force (PF), mean force (MF), and peak rate of force development (RFD) from the displacement-time curve.

4.3.4. Statistical Analysis

Means and standard deviations (SD) were computed for the kinetic and kinematic variables in the AM and PM conditions for Weeks 1 and 2 independently. Thereafter intra-day analyses examining the diurnal effect were conducted using the mean values of six trials from the AM and PM sessions by averaging Weeks 1 and 2 (mean diurnal response). To examine the AM to PM differences in performance, effects were calculated as the mean difference divided by the pooled between-subject SD, and were characterized for their practical significance using the criteria suggested by Rhea [251] for highly trained participants as follows: < 0.25 = trivial, $0.25-0.50$ = small, $0.51-1.0$ = moderate, and > 1.0 = large. Additionally, a substantial performance change was accepted when there was more than a 75% likelihood that the true value of the standardized mean difference was greater than the smallest worthwhile (substantial) effect [144]. Thresholds for assigning the qualitative terms to chances of substantial effects were: $< 1\%$, almost certainly not; $< 5\%$, very unlikely; $< 25\%$ unlikely; $25-75\%$, possibly; $> 75\%$ likely; $> 95\%$ very likely; and $> 99\%$ almost certain. The smallest worthwhile effect on performance or SWC from test to test was established as a “small” effect size ($0.25 \times$ between-participant SD) according to methods outlined previously [143].

When investigating reliability Hopkins [143] has recommended that the systematic change in the mean, as well as measures of absolute and relative consistency (i.e. within-subject variation and retest correlations respectively) be reported. Systematic changes in the mean from AM to AM and PM to PM were examined via the procedures described above for examining the diurnal response. The absolute reliability or typical within-subject variation was quantified via the CV. For trial-to-trial reliability this was calculated as $\sqrt{(\sum SD^2/n)}$ where SD equals the standard deviation for each individual across the 6 trials, and n is the number of subjects. This value was then divided by $\sqrt{6}$ to give the estimated error in the mean of six trials, which represents the variation in the mean if the six trials were to be repeated without any intervening effects. The AM to PM reliability, calculated as the mean change in AM to PM performance on the same day, was quantified as the SD of the change scores divided by $\sqrt{2}$. Week-to-week reliability was calculated using the same formula, based on the change scores from Week 1 to Week 2 for the two morning trials (AM reliability) and then the two afternoon trials (PM reliability). To examine the influence of the number of trials on the reliability outcomes, we calculated the week-to-week CV using

the first trial from Week 1 and Week 2, the mean of trial 1 and 2, the mean of trials 1 – 3, the mean of trials 1 – 4 and so on.

4.4. RESULTS

Performance characteristics for the group across the AM and PM sessions are presented in Table 4.1. No substantial systematic change was observed in any of the variables across the six trials, indicating that learning effects and fatigue did not affect the results within each session. Figure 4.1 illustrates the mean changes for the AM-PM trials, AM-AM trials, and the PM-PM trials. Small to moderate time of day effects were observed for PP, RPP, MP, PV, PF and jump height, with a mean diurnal response of 4.3-6.1% (Figure 4.1A). No substantial changes in the mean were from week to week in either the AM or PM conditions (Figure 4.1B and 4.1C).

Reliability estimates based on the variation within a single session, between sessions within the same day (AM to PM), and from week-to-week are presented in Table 4.2. The trial-to-trial reliability was good for all variables except RFD (range = 1.4-7.7%). The reliability based on the mean of six trials was very high, with CVs less than 3.2% for all variables except RFD (13.3-16.6 %). In addition to exhibiting excellent absolute reliability, PP, RPP, MP, PV, PF and height yielded typical variation scores less than the SWC.

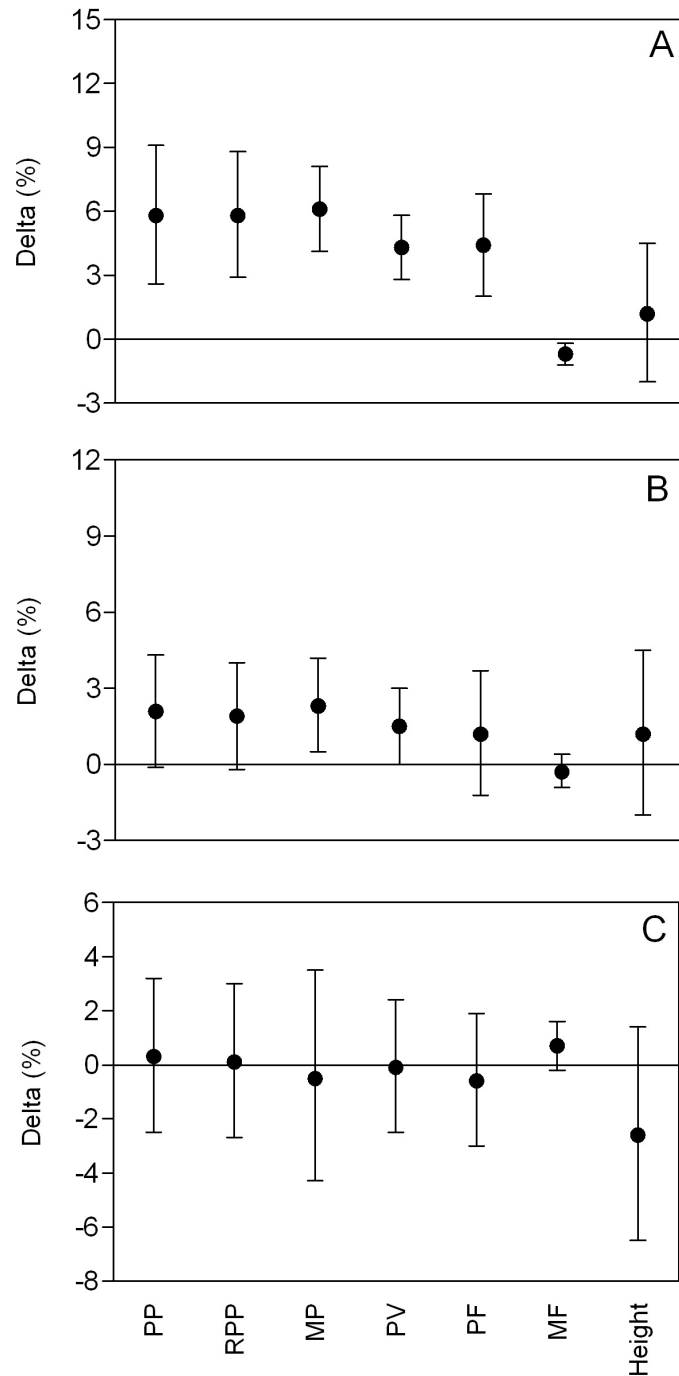


Figure 4.1 Mean changes in performance \pm 90% confidence limits for peak power (PP), relative peak power (RPP), mean power (MP), peak velocity (PV), peak force (PF), mean force (MF), jump height (Height). (A) mean change in performance from AM to PM (average of trials for week 1 and 2); (B) mean change in performance from week 1 to week 2 for AM trials; (C) mean change in performance from week 1 to week 2 for PM trials.

Table 4.1 Mean \pm SD for kinetic and kinematic variables measured during 40kg CMJ. Results were calculated using the mean of 6 trials during each session and averaged for Week 1 and Week 2.

VARIABLE	AM	PM
Peak Power (W)	5457 \pm 453	5719 \pm 424
RPP (W/kg)	53.1 \pm 7.8	55.8 \pm 8.4
Mean Power (W)	2347 \pm 225	2451 \pm 189
Peak Velocity (m/sec)	2.53 \pm 0.17	2.60 \pm 0.19
Peak Force (N)	3015 \pm 375	3116 \pm 363
Mean Force (N)	1435 \pm 105	1433 \pm 111
Jump Height (cm)	28.9 \pm 3.7	30.2 \pm 5.5
RFD (kN/s)	20.9 \pm 7.7	21.7 \pm 8.0

Table 4.2 Coefficients of variation (CV) representing the expected variation from trial-to-trial; for the mean of six trials within a session; between AM and PM sessions; and for the mean of six trials between sessions conducted one week apart. Smallest worthwhile change (SWC) values are also presented for comparisons with the estimates of typical variation.

VARIABLE	Trial to trial CV (%) within a session		CV (%) of the mean of the 6 trials		Within-day CV (%)	Week to Week CV (%)		SWC (%)
	AM	PM	AM	PM		AM	PM	
Peak Power	5.5	5.2	2.3	2.1	3.4	2.5	3.4	2.4
RPP	5.6	5.2	2.3	2.1	3.4	2.4	3.4	3.9
Mean Power	5.3	5.0	2.2	2.0	2.9	2.1	4.7	2.5
Peak Velocity	2.6	2.8	1.1	1.1	2.3	1.7	2.9	1.9
Peak Force	5.5	5.3	2.2	2.2	2.7	2.9	2.9	3.2
Mean Force	1.5	1.4	0.6	0.6	0.8	0.8	1.0	1.9
Height	7.0	7.7	2.9	3.2	6.6	4.3	6.2	4.3
RFD	39.4	32.5	16.1	13.3	15.5	22.5	25.9	10.8

When the mean of the six trials were used to examine week-to-week test-retest reliability a similar pattern emerged with all variables except RFD exhibiting high reliability coefficients (range = 0.8-6.2%). Only height in the PM condition had a CV exceeding 5% (i.e. 6.2%). However, while such values would generally be considered to represent excellent reliability, PP, PF and MF were the only variables where the typical variation was less than the SWC in

both conditions. A number of variables (RPP, MP, PV and height) demonstrated $CV < SWC$ in the AM condition only.

Interestingly, along with changes in AM and PM performance, substantial differences in reliability were also observed for a number of variables across the AM and PM conditions. The differences in AM and PM reliability can be observed in Table 4.2. Based on the analysis, it is likely to very likely (i.e. $> 75\%$ likelihood) that the week-to-week variability in the PM sessions was greater than the variability in the AM sessions for RPP, MP and PV. It was unclear if there were substantial differences in variability between AM and PM for all other variables.

Figure 4.2 illustrates the differences in AM and PM reliability, along with differences in the estimated typical variation as the number of trials included in the analysis increased. For PP, RPP, MP and PV it is evident that PM variability is greater than AM variability, and as the number of trials included in the analysis was increased, the typical week-to-week variation was reduced. A contrasting result was observed for PF with AM variability greater than the PM variability. In addition the low variability achieved for PF in the PM session was not noticeably reduced as more trials were included. For MF, which demonstrated the lowest variability in all analyses, AM and PM reliability was similar, and they both varied very little with the inclusion of additional trials. Similarly the variability for height between the two PM sessions was minimally reduced when a single trial was compared to the mean of 6 trials (6.2% and 4.8% respectively). RFD displayed trends similar to PP, RPP, MP and PV (i.e. greater PM variability and greater reliability with increased trials), however the CVs are greater than what can be considered of practical value (range = 22.5 to 36.5%).

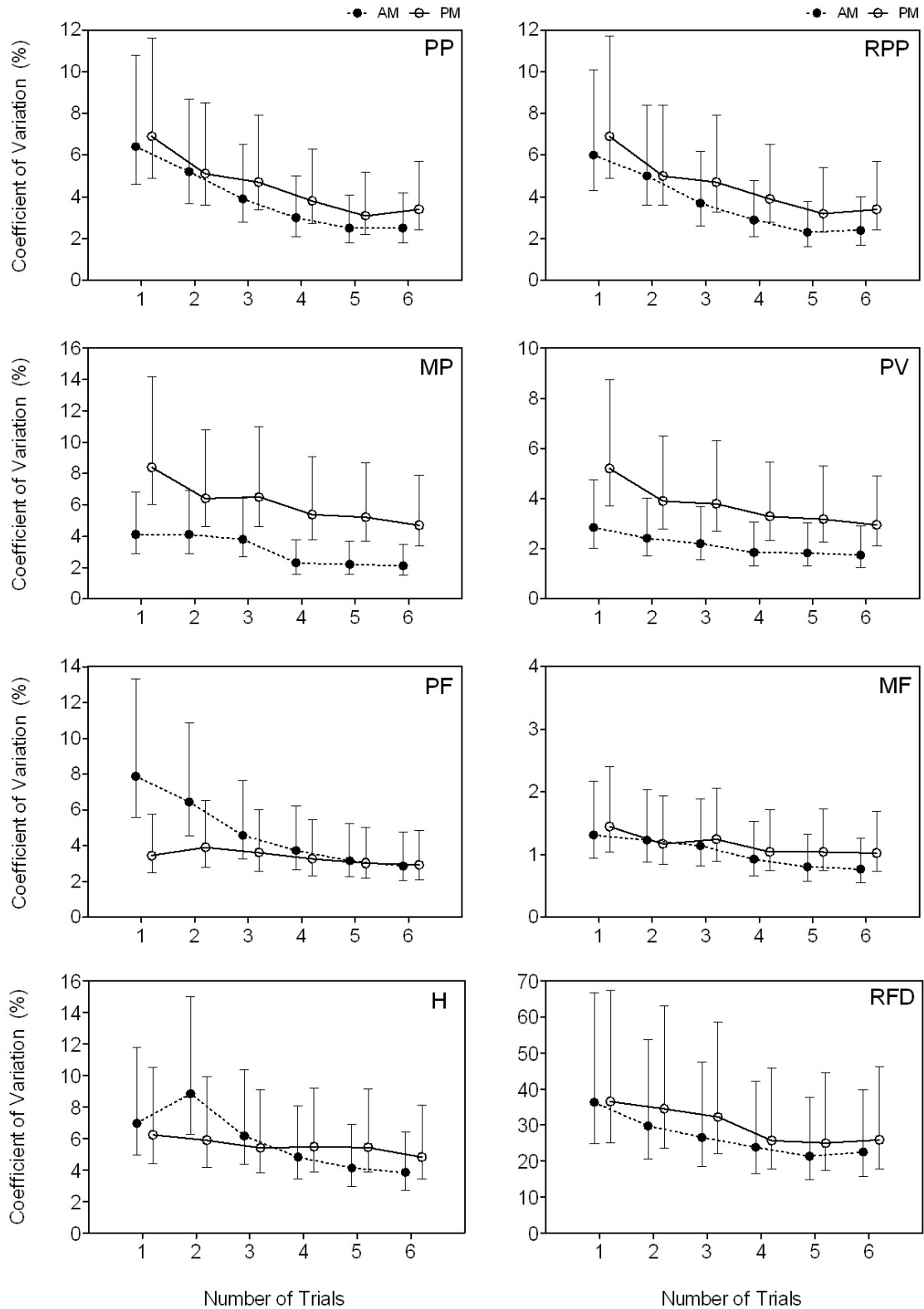


Figure 4.2 Mean coefficients of variation \pm 90% confidence limits for peak power (PP), relative peak power (RPP), mean power (MP), peak velocity (PV), peak force (PF), mean force (MF), jump height (H) and peak rate of force development (RFD) based on the time of day (AM or PM) and the number of trials performed.

4.5. DISCUSSION

To confidently estimate true maximal athletic capacities, and assess real and meaningful changes in performance a greater understanding of how variables are expected to vary both within and between testing sessions is needed. Authors have often reported acceptable reliability for force and power related variables during CMJs, with within-subject variability coefficients ranging from 1.2 to 11.1% [54, 61, 71, 149, 270]. The findings from the present study were similar for a number of variables, with all variables except RFD producing CVs between 0.8 and 6.2%, for trial-to-trial and week-to-week reliability. The novelty of our statistical analysis demonstrates that the variability associated with the time of day that testing is performed affects the extent of variation inherent in performance. Additionally we have shown that while most variables demonstrated “acceptable” reliability, the relationship between the CV and the SWC signifies that limited variables are capable of detecting practically important changes in performance.

It is important to recognise that while both trial-to-trial and short-term (week-to-week) reliability are important, in the context of athletic assessment they serve different purposes. The error estimate associated with trial-to-trial reliability can be attributed to random measurement error, as there is little scope for biological changes [143]. This value assists the practitioner in estimating the amount of error likely to occur around a single measurement within a single session, thus allowing for an accurate estimation of the true likely range of the outcome variable. Our results indicate that if a single trial protocol is used, the practitioner can expect an approximate 4-8 % error for most kinetic and kinematic variables (the error associated with MF was lower at ~1.5 %, while RFD demonstrated considerably greater random error, ranging from 32-40 %). When a six trial protocol was used, the error rate was reduced for all variables, and the variability from trial-to-trial was estimated between 1.1-3.2 %. RFD, however, still remained high at ~13-16 %. Thus the inclusion of six trials in the analysis demonstrated the error associated with each trial was ~1-3 %, which is similar to the 2-3 % reported by Cronin et al. [71] but substantially less than Hori et al. [149] who reported variations of 9.0-11.1% for PF, PP and MP.

When the purpose of testing is to monitor an athlete’s response to training and their recovery between sessions or weekly competitions, the focus is on the short term variability (which includes the trial-to-trial variability). Such short term variability includes the random

measurement error plus associated “normal” or biological variation that occurs over time. This type of reliability is most commonly reported and is useful for estimating the magnitude of error associated with test-retest designs, where subjects are tested pre- and post an intervention, or when performance tests are used for regular athlete monitoring. The current results indicate that when testing was repeated seven days later, additional biological error was present for all variables. For example, PP demonstrated a typical trial-to-trial error of ~2%, which increased to ~3.5% when week-to-week variability was included. While no previous studies have examined week-to-week reliability using similar instrumentation, the range of 1-6 % would satisfy the criteria for acceptable reliability set by most authors in this area.

Although there is no preset standard for acceptable CV values, many researchers have set a criteria of <10% for “good” reliability [18, 61, 270]. Upon meeting this requirement, authors have generally recommended that their test protocols can be used to confidently assess changes in a range of neuromuscular parameters. However, knowing that a change is “real” (i.e. outside of the expected measurement error), does not provide the practitioner with information regarding the meaningfulness of the change. To identify meaningful or worthwhile changes in performance, knowledge of the SWC is needed [145]. It has been suggested that if the typical variation (CV) of a test or variable is less than the SWC, then the test/variable is rated as ‘good’, while a variable with a CV that is considerably greater than the SWC would signify marginal practicality of that variable [240]. Previously, only Cormack et al. [61] compared their reported reliability estimates to what was considered the SWC in performance, and while they reported CVs less than their criterion of 10% for a large number of variables, only MF had a typical variation less than the SWC. In our analysis, MF and PF were the only variables to demonstrate $CV < SWC$ in both AM and PM conditions. While all variables other than RFD easily met the normally accepted criterion of <10%, they were generally not capable of detecting the SWC. Exceptions to this included the AM reliability values for RPP (CV = 2.4%; SWC = 3.9%), MP (CV = 2.1%; SWC = 2.5%) and PV (CV = 1.7%; SWC = 1.9%). Therefore, when implementing a testing program to monitor changes in neuromuscular performance characteristics, the results from the present study suggest that MF and PF would be the most useful variables to monitor. However, confounding issues remain, since it is possible that the most reliable tests are not necessarily the most effective for monitoring performance in athletes [147]. When using an assessment of neuromuscular performance to predict changes in performance readiness in

team sports, or as an indicator of fatigue, it is important to also consider the relationship of the variable to successful performance. Although MF is very reliable, its stable nature may also mean that it is not able to effectively discriminate between positive and negative performance outcomes. While this is yet to be investigated, preliminary findings by the current authors suggest that even during periods of highly stressful training and competition, MF only tends to fluctuate by approximately 1%. Additionally, previous research examining the relationship between kinetic and kinematic variables and dynamic strength tests [230] and sprint performance [130], have not identified MF as an important predictor of successful performance. While MF was not included in these previous analyses, PP, MP and PF relative to body mass were reported to be strong predictors of performance [75, 130, 202, 230]. Therefore researchers require the development of methods that allow for other variables that are more informative (i.e. a stronger relationship to competitive performance) to be capable of detecting the SWC. This can only be achieved by reducing the typical variation associated with the practiced testing methodologies.

To investigate means for reducing the typical variation, we examined the effect of trial size on the week-to-week variability. Though it is well known that increasing the number of trials from which the reliability statistics are generated reduces the noise associated with the test, the number of trials before the error is reduced to an acceptable level is not well documented. Our results indicate that the inclusion of additional trials (up to 6) improved the reliability of PP and RPP by 4-5%. The differences in reliability from the analysis of one to six trials were also practically significant for MP, PV and PF (~1-4%). These findings suggest that the typical variation from week-to-week can be improved by using the average of 6 trials, rather than a single trial protocol. Numerous other studies have strongly suggested that multiple trial protocols are necessary for obtaining stable results in the assessment of lower limb function in a variety of activities [125, 158, 255]. For example, Rodano and Squadrone [255] reported that a 12 trial protocol was needed for establishing stable results for power outputs of the ankle, knee and hip joints during vertical jumping. James et al. [158] indicated that a minimum of four and possibly as many as eight trials should be performed to achieve performance stability of selected ground reaction force variables during landing experiments. We capped the number of trials in our study at six (2 sets x 3 repetitions) as we considered this a viable number when using such a protocol as a weekly monitoring tool with a large squad of players. By using the average of additional

trials, it may be possible to reduce the error further; however it is felt such a protocol would have limited feasibility in the regular training environment of high performance athletes.

Interestingly we found that AM variability was lower than PM variability for a number of variables (Table 4.1), which has important implications when the magnitude of variability is compared with SWC. For RPP, MP, PV and height, greater variability in the PM sessions meant that they were rejected on the basis that the estimated typical error was greater than the signal we are interested in measuring (i.e. $CV > SWC$). That is, while the $CV < SWC$ in the AM condition, indicating that the variables were in fact capable of detecting worthwhile changes in performance, the PM condition did not satisfy this criteria. Hence, since greater variability is present when testing was conducted in the afternoon, it appears that it may be more difficult to identify worthwhile changes in performance and therefore limit the utility of such assessments for monitoring training readiness and recovery between sessions.

4.6. PRACTICAL APPLICATIONS

Practitioners seeking to conduct regular monitoring of an athlete's performance are recommended to standardise the time of day that assessments occur. If maximal performance is paramount, then afternoon testing is likely to produce better results. However if monitoring changes in performance, changes may be more confidently observed if testing occurs in the morning due to smaller week-to-week variability. While mean and peak force were the only variables to demonstrate $CV < SWC$, other variables with acceptable reliability may be more related to performance, or have greater sensitivity to change, and require further investigation. We suggest further work is needed to determine the size of a worthwhile effect in the context of assessing training or competition readiness.

CHAPTER FIVE

Warm-up affects diurnal variation in power output

Full reference for published manuscript:

Taylor, K., Cronin, J., Gill, N., Chapman, D., and Sheppard, J. (2011). Warm-up affects diurnal variation in power output. *International Journal of Sports Medicine*, 32(3): 185-189.

5.1. ABSTRACT

The purpose of this study was to examine whether time of day variations in power output can be accounted for by the diurnal fluctuations existent in body temperature. Eight recreationally trained males (29.8 ± 5.2 yrs; 178.3 ± 5.2 cm; 80.3 ± 6.5 kg) were assessed on 4 occasions following a: (a) control warm-up at 8.00 am; (b) control warm-up at 4.00 pm; (c) extended warm-up at 0800 h; and, (d) extended warm-up at 1600 h. The control warm-up consisted of dynamic exercises and practice jumps. The extended warm-up incorporated a 20 min general warm-up on a stationary bike prior to completion of the control warm-up, resulting in a whole body temperature increase of 0.3 ± 0.2 ° C. Kinetic and kinematic variables were measured using a linear optical encoder attached to a barbell during 6 loaded counter-movement jumps. Results were 2-6 % higher in the afternoon control condition than morning control condition. No substantial performance differences were observed between the extended morning condition and afternoon control condition where body temperatures were similar. Results indicate that diurnal variation in whole body temperature may explain diurnal performance differences in explosive power output and associated variables. It is suggested that warm-up protocols designed to increase body temperature are beneficial in reducing diurnal differences in jump performance.

5.2. INTRODUCTION

Time of day has been repeatedly shown to affect various indices of maximal neuromuscular performance in humans with morning nadirs and afternoon maximum values a common finding in various tests of maximal voluntary strength in both dynamic and isometric conditions [31, 59, 109, 198, 269]. Similarly, the current authors have recently shown that a time of day effect is characteristic of performance in a loaded counter-movement jump, with afternoon improvements of 4.3 to 6.1% in force, peak movement velocity and power output [292].

Although it is possible that the effect of time of day on muscle contractile properties could be attributed in part to intracellular variations in the muscle (e.g. a circadian variation in inorganic phosphate concentration [198]), the more common hypothesis is that performance differences are causally related to the circadian rhythm in body temperature since previous researchers have observed a general parallelism between rhythms of physical performance

and core temperature [19, 77, 248]. The importance of temperature in performance is supported by extensive data from heating and cooling experiments which have demonstrated that maximal anaerobic power declines by 5% for every 1°C drop in muscle temperature [29]. Since body temperature is lowest in the morning (~ 0500 h) and rises throughout the day reaching a plateau between 1400 h and 2000 h [247] it follows that increases in morning temperatures could significantly impact testing results and perhaps dilute the diurnal performance effect previously noted.

Previous authors have extended the pre-assessment warm-up prior to swimming [14] and cycling [20] time trials, with the aim of increasing body temperature before the morning performances to match the body temperature in the afternoon. Findings from these studies lead to the conclusion that time of day differences in performance are not likely mediated by body temperature variation. Conversely Bernard et al., [31] observed that daily variations in anaerobic performance were in phase with the changes in core temperature, and Racinais et al., [243] reported that a passive warm-up which increased morning temperature to afternoon levels blunted the diurnal variation in muscle power by increasing muscle contractility in the morning. Given the conflicting results in the literature to date, and that maximal acyclic tests of power production (such as vertical jumps) occur over a much shorter time period (~300 ms) than the activities previously investigated, we aimed to examine the effects of an extended warm-up period on the time of day differences in vertical jump performance.

5.3. METHODS

5.3.1. Experimental Approach to the Problem

To examine whether increased whole body temperature gained through an extended warm-up affected the known time of day differences in explosive jump performance, subjects completed four separate testing sessions differing in time of day and type of warm-up completed. In a randomised order, jump performance was assessed following: (a) control warm-up at 0800 h (AM control condition); (b) control warm-up at 1600 h (PM control condition); (c) extended warm-up at 0800 h (AM extended condition); and, (d) extended warm-up at 1600 h (PM extended condition). Using a within-subject crossover design,

kinetic and kinematic variables measured during loaded counter-movement jumps (CMJs) were compared between conditions.

5.3.2. Subjects

Eight recreationally trained males (29.8 ± 5.2 yrs; 178.3 ± 5.2 cm; 80.3 ± 6.5 kg) with a minimum of six months resistance training history participated in this study. All subjects were rated intermediate in circadian phase type as determined by the Horne and Östenberg morning-eveningness scale [150]. Subjects were asked to avoid any strenuous lower body exercise as well as refraining from consuming alcohol or caffeine for 48 h prior to all assessments. Additionally they were asked to minimise any alterations in their diet and life style (e.g. sleeping time, etc.) for the entire period, and wake time was standardised between testing days. All procedures were approved by the institutional ethics committee following the principles outlined in by Harriss and Atkinson [131], with written informed consent obtained from each participant prior to data collection.

5.3.3. Procedures

The control warm-up consisted of dynamic exercises and practice jumps equivalent to the standard warm-up for strength and power assessment used in our laboratory. This included two minutes of easy self-paced jogging; 2 x 10 m of walking lunges, high knee skips and heel flicks; 10 x body weight squats; 2 x run-throughs/accelerations (10 m easy jog, 10 m at ~75% max sprint speed, 10 m easy jog); 2 sets of 3 unloaded jumps at ~ 80-90% of perceived maximal effort; and 1 set of 40 kg jumps (~80-90%). This type of dynamic warm-up is characteristically similar to warm-ups previously used in the investigation of vertical jump performance [49, 60, 196, 214, 314]. The extended warm-up incorporated a more extensive general warm-up period with the aim of increasing body temperature to a value equivalent to the values observed during the afternoon control trials. This was achieved with the subjects cycling on a stationary ergometer for 20 minutes at 150-200 W. This protocol established after extensive pilot trials which confirmed that post warm-up body temperature in the morning conditions matched the average afternoon resting body temperature. The general warm-up period was then followed by the control warm-up, so that the effects of the general warm-up on subsequent performance could be directly examined.

Body temperature was measured using a combination of skin and core temperature to estimate overall body temperature. Skin temperature (Mon-a-therm temperature system cables #502-0400, Mallinckrodt Medical, St. Louis, MO) and core temperature measured using ingestible core temperature pills (CorTemp, HQInc, Palmetto Florida) were recorded prior to the warm-up (baseline) and after the warm-up (immediately prior to the jump assessments). Skin thermistors were placed on the chest, forearm, thigh and calf of each subject, and these values were incorporated in the following equations to provide mean skin temperature [245] and subsequently an estimate of overall body temperature [267]:

$$\text{Mean Skin Temperature: } T_{sk} = (0.3 \times (T_{Chest} + T_{Forearm})) + 0.2 \times (T_{Thigh} + T_{Calf})$$

$$\text{Total Body Temperature: } T_b = 0.87 T_{core} + 0.13 T_{sk}$$

Jump assessments consisted of each subject performing a CMJ with a load of 20 kg on an Olympic lifting bar (i.e. total load of 40 kg). Five minutes after the practice jumps, the subject stood erect with the bar positioned across his shoulders and was instructed to jump for maximal height while keeping constant downward pressure on the barbell to prevent the bar moving independently of the body. Each subject performed three repetitions, pausing for ~3-5 s between each jump. Subjects then rested for two minutes before repeating a second set of three jumps. No attempts were made to standardise the starting position, amplitude, or rate of the countermovement. A displacement-time curve for each jump was obtained by attaching a digital optical encoder via a cable (GymAware Power Tool. Kinetic Performance Technologies, Canberra, Australia) to one side of the barbell. This system recorded displacement-time data using a signal driven sampling scheme where position points were time-stamped when a change in position was detected, with time between samples limited to a minimum of 20 ms. The first and second derivate of position with respect to time was taken to calculate instantaneous velocity and acceleration respectively. Acceleration values were multiplied by the system mass to calculate force, and the given force curve multiplied by the velocity curve to determine power. Mean values for power were calculated over the concentric portion of the movement (i.e. from minimum displacement to take-off) along with peak values for velocity, force and power. Jump height was determined as the highest point on the displacement-time curve. High test-retest reliability has previously been established for this assessment protocol (coefficients of variation for all variables < 6%)

[292], while the validity and accuracy of the data collection procedures have also been confirmed using similar methodologies [54, 71].

5.3.4. Statistical Analyses

The mean kinetic and kinematic values of the six jumps for each subject were used to compare performance between conditions. To examine differences in performance between conditions, effect size statistics (ES) were calculated as the mean difference divided by the pooled between-subject SD, and were characterized for their practical significance using the following criteria: <0.2 = trivial, $0.2-0.6$ = small, $0.6-1.2$ = moderate, and >1.2 = large. Additionally, a substantial performance change was accepted when there was more than a 75 % likelihood that the true value of the standardized mean difference was greater than the smallest worthwhile (substantial) effect [144]. The smallest worthwhile change in performance from test to test established as a “small” effect size ($0.2 \times$ between-participant SD) according to methods outlined previously [144].

5.4. RESULTS

Whole body temperature results for AM and PM at baseline were 36.4 ± 0.16 °C and 36.6 ± 0.18 °C (mean \pm SD) respectively (Figure 5.1). Following the AM extended warm-up, body temperature increased to 36.8 ± 0.09 °C which matched the post warm-up value of 36.8 ± 0.38 °C in the PM control condition. The observed increase in whole body temperature following the extended warm-up in the AM condition was 0.44 ± 0.14 °C, which was greater than the 0.26 ± 0.19 °C increase provided by the extended warm-up in the PM condition.

Substantial differences in performance were observed between the AM and PM control conditions across all variables (Table 5.1), providing further evidence of diurnal performance variation. Following control warm-up PM performance was 4-6% higher than AM control performance for peak power, mean power and jump height, and 2-3% higher for peak velocity and peak force. All these differences were greater than the smallest worthwhile changes of 2.8% for jump height, 3.3 % for peak power, 3.1% for mean power, 1.8% for peak velocity and 1.6% for peak force (ES range = 0.2-0.4). Similar improvements

in performance were observed when the AM control and AM extended conditions were compared (ES range = 0.3-0.5).

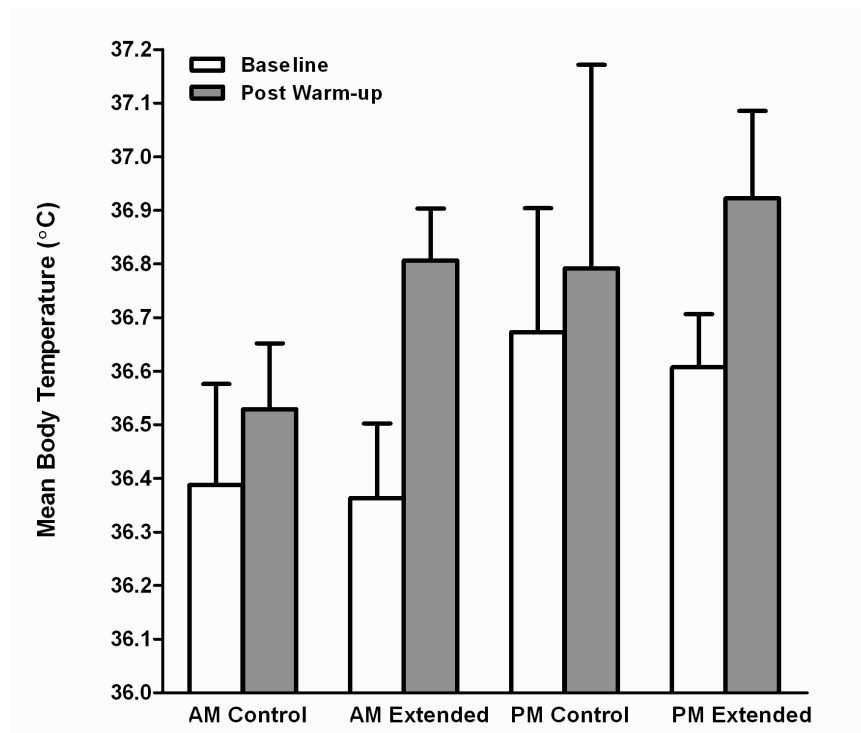


Figure 5.1 Estimated whole body temperature prior to warm-up (baseline) and after warm-up (pre-assessment).

Table 5.1 Mean (\pm SD) for kinetic and kinematic variables measured after the control warm-up in the morning and afternoon (AM Control and PM Control) and after the extended warm-up in the morning and afternoon (AM Extended and PM Extended).

Condition	Peak Power (W)	Mean Power (W)	Peak Velocity (m.s ⁻¹)	Peak Force (N)	Height (cm)
AM Control	3747 \pm 636	2054 \pm 329	2.15 \pm 0.21	1697 \pm 152	26.3 \pm 4.5
AM Extended	4090 \pm 768	2159 \pm 371	2.24 \pm 0.21	1738 \pm 167	27.9 \pm 4.5
PM Control	3899 \pm 543	2152 \pm 312	2.22 \pm 0.16	1733 \pm 149	28.0 \pm 3.7
PM Extended	4047 \pm 705	2223 \pm 361	2.25 \pm 0.22	1761 \pm 157	28.5 \pm 4.1

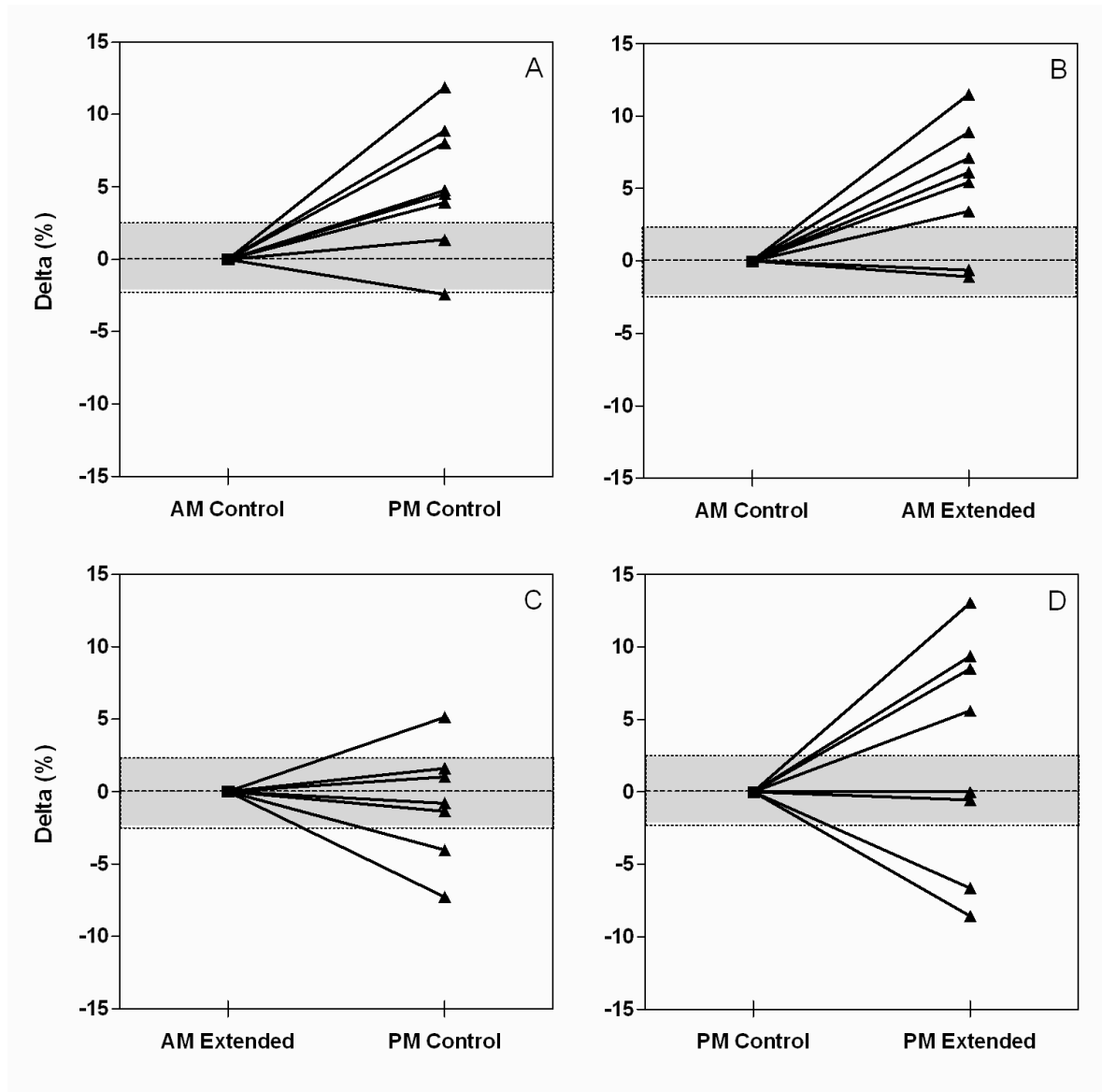


Figure 5.2 Individual changes in mean power across conditions where (A) represents the change in performance between the AM control and PM control conditions; (B) change between AM control and AM extended conditions; (C) change between AM extended and PM control conditions; and (D) change between the PM control and PM extended conditions. Shaded areas represent the smallest worthwhile change in performance.

Figure 5.2 illustrates the individual responses for mean power across the different conditions, where the shaded area represents the SWC. It is clear that for most individuals, performance was substantially better in the AM extended and the PM control conditions when compared with AM control (Figure 5.2A and 5.2B). This trend was maintained across each of the kinetic and kinematic variables analysed.

When the AM extended and PM control conditions were compared, no substantial differences in performance were observed (mean difference <1%; ES range = 0.0-0.1). The only exception to this trend was peak power, where performance was higher after the extended warm-up (4.8%; ES = 0.3). Interestingly, a variety of individual responses were observed when performance in the PM control and PM extended conditions were compared (Figure 5.2D). For peak velocity, peak force and jump height, the overall effects were trivial (ES < 0.2); however the effect of an extended warm-up in the PM sessions for peak and mean power was unclear due to the variety of individual responses.

5.5. DISCUSSION

The results demonstrate that using a short dynamic warm-up routine, as commonly practiced prior to maximal performance testing, results in a substantial 4-6% difference in performance between morning and afternoon testing sessions. The improvements in the afternoon power and jump height are similar to previous research on time of day differences in jumping performance [31, 249, 269, 292]. The novel finding from this study was that incorporating an extended, generalised warm-up period designed to increase body temperature equivalent to a normal whole body temperature experienced in the afternoon reduced the time of day differences in explosive neuromuscular performance.

The influence of temperature on performance was illustrated by the difference in performance between the AM control and the AM extended conditions. Following an increase in body temperature via the extended warm-up we observed a 4-6% improvement in AM jump performance. To our knowledge this is the first study to report this finding. While previous authors have manipulated the pre-event warm-up to remove the diurnal differences in body temperature, their findings contrast our own. Arnett [14] achieved similar morning and afternoon body temperatures by doubling the volume of the morning swim warm-up prior to a 200 m time trial, but still observed significant time of day performance differences. Similarly, Atkinson et al. [20] reported significantly greater performances during afternoon cycling time trials despite the performance of a vigorous warm-up prior to morning trials, leading them to conclude that time of day differences in cycling performance were not likely mediated by body temperature variation. It seems reasonable that these conflicting results may be due to the differences in the nature of the

performance tasks previously examined, whereby the energetic and neuromuscular performance requirements differed substantially to the loaded CMJs in the present study.

Though we cannot directly prove a cause and effect relationship between temperature and performance with the current data, it seems justifiable that the beneficial effect noted is preponderantly a temperature effect, and that other effects of the control warm-up were minimal. This is supported by previous work demonstrating beneficial effects of passive heating on work output in the absence of any preliminary muscular activity [17, 243]. In contrast to this suggestion Škof and Strojnik [274] recommend that the priming of an athlete's neuromuscular system needs to be achieved with both temperature and non-temperature dependent processes, since they observed changes in muscle activation independent of changes in temperature. It is clear from the results of this study that the addition of a general whole body warm-up period to increase body temperature added to the warm-up benefits of the dynamic control warm-up, reducing the time of day performance differences. It therefore appears that the addition of a general warm-up period, which sufficiently increases body temperature to the normally practiced short dynamic warm-up routine is warranted.

While the results from this experiment suggest that increases in body temperature are necessary for achieving maximal performance in the morning, we also observed some negative effects on performance when a similar warm-up was conducted in the afternoon, with two from eight subjects performing substantially worse in this condition. It is possible that this result is due to inter-subject variations in the temperature response to the extended warm-up since the subjects with the greatest temperature response ($> 37.5\text{ }^{\circ}\text{C}$) were generally those that responded negatively. Morrison et al., [219] reported that maximal voluntary force and central activation during 10 s isometric knee extension gradually decreased with an increase in core temperature $> 37.5\text{ }^{\circ}\text{C}$. Other authors have suggested a “ceiling” above which an increase in body temperature fails to further improve muscular performance in vivo [77, 242, 243]. It therefore seems important that prior to the adoption of an extended warm-up protocol in afternoon testing sessions that individual optimal temperatures for ensuring maximal performance are identified.

In conclusion, we found that time of day performance differences in the loaded jump squat can be eliminated by manipulating the pre-assessment warm-up to minimise the diurnal

differences in body temperature. Current practice of a short dynamic warm-up prior to assessment does not promote an increase in body temperature great enough to compensate for the diurnal difference in body temperature. This results in the persistence of substantial and practically important performance differences in morning and afternoon assessments. The addition of a general whole body warm-up period designed to increase body temperature makes it possible to compare performances at different times throughout the day, although more work is needed to determine the critical temperature above which an individual's performance may be impaired.

5.6. PRACTICAL APPLICATIONS

Differences exist between AM and PM performance of explosive activities. The results from this study show that maximal vertical jump performance isn't likely to be demonstrated if testing is scheduled in the morning, limiting the validity of the assessment. It is therefore necessary to identify methods for maximising performance independent of the time of day that the assessment is conducted. We suggest that warm-up protocols designed to increase whole body temperature would be beneficial for reducing these differences and ensuring maximal performance. This is also very important for accurate monitoring of performance changes over time where it may be impractical to standardise the time of day that assessments take place.

CHAPTER SIX

Monitoring neuromuscular fatigue using vertical jumps

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Monitoring neuromuscular fatigue using vertical jumps.

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6.1. ABSTRACT

To assess the effect of deliberate overreaching on loaded and unloaded vertical jump kinetics and kinematics, six subjects (three male and three female resistance trained athletes) participated in four weeks of normal resistance training loading and four weeks of very high loading to induce an overreaching effect. Vertical jump performance and perceptual measures of fatigue and muscle soreness were measured 6 days per week. Using a novel statistical approach to assess the outcomes from a case series ($n=6$), kinetic and kinematic variables that consistently showed impairments in performance across all subjects during overload training were selected as most useful in monitoring neuromuscular fatigue during resistance training. Fatigue induced by deliberate overreaching produced negative effects on unloaded CMJ peak velocity ($1.7\text{-}2.2\ \%/wk^{-1}$), peak force ($2.5\text{-}8.6\ \%/wk^{-1}$) and mean power ($2.2\text{-}4.9\ \%/wk^{-1}$) in all cases. The amplitude of the counter-movement during unloaded jumps was also reduced for all cases during the overreaching phase, suggesting changes in jump technique contribute to alterations in measured mechanical output. Changes in performance of loaded vertical jumps were inconsistent between subjects in normal and overreaching phases. In conclusion, peak velocity, mean power and eccentric displacement in unloaded jumps can be used to monitor the performance status of an athlete during normal and intensified training and competition.

6.2. INTRODUCTION

Vertical jumps have commonly been used to assess acute neuromuscular fatigue and recovery following a range of laboratory-based exercise tasks [43, 276] and sports performances [60, 111, 139, 193]. More recently vertical jumps have also been touted as a convenient tool to monitor neuromuscular fatigue during periods of intensive training and/or competition [56, 62, 93]. Some authors have suggested jump height may provide early indications of overreaching [309, 311], while others have identified that jump height may lack the necessary sensitivity to detect changes associated with significant neuromuscular fatigue [47, 60]. As such, other kinetic and kinematic variables measured during vertical jumps may be more valuable in detecting and monitoring neuromuscular fatigue [60]. Results from a recent survey [291] indicated that practitioners in high performance sports programs popularly employ instrumented vertical jumps to monitor fatigue, however many of the survey respondents indicated uncertainty in regards to which dependent variable is

most informative in their analysis. The purpose of this study was to determine the effect of normal loading and deliberate overreaching on loaded and unloaded vertical jump kinetics and kinematics to assist practitioners in selecting variables sensitive to fatigue-induced changes in neuromuscular status.

6.3. METHODS

To compare the sensitivity of kinetic and kinematic variables to fatigue induced by intensive resistance training, six subjects were recruited. The three male (28.0 ± 5.9 y; 191.2 ± 5.7 cm; 100.8 ± 10.7 kg; Subjects A, B, C) and three female subjects (28.0 ± 0.7 y; 172.3 ± 4.9 cm; 75.6 ± 3.4 kg; Subjects D, E, F) were competitive surf-boat rowers with a consistent resistance training history greater than two years. The training intervention was scheduled throughout the pre-season of their yearly training program, where regular rowing training and metabolic conditioning sessions were minimal and controlled by the lead investigator. Prior to participation all subjects gave written informed consent. Ethical approval was granted by the institutional ethics committees and was in accordance with the guidelines provided by Harriss and Atkinson [128].

Subjects trained four days per week for 12 weeks, where all physical training activities were prescribed and supervised by the lead investigator. The resistance training program was divided into three phases; normal training (T1), intensified overload (T2), and recovery/taper (T3). Each phase was four weeks in duration. The planned total training volume (repetitions \times load) was manipulated throughout T1 in a wave loading fashion typical of an undulating periodised training plan. Throughout T2 the planned training volume was increased by approximately 10% each week to induce high cumulative levels of neuromuscular fatigue. The volume load in the final four weeks of training (T3) was reduced to allow for regeneration. Training consisted primarily of large muscle mass exercises (Table 6.1). The exercise selection remained constant throughout the 12-week training period. Training sessions on Monday and Thursday consisted of exercises and loading parameters chosen to elicit maximal strength adaptations (high-load; controlled eccentric movements; 1-8 repetitions per set; 3-6 sets). On Tuesday and Friday loading parameters targeting improvements in power and rate of force development were prescribed (low-moderate load; fast or maximum speed during concentric motion; 3-5 repetitions per set; 3-6 sets). Recovery days were scheduled on Wednesday and Saturday, where only the

test protocols were performed following warm-up. Instrumented counter-movement jump (CMJ) performance in unloaded and loaded conditions was measured prior to each training session, along with subjective ratings of fatigue and muscle soreness. Subjects were familiarised with all testing procedures on at least three occasions prior the study commencing.

Table 6.1 Exercise selection for each training day throughout the resistance-training program.

Monday	Tuesday	Thursday	Friday
Bench Press	Hang Power Snatch	Deadlift	Clean Pull
Back Squat	Bench Throw	Pull-ups	Box Squat (60% 1RM)
Romanian Deadlift	Power Clean	Spilt Squat	Speed Bench Press
Seated Row	Push Press	Bench Pull	Squat Sled Pull
		Front Squat*	

* Front squat only included in the program for weeks 5-8

6.3.5. Procedures

Prior to each daily training session subjects performed six unloaded and six loaded CMJs. The mean value of the six trials was used in the analysis since we have previously identified that the reliability of this value is sufficient for detecting small but practically important changes in performance [292]. Measurements of CMJ performance were obtained via an optical encoder (GymAware Power Tool. Kinetic Performance Technologies, Canberra, Australia) suspended overhead and attached via a cable to the centre of either a 400 g wooden pole (unloaded condition); or an Olympic lifting barbell with additional load of 10 kg for females and 20 kg for males (loaded condition). The loads were chosen to elicit low load power characteristics from the athletes, since in addition to body weight exercises, such loading parameters are also commonly used for monitoring purposes [291]. The subject stood erect with the bar positioned across their shoulders and were instructed to jump for maximal height while keeping constant downward pressure on the bar to prevent it from moving independently of the body. No attempts were made to standardise the amplitude or rate of the countermovement, rather subjects were encouraged to self-select these variables with the view to obtaining maximum jump height. A displacement-time curve for each jump was obtained from the digital optical encoder. Mean values for force and power were

calculated over the concentric portion of the movement and peak values for velocity, force, and power were also derived from each of the curves. Jump height was determined as the highest point on the displacement-time curve, and eccentric displacement as the lowest point. Additionally, a commercially available force platform (400 Series Performance Force Plate; Fitness Technology, Australia) was used to measure the flight time to contraction time ratio as previously described by Cormack and colleagues [60]. Reliability of each dependent variable was established prior to the study using 10 male subjects with a similar resistance training history to the current pool of subjects (coefficients of variation 2-7%; ICC 0.85-0.98). On completion of all testing procedures each subject completed a questionnaire assessing perceptions of fatigue and muscle soreness. Using a 5-point Likert scale subjects were asked to rate their feelings of fatigue (“Rate your fatigue in the last 24 hours”) and muscle soreness (“Rate your muscle soreness prior to today’s session and throughout warm-up”).

6.3.6. Statistical Analysis

To assess the response of a range of CMJ variables to fatigue induced during intensive overload period, a novel inferential process to assess the consistency of outcomes from a case series was utilised. The purpose was to discover a variable (or variables) measured during vertical jumps that consistently showed impairments in performance across all subjects. In particular, we considered a variable to be sensitive to fatigue induced by intensive training if all subjects displayed a rate of change in performance during T2 that was likely to be negative compared with the rate of change in performance during normal training. Such an approach permits inferences to be made as to which variables may best be used to indicate the status of an athlete during normal and intensified training and competition without relying on mean group changes.

Linear regression was used to estimate the rate of change in performance for each subject during T1 and T2. Data from T3 were analysed but are not presented. The analysis was performed using the Linest function in Microsoft Excel, which provided the standard error for the coefficient of the predictors for estimation (SEE). Descriptive data is presented as the rate of change in each variable per week. All data was log-transformed prior to statistical analysis.

The effect of T2 minus T1 was calculated for each subject using a spreadsheet for combining outcome measures [141]. The magnitude of a smallest meaningful difference between T1 and T2 was calculated as $0.2 \times \text{SEE}$ for each variable, based on the mean SEE for T1 and T2 for individual subjects. A substantial difference in trends was inferred when there was more than 75% likelihood that the true difference in the slope of the two regression lines was greater than the smallest meaningful difference. Thresholds for assigning the qualitative terms to chances of substantial differences were: <1%, almost certainly not; <5%, very unlikely; <25% unlikely; 25 – 75%, possibly; >75% likely; >95% very likely; and >99% almost certain. Data for each subject are presented to enable the evaluation of consistency in results across the dependent variables.

6.4. RESULTS

6.4.1. Training load

Throughout the 12-week study period training prescription had to be manipulated in response to minor injuries or days lost to injury, illness and/or absenteeism. Figure 6.1B represents the actual volume load (kg) in relation to the planned training load (Figure 6.1A) for each subject as a percentage of the first training week. Due to a minor back injury obtained in Week 5, Subject E was unable to complete the prescribed lower body exercises in Weeks 6 and 7, resulting in lower overall loading during the overreaching phase. Due to this, Subject E was not included in further analyses.

6.4.2. Subjective ratings of fatigue and muscle soreness

The T2 training protocol resulted in a general trend for increased perceptions in fatigue, reaching a maximum in the final week of the T2 phase, with reductions coinciding with reduced loading in T3 (Figure 6.2A). Self-reported muscle soreness also increased throughout T2, and similarly lessened with reduced loading in T3 (Figure 6.2B).

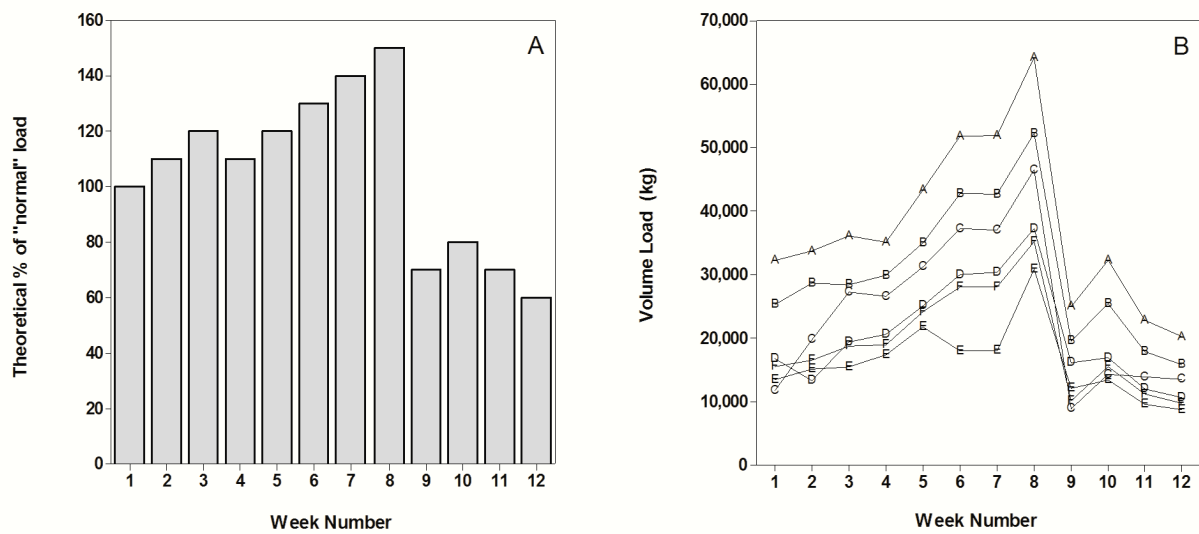


Figure 6.1 Planned (A) and actual individual volume loads (B) throughout normal training (Weeks 1-4), intensive overload (Weeks 5-8), and recovery (Weeks 9-12).

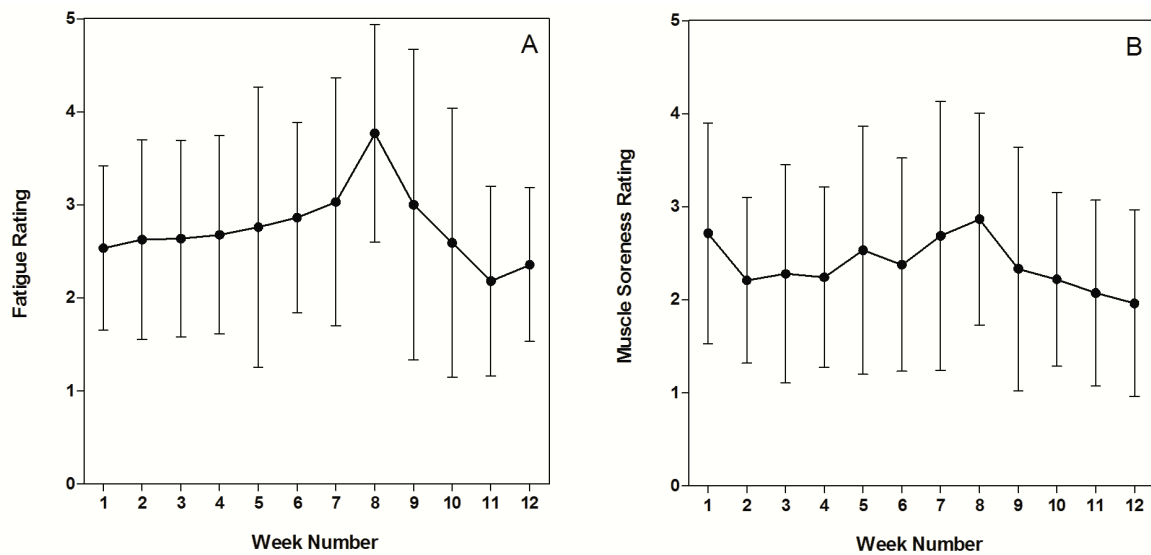


Figure 6.2 Mean \pm SD ratings of perceived fatigue (A) and muscle soreness (B) throughout normal training (Weeks 1-4), intensive overload (Weeks 5-8), and recovery (Weeks 9-12).

6.4.3. Unloaded jump condition

Clear positive performance effects were seen throughout T1 for most subjects, with improvements in jump height, mean and peak power and peak velocity (Table 6.2). T2 performance was reduced in all subjects for jump height (0.7-5.3%), mean power (2.2-4.9%), peak velocity (1.7-3.2%) and peak force (2.5-8.6%). The T2-T1 effect was almost certainly negative for peak velocity in all subjects. The likelihood of a negative effect for mean power and peak force was also greater than 75% in all subjects. Peak power and mean force were less affected by T2, with various responses observed. Clear changes in jump technique were indicated by a reduction in eccentric displacement in all subjects (4.2-8.5%; Table 6.2). There was a negative trend in flight time: contraction time ratio during T2 for all subjects, however the range of individual responses (positive and negative) measured during T1 resulted in an unclear effect for this variable.

6.4.4. Loaded condition

During T1 a range of positive and negative changes (-2.2 to 7.7%) were observed across the variables of interest. Similarly, large ranges of effects were observed between subjects and between variables during the T2 phase (-6.7 to 3.0%). The variability in responses resulted in no variable showing likelihood >75% of a negative effect for all subjects.

Table 6.2 Difference in individual weekly performance trends between normal training (T1) and deliberate overreaching (T2) measured during unloaded vertical jumps.

	T1 $\Delta/\text{week (\%)} \pm 90\text{CL}$	T2 $\Delta/\text{week (\%)} \pm 90\text{CL}$	Effect (T2-T1) (%) $\pm 90\text{CL}$	Likelihood of Negative Effect	Qualitative Descriptor
Eccentric Displacement					
Subject A	5.1 ± 1.2	0.9 ± 0.9	-4.2 ± 1.5	100%	almost certain
Subject B	8.3 ± 1.6	2.5 ± 0.9	-5.8 ± 1.8	100%	almost certain
Subject C	4.7 ± 1.6	-3.8 ± 2.8	-8.5 ± 3.1	100%	almost certain
Subject D	6.7 ± 1.8	1.0 ± 1.9	-5.7 ± 2.6	100%	almost certain
Subject F	4.2 ± 1.1	0.0 ± 1.1	-4.2 ± 1.5	100%	almost certain
Peak Velocity					
Subject A	2.2 ± 0.4	0.1 ± 1.0	-2.0 ± 1.0	99%	almost certain
Subject B	3.7 ± 0.7	0.6 ± 0.7	-3.0 ± 1.0	100%	almost certain
Subject C	2.2 ± 1.2	-1.0 ± 1.2	-3.2 ± 1.6	99%	almost certain
Subject D	3.1 ± 0.6	0.6 ± 1.1	-2.5 ± 1.3	99%	almost certain
Subject F	1.4 ± 0.6	-0.3 ± 0.7	-1.7 ± 0.9	99%	almost certain
Mean Power					
Subject A	1.9 ± 0.6	-0.3 ± 1.7	-2.2 ± 1.8	89%	likely
Subject B	3.5 ± 1.2	-0.5 ± 1.4	-4.0 ± 1.8	100%	almost certain
Subject C	4.0 ± 2.1	-0.9 ± 1.6	-4.9 ± 2.6	99%	almost certain
Subject D	3.1 ± 1.2	0.9 ± 1.9	-2.3 ± 2.2	84%	likely
Subject F	2.0 ± 1.1	-1.6 ± 1.3	-3.6 ± 1.7	100%	almost certain
Peak Force					
Subject A	1.2 ± 0.8	-1.6 ± 1.4	-2.7 ± 1.6	97%	very likely
Subject B	-0.2 ± 1.5	-2.7 ± 1.7	-2.5 ± 2.2	85%	likely
Subject C	5.2 ± 2.0	-3.5 ± 1.9	-8.6 ± 2.7	100%	almost certain
Subject D	1.0 ± 1.5	0.6 ± 1.8	-0.4 ± 2.3	30%	possibly
Subject F	1.7 ± 1.5	-3.5 ± 1.5	-5.2 ± 2.0	100%	almost certain
Jump Height					
Subject A	1.5 ± 0.8	-1.2 ± 1.5	-2.7 ± 1.7	96%	very likely
Subject B	3.4 ± 1.0	0.2 ± 1.0	-3.1 ± 1.4	100%	almost certain
Subject C	3.1 ± 2.1	-2.2 ± 1.5	-5.3 ± 2.6	99%	almost certain
Subject D	1.3 ± 0.9	-1.9 ± 1.9	-3.2 ± 2.1	96%	very likely
Subject F	0.4 ± 1.0	-0.3 ± 1.1	-0.7 ± 1.4	50%	possibly
Peak Power					
Subject A	1.9 ± 0.7	0.5 ± 1.8	-1.4 ± 1.9	67%	possibly
Subject B	2.1 ± 1.1	0.2 ± 1.4	-1.9 ± 1.7	85%	likely
Subject C	1.5 ± 2.5	1.0 ± 2.3	-0.5 ± 3.3	28%	unlikely
Subject D	2.8 ± 1.3	2.5 ± 2.0	-0.4 ± 2.3	30%	possibly
Subject F	2.1 ± 1.0	0.2 ± 2.1	-1.8 ± 2.2	71%	possibly
Mean Force					
Subject A	0.0 ± 0.6	-0.5 ± 1.0	-0.5 ± 1.2	45%	possibly
Subject B	-0.4 ± 0.7	-1.0 ± 0.9	-0.6 ± 1.1	55%	possibly
Subject C	1.5 ± 1.1	0.6 ± 1.1	-1.0 ± 1.5	61%	possibly
Subject D	0.2 ± 0.9	1.1 ± 1.1	0.9 ± 1.4	3%	very unlikely
Subject F	0.5 ± 0.7	-0.6 ± 0.7	-1.1 ± 1.0	86%	likely
FT:CT					
Subject A	1.7 ± 1.0	-2.0 ± 1.8	-3.7 ± 0.6	100%	almost certain
Subject B	-2.8 ± 1.2	-2.7 ± 1.3	0.1 ± 2.2	13%	unlikely
Subject C	2.9 ± 2.1	-3.2 ± 2.8	-6.0 ± 1.1	100%	almost certain
Subject D	-1.6 ± 2.3	-0.4 ± 2.4	1.2 ± 3.9	4%	very unlikely
Subject F	-1.0 ± 1.6	-2.6 ± 1.4	-1.6 ± 1.8	70%	possibly

6.5. DISCUSSION

For a variable to be considered useful in monitoring changes in neuromuscular status, it is arguable that it needs to be capable of reflecting improvement brought about by an appropriate training stimulus and/or sensitive enough to detect the impact of fatiguing interventions. The results from this study provide evidence that not all kinetic and kinematic variables measured during vertical jumps are useful in monitoring neuromuscular status during intensified resistance training regimes. In particular, variables measured during unloaded countermovement jumps seem more sensitive than the same variables measured during loaded jump performance, and measures reflecting modifications to jump technique may be important.

Higher than normal levels of fatigue were evident during the intensive training phase of this study as indicated by progressive increases in the athlete's level of perceived fatigue, which was reduced when the training load lessened in the taper phase. Muscle soreness values also increased in the expected manner during a period of uncharacteristically high loading for these athletes. Coinciding with the high levels of fatigue and soreness, eccentric displacement during unloaded vertical jumps decreased in all subjects throughout four weeks of intensified training. We are not aware of previous studies directly measuring kinematic changes during the eccentric portion of a CMJ in response to fatigue accumulated during successive training sessions. A number of studies have however confirmed alterations in eccentric displacement following acute fatiguing protocols. For example, Rodacki et al. [254] observed a 20% reduction in eccentric displacement following acute fatigue induced by repetitive CMJs. This reduction coincided with reduced knee flexion, whilst hip and ankle joint angular displacement remained unchanged. Conversely reductions in both hip and knee angles at take-off during hopping tasks have been reported in response to an acute fatiguing intervention [23]. Whilst knee and hip angles were not measured directly in the current study, it is possible that the change in eccentric displacement occurred as a product of reductions in either, or both of these joint angles. The reduction in the amplitude of the countermovement has generally been interpreted as a subconscious strategy employed to sustain (or maximise) performance under fatigue. Reducing the amount of knee flexion increases joint stiffness at the end of the negative phase of the jump [254]. This increase in joint stiffness is thought to be important in maintaining the efficiency of the stretch-shortening cycle in fatigued conditions by keeping the amortisation phase short.

Rodacki and colleagues [254] also suggest that stiffening the leg segments earlier in the negative phase may be a strategy for avoiding muscle damage. It is hypothesised that if fatigued subjects recruited their impaired muscles too late (i.e. when the knee is in a deeper position and the muscle tendon units are relatively more stretched), greater sarcomere “slipping” and myofibrillar disruption may occur. Both of these altered strategies may help to explain the reduced eccentric displacement observed in this study during the overreaching training phase. Further research is needed however to confirm these findings in subjects tested in a relatively rested state (i.e. 24 hours after the previous training session) during training periods involving high levels of neuromuscular stress.

It can be observed from the current results that there are clear substantial reductions in mean power, peak movement velocity and peak force during the concentric portion of the jump during the intensive overload training phase in five out of five subjects. Previous research has shown that changes in the eccentric phase of a CMJ are strongly correlated with changes in kinetic and kinematic variables during the subsequent concentric phase [64]. We suggest that in this study, changes in the eccentric phase, via alterations in the amplitude of the countermovement, also influenced the mechanical power output during the concentric phase of the jump. To our knowledge no previous studies have reported changes in any of these CMJ performance variables throughout a fatiguing training period. Evidence does exist however showing reductions in peak force [205] and mean power [60] in response to acute fatigue following team sport competition. Therefore, along with changes in eccentric displacement, changes in movement velocity, mean concentric power or peak concentric force may provide practitioners with a useful tool to monitor the neuromuscular status of their athletes.

Jump height also appeared sensitive to changes in neuromuscular status, however this result was not consistent across all subjects who participated. Specifically, clear negative performance changes were observed for only four out of five subjects (Table 6.2). Based on the small number of cases in this study, the authors feel that such an inconsistent result reduces the confidence that jump height can provide practitioners access to an easily administered performance test to monitor neuromuscular changes during intensive resistance training. This recommendation is in keeping with results showing small or insignificant changes in jump height following phases of deliberate overreaching [47, 65, 217] and intensified training [211].

The flight time: contraction time variable has been postulated as a variable most sensitive to changes in neuromuscular status following an Australian Rules Football match [60], and has since been used to monitor recovery from exposure to Rugby League competition [204]. In this study, negative responses in flight time: contraction time were observed during T2 for all subjects. However, despite the majority of subjects displaying clear reductions in this variable after the overload phase, it was less sensitive to the fatigue induced by high volume resistance training than eccentric displacement. This raises the prospect that markers of neuromuscular status may have activity specific applications. For example, flight time: contraction time may be useful in monitoring the neuromuscular response to team sport performance involving repetitive high velocity stretch-shorten cycle contractions, but less sensitive to the specific fatigue induced by the resistance training protocol in the current research. Further research is required to determine the most useful variables for specific environments.

It is noteworthy that peak power and mean force measures seem inappropriate for monitoring changes in neuromuscular status brought about by a period of intensive resistance training. No negative responses were seen for peak power during T2, which is similar to findings of Hoffman and colleagues who noted that CMJ peak power was maintained pre- to post- match in soccer and football respectively [137, 139]. Trivial changes in CMJ peak power have also been observed following an Australian Rules Football match [60]. Minimal changes were seen in either direction for mean concentric force during normal training or the overload phase. Due to high reliability of this variable along with the ability to confidently detect smallest worthwhile changes in performance [61, 292], it has previously been suggested that it may be a useful variable for athlete monitoring. The results from this study however confirm that the most reliable variables are not necessarily the most effective for monitoring performance in athletes [147], since mean force was unresponsive to both normal training where positive adaptations were observed in other performance variables, and during intensified training where a high degree of fatigue was present.

Based on these findings it appears that monitoring CMJ eccentric displacement enables practitioners a good tool for monitoring changes in neuromuscular status during periods of heavy resistance training. Reductions in mean concentric power and peak movement

velocity can also be expected. Variables measured during loaded jumps however were less sensitive to changes in the training stimulus, with negative effects seen in T2 for some, but not all subjects. It is likely that these results are specific to the resistance training stimulus applied in this study, and therefore more work is needed to confirm the applicability of this monitoring system in other sports and training environments. Given the small number of cases in this study, further work is also required to prove the generalisability of the current findings.

6.6. CONCLUSIONS

Clear changes in jumping technique are evident in response to periods of intensified training and therefore measuring eccentric displacement during an unloaded countermovement jump may provide practitioners with a simple method for monitoring neuromuscular fatigue during these periods. Peak velocity, peak force and mean power measured during the concentric portion of the jump may also be useful indicators of neuromuscular status. Future research is required to determine the thresholds of changes important for detecting maladaptive states and identify the most sensitive variables for specific training environments.

CHAPTER SEVEN

*Typical variation in jump performance is influenced by
training phase*

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Taylor K, Hopkins WG, Chapman DW and Newton MJ. (In review) Error of measurement in jump performance is influenced by training phase. *International Journal of Sports Physiology and Performance*.

7.1. ABSTRACT

The purpose of this study was to calculate the coefficients of variation in jump performance for individual participants in multiple trials over time to determine the extent that there are real differences in the error of measurement between participants. The effect of training phase on measurement error was also investigated. Six subjects participated in a resistance training intervention for 12 weeks with mean power from a countermovement jump measured 6 d.wk^{-1} . Using a mixed model meta-analysis, differences between subjects, within-subject changes between training phases, and the mean error values during different phases of training were examined. Small, substantial factor differences of 1.1 were observed between subjects, however the finding was unclear based on the width of the confidence limits. The mean error was clearly higher during overload training compared to baseline training, by a factor of $\times/\div 1.3$ (90% confidence limits 1.0-1.6). The random factor representing the interaction between subjects and training phases revealed further substantial differences of $\times/\div 1.2$ (1.1-1.3), indicating that on average, the error of measurement in some subjects changes more than others when overload training is introduced. The results from this study provide the first indication that within-subject variability in performance is substantially different between training phases, and possibly different between individuals. The implications of these finding for monitoring individuals and estimating sample size are discussed.

7.2. INTRODUCTION

Interpretation of changes in athletic performance relies on knowledge of the size of changes that have practically important consequences for the performance outcome being assessed. It is suggested that sports researchers and practitioners determine the magnitude of this change using *a priori* theorising based on previous research [220]. When *a priori* theorising is not possible based on available evidence, however, it is suggested that changes greater than the measurement error can be used to interpret real changes in performance [177, 220]. For example, Coutts and colleagues [65] concluded that a reduction of 2.3cm in vertical jump height was practically important since the change was greater than their reported measurement error for that test. That is, the observed signal was greater than the noise associated with the test, and therefore a real change can be said to have occurred.

Traditionally, measurement error is quantified via sample-based reliability studies using test-retest procedures, where the difference in consecutive pairwise repeated measures from a group of subjects are averaged. This method for calculating typical error is based on the assumption that the typical error has the same average magnitude for every subject. In this situation however, the value of the average typical error will be too high for some subjects and too low for others. By calculating the coefficient of variation in performance for individual participants in multiple trials, several groups of researchers have found differences in reliability between individuals in maximal and submaximal exercise performance [168, 183, 206]. Likewise, anecdotal evidence from our lab has indicated that there may be a meaningful difference between individuals in the magnitude of typical variation observed in vertical jump performance, but this is yet to be quantified.

The vertical jump is a popular performance test used to indicate neuromuscular adaptations to training and to monitor changes due to fatigue. Recently conducted studies using retest designs to estimate the error of measurement in vertical jumping outcome variables are plentiful [12, 15, 50, 54, 61, 70, 71, 127, 148, 149, 196, 214, 215, 270, 279, 292]. In 2001 Hopkins [147] combined a range of previously reported error of measurement values in a meta-analysis, and reported an unexplained wide variation in the values between studies. Along with real differences in variability between individuals, we suggest that training factors may also play a role, since the observed error is specific to the situation in which the retest scores were taken from. To our knowledge no research exists examining differences in the error of measurement between training phases or differences between individuals using performance tests. The purpose of this study is therefore to examine if differences in within-athlete variability exist in vertical jump performance. We will also examine differences in variability between phases of training, where fatigue levels may influence the variability in performance.

7.3. METHODS

7.3.5. Subjects

Three male (28 ± 5.9 years; 191 ± 5.7 cm; 101 ± 10.7 kg) and three female (28 ± 0.7 years; 172 ± 4.9 cm; 76 ± 3.4 kg) strength-trained athletes volunteered to participate in the study after being informed of potential risks. All experimental procedures were approved by the

ethics committees of the Australian Institute of Sport and Edith Cowan University, and written, informed consent was obtained from the subjects before any testing was conducted.

7.3.6. Design

The subjects completed 12 weeks of prescribed resistance training sessions under the direct supervision of the lead investigator. Countermovement jump performance was assessed 6 d.wk⁻¹. The measurement error, which includes the analytic or technical error plus the day-to-day biological variation influenced by training factors, was estimated from pairwise changes in performance for each subject, during each phase of training.

7.3.7. Training

The training program was divided into three phases; baseline training, intensive overload, and recovery/taper; each four weeks in duration. The planned total training volume (repetitions x load) was manipulated throughout baseline training in a wave loading fashion typical of an undulating periodised training plan. Throughout the overload period the planned training volume was increased by approximately 10%. The volume load in the final four weeks of training was reduced by approximately 50% (while maintaining similar intensities) to allow for regeneration. The exercise selection remained constant throughout the 12-week training period, and incorporated a range of compound exercises for the lower and upper body. Training sessions on Monday and Thursday consisted of exercises and loading parameters chosen to elicit maximal strength adaptations (high-load; controlled eccentric movements; 1–8 repetitions per set; 3–6 sets). The loading parameters for training on Tuesday and Fridays targeted improvements in power and rate of force development (low - moderate load; fast or maximum speed during concentric motion; 3–5 repetitions per set; 3–6 sets). Recovery days were scheduled on Wednesday and Saturday. On each Wednesday and Saturday subjects performed the warm-up and CMJ assessments followed by a range of flexibility exercises and self-administered myofascial release techniques for the major muscle groups.

7.3.8. Test Procedures

Performance was measured 6 d.wk⁻¹, prior to each training session. Each training session was conducted at the same time of day for each athlete. Performance was measured using an optical encoder (GymAware Power Tool. Kinetic Performance Technologies, Canberra,

Australia) suspended overhead and attached via a cable near the centre of a 400g wooden pole. Following a warm-up consisting of 10 min cycling on a stationery ergometer, 10 min of dynamic exercise drills aimed at activating the primary muscles and increasing joint range of motion, and a series of practice jumps, subjects performed two sets of three repetitions of the a countermovement jump (CMJ), pausing for ~3-5 s between each jump, with 2-3 min rest prior to repeating the second set of three maximal jumps. To perform the jumps the subjects stood erect with the bar positioned across their shoulders and were instructed to jump for maximal height while keeping constant downward pressure on the bar to prevent it from moving independently of the body. No attempts were made to standardise the amplitude or rate of the countermovement. A displacement-time curve for each jump was obtained from the digital optical encoder. Power was calculated via double differentiation of the displacement-time data, with the mean value over the concentric portion of the movement used to quantify performance. The mean value of the six jumps was used in the subsequent analysis to improve the precision in each of the daily measurements [292].

7.3.9. Statistics

All analyses were performed via log transformation to allow estimation of effects, variabilities, and uncertainties in percent units. The typical error of measurement in each subject's performance was estimated for each training phase (baseline, overload and recovery) by dividing the standard deviation of the consecutive pairwise changes in log-transformed power by $\sqrt{2}$ [79]. Degrees of freedom for each of these estimates were the number of change scores minus 1. Change scores for differences > 2 d (arising from missed sessions due to injury or absenteeism) were excluded, since it was felt that systematic changes could influence the overall magnitude of change in time periods greater than 2 d.

For further analysis the subjects' errors of measurement in each phase were treated in the same manner as study estimates in a meta-analysis, since each error of measurement had sampling uncertainty analogous to the standard error of each estimate of an effect in a meta-analysis. The meta-analytic mixed model had a random effect to estimate differences between subjects as a standard deviation, a random effect to estimate within-subject changes between training phases as a standard deviation, and a fixed effect to estimate mean values in each training phase. The variable meta-analysed was the log-transformed variance (the

error of measurement squared, at this stage not back-transformed). The weighting factor for each estimate in the meta-analysis was the inverse of the sampling variance of the log of the variance, which was given by $2/\text{degrees of freedom}$ [5]. The means given by the fixed effect were back transformed to coefficients of variation. The differences between the means were expressed as factor effects, while the differences between subjects and the differences within subjects between phases were expressed as factor standard deviations. All estimates are shown with 90% confidence limits.

Inferences about the substantiveness of true differences between the estimates of error between subjects and between phases were made in relation to the thresholds for substantial ratios of 0.9 and 1.1 as defined by Hopkins [147] and Gore [113] based on the corresponding effects on sample size. The precision of the estimates were interpreted using the confidence limits of the ratio in the same manner as above. That is, an outcome was deemed unclear if the confidence interval overlapped the thresholds of 0.9-1.1 used to indicate substantially higher or lower error of measurement values.

7.4. RESULTS

An example of the raw data obtained for one subject is presented in Figure 7.1. The mean (\pm SD) number of change scores for each subject during baseline, overload and recovery were 21 ± 2 , 20 ± 3 and 18 ± 4 respectively. The within-subject errors of measurement derived from the consecutive pairwise changes for the six subjects ranged from 2.4 to 5.8% (Table 7.1). The meta-analysis revealed factor differences between subjects of $\times/\div 1.12$, which is consistent with marginally small real differences between subjects, although the widths of the confidence limits (0.88-1.23) make the finding unclear.

The mean within-subject error of measurement was 3.4% (confidence limits 2.9-4.1%) during baseline training, 4.4% (3.7-5.3%) during overload, and 4.1% (3.5-4.9%) during recovery. The difference between errors during baseline and overload was substantial, although small: $\times/\div 1.29$ (1.04-1.60). Similarly, the error during recovery was substantially higher than during baseline ($\times/\div 1.20$; 0.96-1.49). The errors of measurement for overload and recovery were not substantially different ($\times/\div 1.07$; 0.86-1.34), although this effect is unclear. The figure illustrates a subject who showed the pattern of greater variability in the overload and recovery phases.

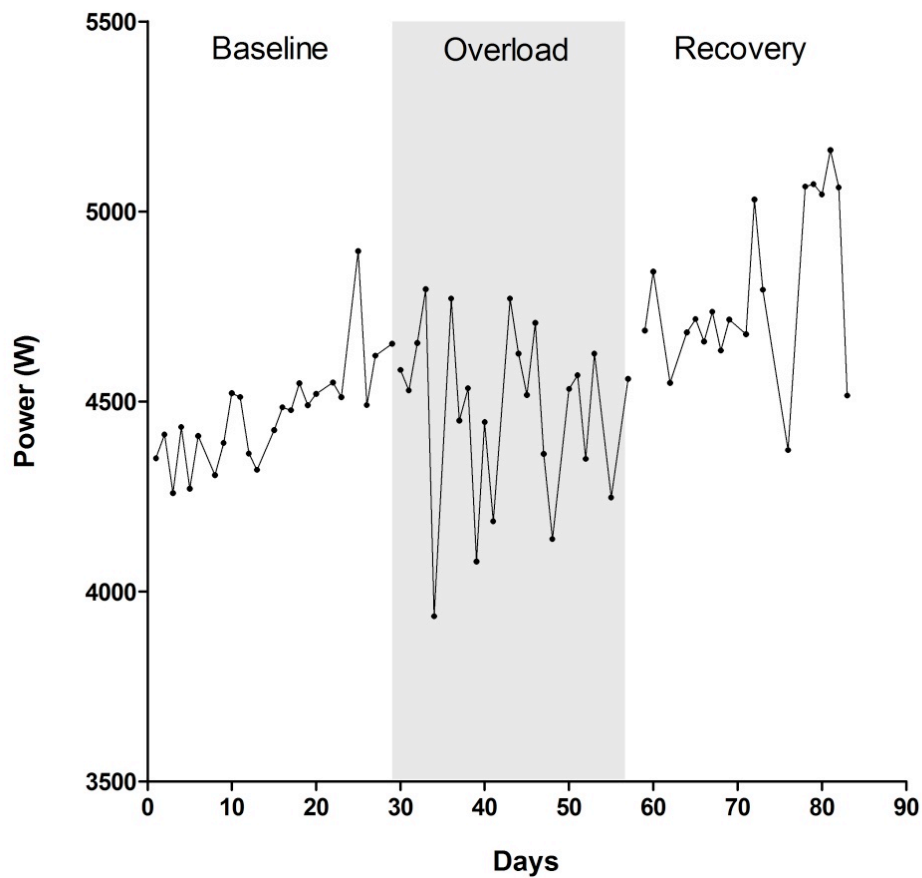


Figure 7.1 Representative data from a single subject showing raw data for mean power during baseline, overload and recovery phases.

The random effect represented by the interaction between subjects and phases showed that the error of measurement for each subject changed by a factor of typically $\times/\div 1.13$ as they moved from one phase to the next. That is, subjects varied from the fixed increase of 1.29 (going from baseline to overload) by a random factor of 1.13, meaning that the error of measurement for some subjects as they move into overload could increase by as much as 46% ($1.29 \times 1.13 = 1.46$) or as little as 14% ($1.29 \div 1.13 = 1.14$).

Table 7.1 Standard deviation of consecutive pairwise changes in mean power for each subject during baseline, overload and recovery phases.

Subject	Baseline	Overload	Recovery
A	2.4	4.5	3.9
B	5.8	3.7	3.2
C	3.9	4.9	5.3
D	2.9	4.2	3.6
E	3.9	4.9	4.9
F	2.6	3.7	3.4

7.5. DISCUSSION

The results from this study provide the first indication that within-subject variability in performance, measured as power in a countermovement jump, is substantially different between different training phases and possibly between individuals. Together these findings imply that sample-based reliability studies may have limited applicability for researchers and practitioners interested in using the estimates derived from such studies as thresholds for decision-making when monitoring individuals. The current findings also have implications for estimating sample size, since sample size is proportional to the square of the typical error [143].

Given the current findings and the associated limitations with sample-based reliability studies, an alternative method is to estimate the error for individual subjects using multiple trials, as we have done in this preliminary investigation. Unlike a number of performance tests typically used to assess maximum performance in athletes, the vertical jump provides a convenient and easily implemented tool for gathering a large amount of data on changes in individual performance capacity, without interfering with training or competition. It is these advantages that contribute to the popularity of using vertical jumps to monitor fatigue in a range of high performance sport programs. Within these environments, practitioners have reported using absolute thresholds of 5-10% for assessing changes in jump performance based on the mean error of measurement reported in published sample-based reliability studies, or from values calculated in a similar fashion from their own samples [291]. The results from the current study indicate, however, that the error of measurement between athletes is substantially, although not conclusively, different from the mean error value. This

finding confirms that where possible, it is more appropriate to use the athlete's own typical error value, rather than an average value derived from a sample-based study, for delimiting thresholds of change used to interpret changes in individual performance. The small and unclear magnitude of the differences, however, indicates that no additional between-subject factor is needed in the calculation of sample size to account for differences in error between subjects. That is, there are no real implications for sample size arising from the small difference in error between subjects because when researchers use the average value of measurement error this variation is already taken into account.

The clear increase in error in the overload phase in this study indicates that it is also important to readjust the thresholds for interpreting changes during different phases of training. We speculate that the increase may be explained by greater disruptions to homeostasis following acute training bouts when athletes are exposed to continuous periods of high intensity training, especially when there is insufficient recovery between sessions. Whatever the cause, the greater magnitude of variability throughout such periods should be taken into account in the same way that individual differences are when monitoring an individual.

In addition to the implications for monitoring individuals, the differences in typical error from phase to phase have a considerable impact on sample-size calculations, since sample size is proportional to the square of the typical error [143]. The larger mean error during the overload phase is one factor that will increase the number of subjects required within a study. Importantly however, the additional random effect included in this analysis revealed that subjects differed in how much their error increased from phase to phase. These differences in the changes in error between phases within individuals presumably reflect differences in the way that individuals adapted to, or coped with the overload. Based on the \times/\div factor of 1.13 it was shown that for some subjects the increase in error from baseline to overload could actually be as high as 1.46, resulting in the need for approximately two times more subjects to confidently assess a change in performance in an intervention involving an overload training period.

These same considerations apply to the number of repeated measurements required to establish trends or other effects confidently when monitoring an individual. Conceptually, the number of measurements required within a subject in order to define a trend with

reasonable confidence is probably of the same order of the sample size needed to give a clear indication of the change in the mean in group research designs.

7.6. PRACTICAL APPLICATIONS

When using typical error values to set thresholds for interpreting change in vertical jump performance, the value should be derived from data specific to the phase of training. The differences between subjects may also be important, but certainly the differences in error as individuals respond to different phases of training are an issue. When repeated measurements on athletes span training phases, researchers and practitioners should be aware that there will be substantial differences in the errors between individuals.

CHAPTER EIGHT

*Relationship between changes in jump performance and
laboratory measures of low frequency fatigue*

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Relationship between changes in jump performance and laboratory measures of low
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8.1. ABSTRACT

Aim: The ratio of force evoked by low- and high-frequency electrical stimulation has been used to quantify neuromuscular fatigue, but its relationship to fatigue in practical performance tests is unclear. The purpose of this study was to investigate the relationship between the ratio and performance of a countermovement jump. **Methods:** Six resistance-trained athletes completed 12 weeks of resistance training in three, 4-wk phases of normal training, deliberate overreaching, and a taper. Instrumented countermovement jumps, maximal voluntary isometric force, and force of the knee extensors elicited by 10- and 100-Hz stimuli were assessed weekly. Relationships between measures were quantified as mean within-subject correlations. **Results:** Only small correlations (0.14 to 0.31; between-subject SD \sim 0.30) were observed between the 10/100-Hz ratio and measures of jump performance, while the correlations with maximum voluntary force and perceived fatigue were small and trivial (-0.10 and -0.06 respectively). The highest mean correlation observed was only -0.32, between perceived fatigue and maximum voluntary force. **Conclusion:** Fatigue measured by electrical stimulation appears to have little or no role in the fatigue of muscle performance in a practical setting, however the within-subject correlations were likely underpowered and therefore should be interpreted with care.

8.2. INTRODUCTION

Acute fatigue after-effects of a training stimulus can be both neural and metabolic in nature. Metabolic fatigue is generally short-lasting with full recovery coinciding with cessation of activity and normalisation of cellular energy potential [114]. Neuromuscular fatigue is a more complex phenomenon and can have much longer lasting effects. The mechanisms involved have been thoroughly investigated [7, 107] and can be central or peripheral in origin. Peripheral neuromuscular fatigue can be further divided into low- and high-frequency fatigue, categorised by changes in the force elicited by low- and high-frequency electrical stimulations respectively [82]. It has been suggested that low frequency fatigue (LFF) is likely prevalent in competitive elite sport [93] and is particularly insidious due to its long-lasting effects on muscle's low-frequency force-generating capacities [81, 163]. Along with the potential to impair sports performance via reductions in force producing capabilities, LFF may also result in a greater sense of effort during daily activities, since an increase in central nervous system drive is needed to achieve pre-requisite sub-maximal

forces [169]. These alterations may result in the perception of “heavy legs”, which is especially apparent during low exercise intensities and daily activities [93, 301]. Regular monitoring of LFF is considered important for the management of training- and competition-induced fatigue in high performance sport, but quantifying LFF in a field setting is difficult because of the technical challenges associated with its measurement [93].

The primary clinical method for assessing LFF is by percutaneous nerve or muscle stimulation. Its presence is confirmed by examining changes in the ratio of low frequency (e.g. 10-20 Hz) tetanic stimulation to high frequency (e.g. 50-100 Hz) tetanic stimulation. The measurement of LFF using clinical methods is impractical for use in an applied setting on a regular basis because of the time and expertise required to complete individual assessments [93]. Hence, recent research has sought to identify more convenient field-based assessment procedures for measuring LFF. Cormack et al., [62] tracked a variety of vertical jump variables across a season of Australian Rules Football and concluded that the flight time to contraction time ratio from a countermovement jump (CMJ) may be a useful indicator of LFF between matches. Similarly Ronglan et al., [257] reported decrements in CMJ height over three days of elite handball competition and suggested the change was indicative of neuromuscular fatigue accumulated throughout the competition. Additional work describing the fatigue effects and time course of recovery using vertical jumps has been performed in a number of settings including soccer [137], tennis [111], wrestling [180] environments [223, 311]. Such studies have assumed that changes in jump performance are indicative of neuromuscular fatigue, frequently citing peripheral neuromuscular fatigue as the root of performance changes.

Few studies have compared the responses of clinical measures of neuromuscular fatigue with the more practical field-based measures currently being utilised to describe neuromuscular fatigue and recovery. Following a marathon race, Petersen et al., [236] observed decreased muscle power in a CMJ, without concomitant changes in muscle twitch characteristics, suggesting that peripheral fatigue was not responsible for the changes in CMJ performance. Similarly, the relationship between functional performance tests and LFF following 100 maximal intensity drop jumps was unclear, with decreases in low frequency stimulated force larger than the reported decreases in jump height [275, 278]. To our knowledge only Raastad and colleagues [241] have observed a similar time course of changes in low frequency stimulated force and jump height. While this single study provides

some indication of a relationship between LFF and jump performance, direct comparisons have not been reported.

Since minimal data exists comparing the changes in CMJ performance with clinical based measures of LFF, a greater understanding of the relationship between such practical field-based assessments and clinical tests of LFF is needed. The purpose of this study was to examine whether changes in CMJ variables are closely related to changes in clinical measures of LFF during periods of regular and intensified resistance training. In addition to examining this relationship, information was sought regarding the origin of neuromuscular fatigue when fatigue is accumulated during consecutive training bouts rather than a single exercise bout as has been most commonly studied previously.

8.3. METHODS

8.3.1. Subjects

Three males (28.0 ± 5.9 years; 191.2 ± 5.7 cm; 100.8 ± 10.7 kg) and three females (28.0 ± 0.7 years; 172.3 ± 4.9 cm; 75.6 ± 3.4 kg) with a consistent resistance training history greater than two years completed the prescribed resistance training sessions. Prior to participation all subjects provided written informed consent, with ethical approval gained through the Institutional Ethics Committee.

8.3.2. Training Structure

Subjects trained four days per week, where all physical training activities were prescribed and supervised by the lead investigator. The training program was divided into three, four-week mesocycles. The first phase (T1) was designed to mimic a normal training response with incremental improvement in CMJ performance. Phase two (T2) was structured to include 4 weeks of deliberate overreaching to induce substantial levels of neuromuscular fatigue. The third and final phase (T3) was designed to allow for maximal recovery and adaptation from a four-week taper period. A resistance training model was used due to the ability to easily manipulate and quantify training loads. Training sessions consisted of a variety of lower and upper body exercises (Table 8.1) including high-load (80–100% of 1RM, 1–8 repetitions per set, 3–6 sets) and high-speed (low–moderate loads, 3–5 repetitions per set, 3–6 sets, fast or maximum speed during concentric motion) protocols. This type of

training program was designed to be similar to a typical period of intensive resistance training high performance athletes from a variety of strength and power sports utilise. The planned total training volume (repetitions x load) was manipulated throughout T1 in a wave loading fashion typical of an undulating periodised training plan. Throughout T2 the planned training volume was increased by approximately 10% each week to induce an overreaching effect. The volume load in the final four weeks of training (T3) was dramatically reduced, while maintaining similar intensities, to allow for regeneration and supercompensation in performance.

Table 8.1 Exercise selection for each training day throughout the resistance-training program.

Monday	Tuesday	Thursday	Friday
Bench Press	Hang Power Snatch	Deadlift	Clean Pull
Back Squat	Bench Throw	Pull-ups	Box Squat (60% 1RM)
Romanian Deadlift	Power Clean	Spilt Squat	Speed Bench Press
Seated Row	Push Press	Bench Pull	Squat Sled Pull
		Front Squat*	

* Front squat only included in the program for weeks 5-8

8.3.3. Test Procedures

Each testing session occurred on Day 6 of the training week and began with a 20 min warm-up, which included 10 min cycling at a self-selected intensity, followed by a range of mobility and activation exercises which increased in intensity throughout the warm-up period. CMJ performance was assessed with the subject holding a 400 g wooden pole and performing two sets of three CMJs, with the mean value for the six repetitions used for analysis. To perform the CMJs the subject stood erect with the bar positioned across their shoulders and was instructed to jump for maximal height while keeping constant downward pressure on the pole to prevent the bar moving independently of the body. No attempts were made to standardise the amplitude or rate of the countermovement. A displacement-time curve for each jump was obtained by attaching a digital optical encoder via a cable (GymAware Power Tool. Kinetic Performance Technologies, Canberra, Australia) near the centre of the pole. The first and second derivate of position with respect to time was taken to

calculate instantaneous velocity and acceleration respectively. Acceleration values were multiplied by the system mass to calculate force, and the given force curve multiplied by the velocity curve to determine power. The kinetic and kinematic variables selected for analysis were determined in a previous analysis which showed that mean concentric power, peak concentric velocity, peak concentric force and maximum eccentric displacement were most sensitive to fatigue induced by a deliberate overreaching training phase (K Taylor, unpublished data). Maximum jump height was included as an additional dependent variable to allow for comparisons with previous research.

Following CMJ assessment, electrically elicited force characteristics of the leg extensor muscles were obtained via percutaneous stimulation of the femoral nerve. All muscle contractile measurements were conducted on the right knee extensor muscles and measured using a custom isometric dynamometer consisting of a chair and force transducer (Model:9331A quartz force link and Model 5011B charge amplifier. Kistler Instruments, Winterthur, Switzerland). A cable connected the force transducer to the athlete's shank via a strap secured superior to the lateral malleolus. The athletes were placed in a seated position and were securely strapped into the chair with a trunk-thigh angle of 90°. The knee angle was fixed at 90° of flexion (0° corresponding to full extension). The cathode was initially placed in the femoral triangle 3-5 cm below the inguinal ligament and just lateral to the femoral artery. It was repositioned systematically to determine the best location for subsequent stimulations, with the position that resulted in the largest quadriceps twitch response used on each test occasion. The anode was positioned at the gluteal fold opposite the cathode. A high voltage stimulator (Digitimer DS7A, Hertfordshire, United Kingdom) was used to deliver a square-wave stimulus with a 1-ms duration, 400 V maximal voltage, and intensity ranging from 130 to 160 mA. The optimal intensity of stimulation was set by progressively increasing the stimulus intensity (10 mA increments) until a plateau in the elicited twitch was observed. This value was checked for maximality throughout the 12 weeks of testing. Approximately 2 min after establishing the maximal stimulation intensity, the test contractions were performed. Double pulse stimulation was chosen to approximate tetanic stimulation [161, 303]. Test contractions began with three paired stimulations at 10 Hz (100-ms interstimulus interval), followed by three paired stimulations at 100Hz (10-ms interstimulus interval). Twenty seconds rest was allowed between all paired stimulations, with approximately 1 min between low- and high- frequency sets of stimulations. The average maximum elicited torque from each of the stimulated contractions was used to

determine the 10/100-Hz ratio. Following a 1 min rest period, a single maximum voluntary contraction of the leg extensors was performed, where the subject was asked to produce maximal force as quickly as possible and maintain the contraction for 5s. The maximal voluntary torque elicited during this contraction was used in the analysis.

On completion of all testing procedures each subject was asked to rate their level of perceived fatigue using a five point Likert scale where 1 = no fatigue, and 5 = extremely fatigued.

8.3.4. Statistical Analyses

Descriptive statistics (means \pm standard deviations; SD) were used to describe the weekly time-course of neuromuscular and performance changes. Changes are reported as the difference in the outcome score relative to the each subjects mean score during the 12 week training intervention. To investigate the relationship between the low-to-high frequency force ratio, CMJ performance and perceptual ratings of fatigue, matched pairs were obtained for each of the dependent variables from the assessments conducted on Day 6 of each training week. Pearson's correlation coefficients were calculated for matched pairs of dependent variables for each subject, with the mean (\pm SD) r value reported. The magnitudes of the correlation coefficients were interpreted as <0.10 , trivial; $0.10-0.29$, small; $0.30-0.49$, moderate; ≥ 0.50 , large [58]. All variables except for self-rated fatigue were log-transformed prior to analysis to reduce non-uniformity of error.

8.4. RESULTS

Fifty-two matched pairs of dependent variables were used to determine relationships between dependent variables (9 ± 2 per subject, mean \pm SD). Technical problems prevented nerve stimulation procedures being conducted in Weeks 1 and 2 for all but one subject.

8.4.1. Time course of changes

A wide variety of individual weekly responses to the training protocol were observed (Figure 8.1). On average, self-reported fatigue ratings increased with the onset of T2, decreasing with the reduction in training load in T3. The onset of T2 also coincided with the largest reductions in the 10/100-Hz ratio, knee extensor maximal voluntary torque, jump

height and all remaining kinetic and kinematic variables measured during CMJs. While fatigue remained elevated during the overreaching period, an unexpected recovery of physiological and performance variables occurred following the initial reduction in Week 5. During the recovery phase in T3, improvements in performance tended to correspond with the reduced training load and reduced perceptions of fatigue. The 10/100-Hz ratio showed a large recovery in the first week of T3, with secondary reductions throughout the remainder of the taper.

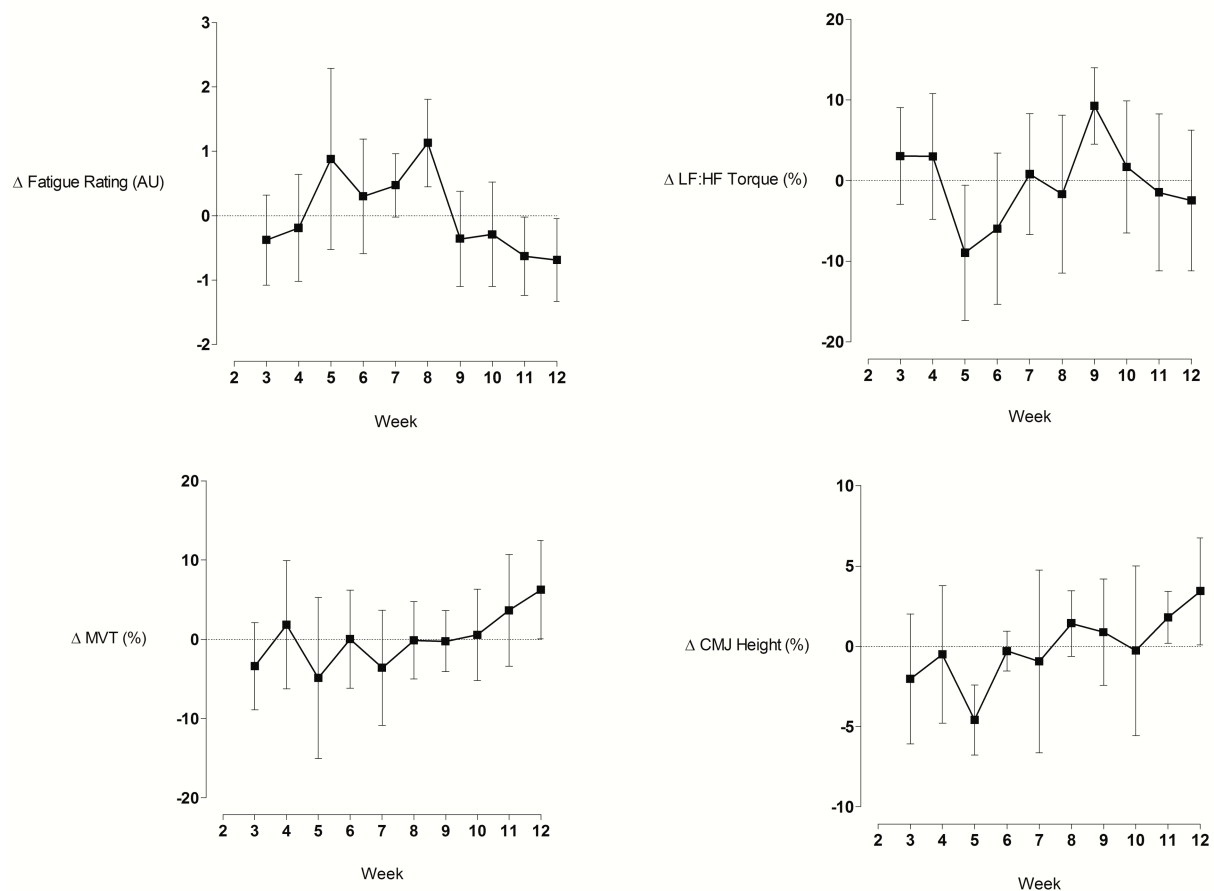


Figure 8.1 Time course of physiological, performance and perceptual measures during the 12-week training intervention. Values (mean \pm SD) are presented as the difference of the weekly value in relation to the overall individual mean score. Abbreviations: LF; low frequency, HF; high-frequency, CMJ; countermovement jump; MVT; knee extensor maximal voluntary torque.

8.4.2. Relationships between variables

The large range in intra-individual changes in the dependent variables in response to training supported the use of separate correlational analyses for each subject. As an example, Figure 8.2 illustrates the within-subject relationships between the 10/100-Hz ratio and CMJ mean power. On average, the countermovement-jump variables had only small correlations with 10/100-Hz torque ratio and maximum voluntary torque, while the correlations with fatigue rating were trivial (Table 8.2). The typical between-subject SD for the correlations was ~ 0.30 . We found an SD of 0.33 when we used a spreadsheet [142] to generate samples of size 9 drawn from a population with a true small or trivial correlation; that is, the between-subject variations in the correlations between the measures in this study is what would be expected given normal sampling variation and no real differences in the correlations between subjects.

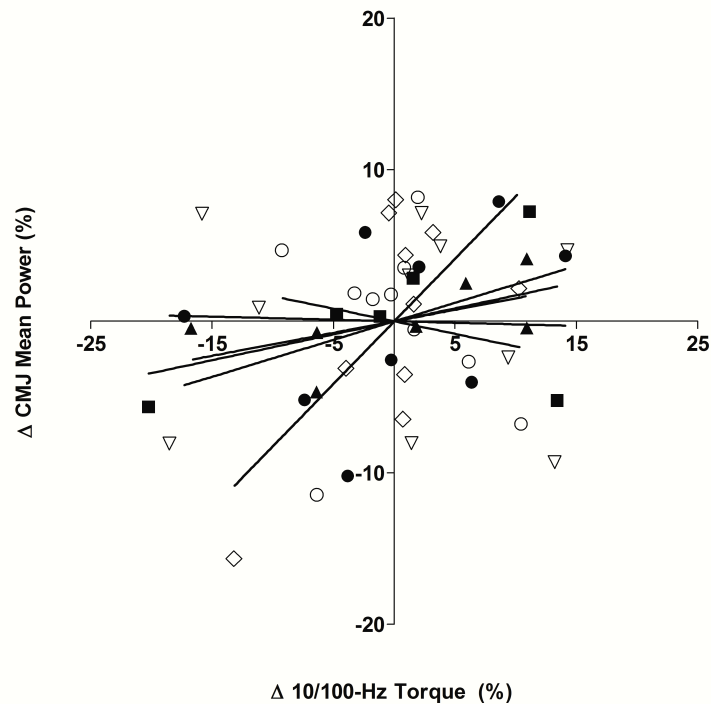


Figure 8.2 Within-subject changes for CMJ mean power and 10/100-Hz torque ratio, with regressions lines for each subject. Closed and open symbols represent males and females respectively.

8.5. DISCUSSION

Changes in CMJ performance have previously been shown to track fatigue and recovery following acute and serial bouts of fatiguing exercise. What is unknown is the origin of this fatigue and how it relates to the changes in CMJs. The major finding from this study is that changes in LFF, measured via standard clinical procedures, account for only small to moderate changes in CMJ performance. As such, this finding indicates that although LFF may play a role in changes in CMJ performance ability during periods of intensive training, it is not the primary mechanism. This finding does not support the use of CMJs as a surrogate measure of low-frequency neuromuscular fatigue. An important secondary finding was the lack of relationship between changes in neuromuscular function and functional performance and the level of fatigue perceived by the athletes. However, further research may be required to confirm both of these main findings given the small number of observations for each subject in this sample and the resultant large amount of uncertainty in the observed effects.

Table 8.2 Within-subject Pearson's correlation coefficients (mean \pm SD) for the ratio of low- to high-frequency stimulated force, maximal voluntary force of the knee extensors, self-rated perceptions of fatigue, and kinetic and kinematic variables measured from a countermovement jump.

	LF:HF torque	MVT	Fatigue rating
CMJ peak force	0.31 \pm 0.33	-0.06 \pm 0.26	0.10 \pm 0.32
CMJ mean power	0.30 \pm 0.33	0.10 \pm 0.16	-0.08 \pm 0.34
CMJ peak velocity	0.27 \pm 0.26	0.23 \pm 0.32	-0.07 \pm 0.30
CMJ height	0.24 \pm 0.27	0.15 \pm 0.34	0.07 \pm 0.42
CMJ eccentric displacement	0.14 \pm 0.27	0.28 \pm 0.44	-0.06 \pm 0.35
Fatigue rating	-0.06 \pm 0.32	-0.32 \pm 0.33	
MVT	-0.10 \pm 0.34		

Abbreviations: LF; low frequency, HF; high-frequency, CMJ; countermovement jump, MVT; maximal voluntary torque

8.5.1. Changes in muscle contractile function with repeated bouts of training

A secondary aim of this investigation was to directly examine peripheral contributions to fatigue associated with consecutive bouts of daily training in athletes. The exercise in the present study was characterised by resistance training sessions involving high-intensity whole body movements. Tests of neuromuscular function occurred at the end of the training

week, after ~24 hours of recovery from the previous training session. Neuromuscular fatigue was particularly evident following the first week of deliberate overreaching (Figure 8.1), after the training load was initially increased from what would be considered a “normal” training load for these subjects. Given the 24 h recovery period, the most likely peripheral mechanism responsible for delayed recovery lies within the excitation-contraction (EC) processes [163]. It is commonly accepted that the long-lasting depression of force capacity of the musculature that is associated with LFF may be a consequence of some damage to the structure of the muscle fibre and/or alterations in the EC coupling mechanism caused by a reduction in the release of calcium from the sarcoplasmic reticulum [41, 163].

Kamandulis et al. [166] reported that during 3 weeks of drop jump training, the initial reduction in force evoked by low-frequency stimulation remained evident during the entire training period and persisted for 10 days following the last training session. Based on this report we hypothesised that four consecutive weeks of high volume resistance training in this study would progressively increase the magnitude of LFF. Our hypothesis was not supported by our results; an unexpected recovery in stimulated force (10/100-Hz ratio) occurred during Weeks 6-9 following an initial decrease in Week 5. We suggest that this could be due to two factors. Firstly, it is possible that the recovery of LFF following the initial decrease in Week 5 is a result of rapid adaptation to the exercise stress. In instances involving large amounts of eccentric work resulting in muscle damage, this phenomenon is referred to as the repeated bout effect, whereby protective mechanisms appear to limit further damage to the muscle [55, 228]. This effect has been observed in as little as 5 d, where significantly smaller changes in muscle force were produced by a second bout of identical exercise, even prior to full recovery from the first session [80]. Such a mechanism may account for the smaller effects of the deliberate overreaching protocol on force measures in this study. This is also supported by results from Fry et al., [100] who exposed athletes to two weeks of daily resistance training designed to induce overtraining and also failed to observe a progressive decline in muscle force characteristics. In their study, stimulated force recovered slightly in Week 2 after an initial large reduction in Week 1. Secondly, there was a large amount of individual variation in the responses, which is consistent with the large variability in the severity of strength loss and associated recovery profiles exhibited in response to a range of standardised exercise protocols [27, 116, 152, 229]. With a small sample of six subjects, it is possible that the mean response presented here is not truly representative of all athletes’ typical responses. It is likely that a larger

sample is needed to confirm the time course of changes in neuromuscular function during and following repetitive bouts of athletic training.

8.5.2. Relationships between knee extensor force and jump performance

We observed relatively similar temporal profiles of 10/100-Hz ratio and a range of variables measured during CMJ performance. This temporal association was supported by small correlation coefficients, suggesting that LFF plays a minor role in changes in CMJ performance during regular athletic training. The small magnitudes of the relationships indicate that a range of other mechanisms influence functional exercise performance when athletes are exposed serial bouts of high intensity and high volume resistance training. Apart from LFF, central fatigue has also been implicated as a long lasting form of fatigue in athletes [105]. A decrease in maximal voluntary force can occur as a result of both central and peripheral factors. By comparing changes in voluntary force with changes in stimulated force we gain some insight into whether a failure of central drive plays a major role in the fatigue and recovery of force exhibited during consecutive weeks of high intensity and high volume resistance training. The dissociation between changes in stimulated force and voluntary force suggests that the fatigue experienced by subjects in this study was due to changes in both the muscle itself (peripheral fatigue) and changes in central drive. Few studies have examined the contribution of central fatigue to force reductions exhibited following serial exercise bouts. Following 3 d of submaximal cycling, Stewart and colleagues determined that fatigue was mostly peripheral in nature [287]. Similarly Fry et al. [100] concluded that decrements in maximal squat strength in response to daily high-intensity resistance training was the result of peripheral and not central fatigue. In comparison, Koutedakis et al. [178] showed that unlike control subjects, overtrained subjects presented an activation deficit (impairment in central drive) and suggested that overtraining is a central rather than a peripheral phenomenon. Similar enduring reductions in corticomotor output have been observed to exist following 20 d of repetitive endurance cycling [258]. While many researchers have dismissed the role of central activation failure as a contributor to long lasting fatigue, more work is required to elucidate its role during regular athletic training consisting of serial bouts of intensive training.

A range of methodological considerations may also help to explain the lack of strong relationships between the clinical measures of LFF and CMJ variables. Firstly, there are

clear differences in the ability of fatigued muscles to generate dynamic power and isometric force [53, 74, 157, 278]. Along with differences in the extent of measured fatigue via dynamic and isometric contractions, different recovery profiles have also been observed following the initial decrease in force or power [44]. Wakeling et al. [306] recently showed that maximum power output from a limb is not obtained with all activated muscle operating at their individual peak power output, suggesting that an impaired coordination with fatigue can also reduce maximal power output during athletic activities. The impairment in muscular power production is also manifested in a reduced sensorimotor drive and proprioception ability with fatigue [106]. It is the potential combination of reduced muscular power output and sensorimotor drive via the afferent nerve feedback loop and how this interaction influences dynamic movement that requires systematic investigation. Isometric force measures underestimate functional impairment, and a power measure has been reported to be more appropriate to assess performance in dynamic exercise [46]. We suggest that despite the small relationships between clinical measures of long lasting neuromuscular fatigue and functional performance, jumps may still be useful in monitoring athletic fatigue, which is multifactorial in nature. However, the current findings indicate that CMJs cannot be used to predict or estimate the amount of LFF fatigue present following repeated bouts of competition/training. We would caution researchers and practitioners against using CMJ as a specific measure of LFF.

8.5.3. Perceptual ratings of fatigue

A novel finding in the current study was the lack of correlation between physiological and performance changes with perceptual measures of fatigue. We hypothesised that there would be a strong relationship between LFF and self-rated fatigue since LFF is explained as a failure of EC coupling, which impairs both maximal and submaximal force-generation. Thus, a given submaximal force will require increased motor unit recruitment and/or firing that will increase the perception of effort [44], which is what athletes typically refer to as “heavy legs” [93]. We also expected a relationship between changes in self-rated fatigue and CMJ performance based on the same hypothesis. To our knowledge other studies investigating self-rated fatigue and physiological changes in force production are limited. Fry and colleagues [100] reported that 1-RM strength decrements were accompanied by a decreased perception of strength, although the relationship was not examined directly. Most other studies investigating self-reported measures and changes in performance have

involved intensified periods of training for endurance activities, and have successfully linked performance changes with alterations in perceived stress, recovery and mood state. For example 3km time trial performance and Daily Analysis of Life Demands (DALDA)[261] scores during intensified training in triathletes were significantly correlated [68], as were performance changes and DALDA scores during two weeks of intensified cycling training [121]. Moderate associations have also been reported between increases in stress and reductions in maximal ramp-like running test performance during a season of professional football [86]. Similar to the current results, other authors have reported disparate findings between changes in self-reported measures and performance changes [252, 282]. This uncoupling of the response between what an athletes' perceived level of fatigue and how they can actually perform a required task is an area that requires further exploration, especially in the context of activities requiring high levels of force and power production.

8.6. CONCLUSIONS

To our knowledge the current study is the first to directly examine the relationship between changes in laboratory measures of LFF and changes in CMJ performance. We propose that the changes in functional performance during periods of high training loads are due to a variety of physiological changes that occur with fatigue, including both central and peripheral mechanisms. While small relationships exist between changes in jump performance and the magnitude of LFF, the findings suggest that LFF is not the primary mechanism responsible for changes in jump performance. Researchers may need to reconsider the use of vertical jumps as an indicator of peripheral neuromuscular fatigue, instead relying on them only to give an overall indication of fatigue that is multifactorial in nature.

CHAPTER NINE

Summary and Recommendations

9.1. THESIS SUMMARY AND DISCUSSION

Discovering methods for predicting non-functional over-reaching (NFO) and overtraining have been high on the agenda of applied sport scientists for many years. In Chapter 3 it was demonstrated that vertical jump performance is popularly monitored in high performance sports programs in the attempt to identify early signs of fatigue associated with maladaptive states. However, results from this study also highlighted that practitioners utilising such tests remain uncertain about a range of methodological issues surrounding the data collected during regular athlete monitoring. For instance, many survey respondents indicated that they are unsure which are the most appropriate outcome variables to monitor when measuring jump performance. It was also apparent that most practitioners largely rely on visual analysis of trends or arbitrary thresholds for determining what they consider to be important change in performance. Based on this evidence the overarching aim of the remainder of the thesis was to enhance our working knowledge of how best to monitor changes in vertical jump performance to elucidate whether or not an athlete is coping with the prescribed training and/or competition demands. The main findings in relation to the overarching question are summarized herewith.

In Chapter 4 the reliability of a range of variables measured during CMJ performance was examined. Gaining a greater understanding of these values is critical for determining the most appropriate variables to monitor while ensuring that small but practically important changes in performance are measurable. The major finding in terms of reliability was that all CMJ variables apart from RFD were highly reliable (CV range 0.8 – 6.2%), both within and between test occasions. Most variables were also reliable enough to detect small and practically important changes in performance. This conclusion, however, was contingent on using the average value of multiple trials. For most outcome variables, the variability from test to test was only less than the SWC value when four or more trials were averaged. This is an important consideration since the results in Chapter 3 indicated that a large proportion of practitioners reported implementing protocols consisting of three trials, where the best value was often used in further analyses. The other significant finding from this study regarding reliability was that test-retest reliability for trials performed in the morning was generally greater than the corresponding values for afternoon assessments. This implies that practitioners should aim to conduct performance assessments in the morning, however such

a recommendation is confounded by the remaining outcome, which was that performance is 4-6% higher in the afternoon.

Since obtaining a valid representation of an athlete's true maximal capacity is theoretically of as high importance as obtaining reliable results, the experimental study presented in Chapter 5 was designed to investigate methods for reducing the time of day effect on CMJ performance. This was considered important since there are often circumstances within the high performance training environment which would prevent jump performance being assessed at the same time of day (e.g. when training sessions on the same day are of interest, or other situations where schedules do not permit the standardisation of assessment times). We were able to show that body temperature can be manipulated via an extended warm-up to compensate for lower body temperature in the morning (diurnal variation of body temperature). This finding allows practitioners to compare performances when it is not possible to standardise the time of day jump assessments are performed. Care, however, should be taken to ensure that extended warm-ups performed prior to afternoon performance assessments do not surpass individual thresholds in body temperature which may compromise performance.

After establishing and quantifying the normal variation in regular CMJ performance in Chapters 4 and 5, a 12-week resistance training intervention was conducted to induce high levels of neuromuscular fatigue in experienced athletes. The purpose of this intervention was to identify the magnitude of change in CMJ performance that predicted an overtraining response. Unfortunately, even though there were a range of inter-individual responses during taper, with some subjects showing clear signs of non-functional overreaching, no clear outcome appeared to be predictive of NFO. The usefulness of this information in detecting early signs of overtraining or non-adaptive states is therefore questionable and may not be easily utilised in regular fatigue monitoring systems. More work is needed however to confirm this finding.

The data from this study did, however, provide several other novel findings that have important implications for practitioners using vertical jumps to monitor changes in athlete performance. Using a novel single-subject research design, the response of athletes during the intensified training phase was monitored using unloaded and loaded CMJs to answer several important questions regarding the analysis of CMJ performance variables during

daily training. Firstly, a comparison of kinetic and kinematic variables assessed during loaded and unloaded CMJs was conducted to establish which variables were most sensitive to neuromuscular fatigue experienced during overload training (Chapter 6). The findings indicated that unloaded jumps were more useful than loaded jumps in tracking negative changes in performance during the overload phase. While jump height has been used previously to assess performance during and subsequent to planned periods of overload, the findings from this study indicate that it is not the most appropriate variable to monitor since not all athletes in this study responded in the predicted manner when changes in jump height were analysed. Instead, it appears that peak velocity, mean power and peak force in the concentric phase of the jump may be more sensitive to fatigue induced changes. It is possible that these performance changes are caused by reductions in the amplitude of the countermovement sub-consciously chosen by the athletes. Hence, quantifying changes in this kinematic variable may be of great interest for practitioners monitoring the fatiguing effects of training and competition.

Based on the single-subject trends presented in Chapter 6, the general responses to the first 4 weeks of normal training were large (8-16%) compared to studies of previous strength trained athletes (e.g. [129, 132]). A possible explanation for the large difference in the reported outcomes compared to previous studies is the way in which performance changes were calculated. That is, in this series of single-subject experiments we measured performance almost daily in an attempt to develop an understanding of the performance fluctuations between training sessions. In contrast, the relatively long intervals between assessments used in previous research reveals a limited profile of performance potential throughout different training phases. When we calculated the change in performance using baseline values from week 1 and the values at the conclusion of week 4 (i.e. a pre-post research design), changes in mean concentric power output over the 4 week period were 1-10% for individual subjects, which was considerably different to the reported results of 8-16%. We feel that the advantage of the design of the current analysis is that it allowed for a more detailed analysis of individual trends and avoided the use of tests of statistical significance, which may mask small but practically important changes in physical performance capacity [146, 220]. In a similar fashion, the time course and magnitude of change during the overload training phase differed greatly when the changes were analysed using single-subject data and as the mean change in performance of the group using only the weekly scores (as in Chapter 8). This has important implications for monitoring and for

research studies using vertical jumps as a dependent variable, since the timing and frequency of assessment may mask the true response.

Another novel outcome of the 12-week training intervention was the observation that typical variation in jump performance is different between subjects and was influenced by training phase. The results presented in Chapter 7 provide the first indication that within-subject variability in performance is substantially different between individuals, and between different training phases. Such a finding implies that sample-based reliability studies, as was conducted in Chapter 4, may have limited applicability when using the typical variation, or error of measurement, to distinguish changes that are greater than the measurement error. That is, given the small but substantial differences in this threshold for individual athletes, it is more appropriate to use the athlete's own typical variation for delimiting the thresholds, rather than the error value calculated in a sample-based reliability study. It is also critical to readjust the level of typical variation used for defining the thresholds throughout different phases of training or competition since it appears that magnitude of variability increases with an increase in the fatigue state of an athlete.

The final part of this experimental study produced a comparison between CMJ performance and laboratory measures of low-frequency neuromuscular fatigue (Chapter 8). This comparison was considered important since changes in CMJ performance following fatiguing exercise and intensified training or competition have been attributed to neuromuscular fatigue without confirmation of this relationship. In some cases, authors have speculated that low frequency peripheral fatigue (LFF) in particular is the cause of training fatigue as it is the longest lasting form of fatigue, which is also likely to have the most profound effect on day to day performance in high performance athletes [93]. To our knowledge this is one of the first studies to report that changes in CMJ performance does not track equally with laboratory-based measures of LFF. Instead, the findings indicate that changes in functional performance during periods of high training loads are due to a variety of physiological changes that occur with fatigue, including both central and peripheral mechanisms. While small relationships exist between changes in jump performance and the magnitude of LFF, the findings suggest that LFF is not the primary mechanism responsible for changes in jump performance. These findings suggest that researchers may need to reconsider the use of vertical jumps as an indicator of peripheral neuromuscular fatigue,

instead relying on them only to give an overall indication of fatigue that is multifactorial in nature.

9.2. PRACTICAL APPLICATIONS

Based on the findings from the studies presented in this thesis, the following practical recommendations are made for practitioners engaging in monitoring fatigue in athletes via assessment and analysis of CMJ performance:

- Consider using the mean value for multiple trials (greater than four) to ensure the most reliable results.
- Where possible, manipulate the pre-test warm-up to account for diurnal variations in body temperature.
- Performance reductions during intensified training are most evident for peak velocity, mean power and peak force during unloaded CMJs and therefore these variables are most useful in monitoring fatigue.
- Use unloaded rather than loaded jumps since they are more sensitive to fatigue induced performance changes during intensified training. It is possible that performance changes are due to subtle changes in technique (the amplitude of the countermovement) rather than absolute changes in physiological capacity to produce force/power. Thus if possible, it is recommended that this measure is included in the range of variables monitored.
- Monitor trends in performance changes from assessments performed frequently, longer intervals between tests may mask important trends.
- Since the typical variation in performance is substantially different between athletes, it is important to delimit thresholds for unusual changes using individual data. By calculating the value for the typical variation via consecutive pairwise change scores, systematic changes in their performance capability will not impact the outcome.
- The current practice of using one standard deviation of an athlete's typical variation in performance, as indicated by a small number of practitioners, is applicable for describing the magnitude of changes likely to occur 68% of time. It is suggested here that greater thresholds, based on probability, are required for identifying large changes that occur less frequently. We suggest 1.2, 2.3 and 3.6 standard deviations as the thresholds for identifying unlikely (20% probability or 1 in 5), very unlikely

(5% probability or 1 in 20) and most unlikely (0.5% probability or 1 in 200) changes in performance.

- Relying on perceptual measures of fatigue is not likely to provide representative indications of the level of physiological fatigue (i.e. compromised ability to produce force). More research is needed to understand the inter-relationship between changes in functional neuromuscular performance and perceptual measures of fatigue.

9.3. RECOMMENDATIONS FOR FUTURE RESEARCH

The research presented in this thesis has broadened our understanding of how vertical jumps can be used in the daily training environment of high performance athletes to monitor fatigue. Given the methodological considerations explored in this body of research, a range of research questions remain to be answered to further understand how jumps can be used to identify early markers of overtraining. The following areas require further investigation.

1. While it is recommended that the symptoms associated with overtraining should be monitored continuously during the course of athletic training so that training volumes can be adjusted as soon as negative symptoms begin to appear [218], more information is required to establish thresholds of negative changes requiring intervention. Estimating the magnitude of these thresholds is difficult since numerous instances of NFO are required, which may be difficult to achieve without putting athletes at risk of long-term negative adaptations and symptoms associated with overtraining.
2. Importantly, given the increased professionalism of sports and the subsequent increase in the volume and frequency of training required for competitive performances at the elite level, it will also be necessary to understand how these thresholds may change in the developing elite pubescent athlete.
3. Once appropriate thresholds are established, it will be important to determine if the manipulation of training loads based on changes in CMJ performance assist in enhancing training adaptations and/or preventing instances non-functional overreaching or overtraining.

4. While a large proportion of practitioners integrate measures of perceptual fatigue and well-being into their monitoring systems, more research is needed to establish how these measures relate to predicting NFO and overtraining. Given that we observed an uncoupling of the response between what an athlete perceives as difficult or unachievable and how they can actually perform a required task (Chapter 8), it is suggested that this is an area that requires much further exploration, especially in the context of overreaching.
5. I have indicated that fatigue and NFO is a multifactorial state in the elite athlete but that there were only small agreements between CMJ and the clinical measures of neuromuscular fatigue. Further examination of the CMJ kinematic variables may elucidate a methodology for providing insight to mechanisms, such as the tendon complex, that contribute to the force/power production of a SSC movement but are not necessarily directly assessed with the measurements utilised in the experiments described in this thesis.

REFERENCE LIST

1. Abiss C and Laursen P. (2007). Is part of the mystery surrounding fatigue complicated by context? *Journal of Science and Medicine in Sport*, 10: 277-279
2. Achten J and Jeukendrup A. (2003). Heart rate monitoring. Applications and Limitations. *Sports Medicine*, 33(7): 517-538
3. Adams K, O'shea J, O'shea K, et al. (1992). The effect of six weeks of squat, plyometric and squat-plyometric training on power production. *Journal of Applied Sport Science Research*, 6(1): 36-41
4. Adlercreutz H, Harkonen M, Kuoppasalmi K, et al. (1986). Effect of training on plasma anabolic and catabolic stress hormones and the response during physical exercise. *International Journal of Sports Medicine*, 1: 27-28
5. Ahn S and Fessler J. (2003). Standard errors of mean, variance, and standard deviation estimators. University of Michigan, EECS Department <http://web.eecs.umich.edu/~fessler/papers/files/tr/stderr.pdf>.
6. Alen M, Pakarinen A, Hakkinen K, et al. (1988). Responses of serum androgenic-anabolic and catabolic hormones to prolonged strength training. *International Journal of Sports Medicine*, 9: 229-233
7. Allen D, Lamb G, and Westerblad H. (2008). Skeletal muscle fatigue: cellular mechanisms. *Physiological Reviews*, 88: 287-332
8. Allen D, Lannergren J, and Westerblad H. (1995). Muscle cell function during prolonged activity: cellular mechanisms of fatigue. *Experimental Physiology*, 80: 497-527
9. Amann M and Secher NH. Last Word on Point:Counterpoint: Afferent feedback from fatigued locomotor muscles is an important determinant of endurance exercise performance. *Journal of Applied Physiology*, 108(2): 469-
10. Amann M and Secher NH. (2010). Point: Afferent Feedback from Fatigued Locomotor Muscles is an Important Determinant of Endurance Exercise Performance. *Journal of Applied Physiology*, 108(2): 452-454
11. Andersson H, Raastad T, Nilsson J, et al. (2008). Neuromuscular fatigue and recovery in elite female soccer: effects of active recovery. *Medicine and Science in Sports and Exercise*, 40(2): 372-380
12. Aragon-Vargas L. (2000). Evaluation of four vertical jump tests: Methodology, reliability, validity, and accuracy. *Measurement in Physical Education and Exercise Science*, 4(4): 215-228
13. Arnaud S, Zattara-Hartmann C, Tomei C, et al. (1997). Correlation between muscle metabolism and changes in M-wave and surface electromyogram: dynamic constant load leg exercise in untrained subjects. *Muscle and Nerve*, 20: 1197-1199
14. Arnett M. (2002). Effects of prolonged and reduced warm-ups on diurnal variation in body temperature and swim performance. *Journal of Strength and Conditioning Research*, 16(2): 256-261
15. Arteaga R, Dorado C, Chavarren J, et al. (2000). Reliability of jumping performance in active men and women under different stretch loading conditions. *Journal of Sports Medicine and Physical Fitness*, 40: 26-34
16. Ascensao A, Leite M, Rebelo A, et al. (2011). Effects of cold water immersion on the recovery of physical performance and muscle damage following a one-off soccer match. *Journal of Sports Sciences*, 29(3): 217-225
17. Asmussen E and Boje O. (1945). Body temperature and capacity for work. *Acta Physiologica Scandinavia*, 10: 1-22
18. Atkinson G and Nevill A. (1998). Statistical methods For assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine*, 26(4): 217-238

19. Atkinson G and Reilly T. (1996). Circadian variation in sports performance. *Sports Medicine*, 21: 292-312
20. Atkinson G, Todd C, Reilly T, et al. (2005). Diurnal variation in cycling performance: Influence of warm-up. *Journal of Sports Sciences*, 23(3): 321-329
21. Atlaoui D, Duclos M, Gouarne C, et al. (2004). The 24-h cortisol/cortisone ratio for monitoring training in elite swimmers. *Medicine and Science in Sports and Exercise*, 36(2): 218-224
22. Atlaoui D, Pichot V, Lacoste L, et al. (2007). Heart rate variability, training variation and performance in elite swimmers. *International Journal of Sports Medicine*, 28: 394-400
23. Augustsson J, Thomee R, Linden C, et al. (2006). Single-leg hop testing following fatiguing exercise: reliability and biomechanical analysis. *Scandinavian Journal of Medicine and Science in Sports*, 16: 111-120
24. Baker A, Kostov K, Miller R, et al. (1993). Slow force recovery after long-duration exercise: metabolic and activation factors in muscle fatigue. *Journal of Applied Physiology*, 74(5): 2294-2300
25. Banfi G, Marinelli M, Roi G, et al. (1993). Usefulness of free testosterone/cortisol ratio during a season of elite speed skating athletes. *International Journal of Sports Medicine*, 14(7): 373-379
26. Bannister E, Modelling elite athletic performance, in *Physiological testing of the high performance athlete*, Macdougall, J, Wenger, H, and Green, H, Editors. 1991, Human Kinetics: Champaign, Illinois. p. 403-424.
27. Beaton L, Tarnopolsky M, and Phillips S. (2002). Variability in estimating eccentric contraction-induced muscle damage and inflammation in humans. *Canadian Journal of Applied Physiology*, 27: 516-526
28. Behm D and St-Pierre M. (1997). Effects of fatigue duration and muscle type on voluntary and evoked contractile properties. *Journal of Applied Physiology*, 82(5): 1654-1661
29. Bergh U and Ekblom B. (1979). Influence of muscle temperature on maximal muscle strength and power output in human skeletal muscles. *Acta Physiologica Scandinavica*, 107(1): 33-37
30. Bergstrom M and Hultman E. (1991). Relaxation and force during fatigue and recovery of the human quadriceps muscle: relations to metabolic changes. *Pflügers Archiv European Journal of Physiology*, 418: 153-160
31. Bernard T, Giacomoni M, Gavarry O, et al. (1998). Time-of-day effects in maximal anaerobic exercise. *European Journal of Applied Physiology*, 77: 133-138
32. Bigland-Ritchie B, Kukulka C, Lippold O, et al. (1982). The absence of neuromuscular transmission failure in sustained submaximal contractions. *Journal of Physiology*, 330: 265-278
33. Bishop P, Jones E, and Woods K. (2008). Recovery from training: a brief review. *Journal of Strength and Conditioning Research*, 22(3): 1015-1024
34. Bompa T (1983). Theory and methodology of training. Dubuque, IA: Kendall/Hunt Publishing Company.
35. Booth F and Thomason D. (1991). Molecular and cellular adaptation of muscle in response to exercise: perspectives of various models. *Physiological Reviews*, 71(2): 541-585
36. Borresen J and Lambert M. (2007). Changes in heart rate recovery in response to acute changes in training load. *European Journal of Applied Physiology*, 101: 503-511

37. Borresen J and Lambert M. (2008). Autonomic control of heart rate during and after exercise. *Sports Medicine*, 38(8): 633-646
38. Bosquet L, Merkari S, Arvisais D, et al. (2008). Is heart rate monitoring a convenient tool to monitor over-reaching? A systematic review of the literature. *British Journal of Sports Medicine*, 42: 709-714
39. Bresciani G, Cuevas M, Molinero O, et al. (2011). Signs of overload after an intensified training. *international Journal of Sports Medicine*, 32: 338-343
40. Brink M, Visscher C, Arends S, et al. (2010). Monitoring stress and recovery: new insights for prevention of injuries and illnesses in elite youth soccer players. *British Journal of Sports Medicine*, 44(11): 809-815
41. Bruton J, Lannergren J, and Westerblad H. (1998). Mechanisms underlying the slow recovery of force after fatigue: importance of intracellular calcium. *Acta Physiologica Scandinavica*, 162: 285-293
42. Buchheit M, Mendez-Villanueva A, Quod MJ, et al. (2010). Determinants of the variability of heart rate measures during a competitive period in young soccer players. *European Journal of Applied Physiology*, 109(5): 869-878
43. Byrne C and Eston R. (2002). The effect of exercise-induced muscle damage on isometric and dynamic knee extensor strength and vertical jump performance. *Journal of Sports Sciences*, 20: 417-425
44. Byrne C and Eston R. (2002). Maximal intensity isometric and dynamic exercise performance following eccentric muscle actions. *Journal of Sports Sciences*, 20: 951-959
45. Cady E, Elshove H, Jones D, et al. (1989). The metabolic causes of slow relaxation in fatigued human muscle. *Journal of Physiology*, 418: 327-337
46. Cairns S, Knicker A, Thompson M, et al. (2005). Evaluation of models used to study neuromuscular fatigue. *Exercise and Sport Sciences Reviews*, 33(1): 9-16
47. Callister R, Callister R, Fleck S, et al. (1990). Physiological and performance responses to overtraining in elite judo athletes. *Medicine and Science in Sports and Exercise*, 22(6): 816-824
48. Callister R, Callister RJ, Fleck SJ, et al. (1990). Physiological and performance responses to overtraining in elite judo athletes. *Medicine and Science in Sports and Exercise*, 22(6): 816-824
49. Carlock J, Smith S, Hartman M, et al. (2004). The relationship between vertical jump power estimates and weightlifting ability: a field-test approach. *Journal of Strength and Conditioning Research*, 18(3): 534-539
50. Caruso JF, Daily JS, McLagan JR, et al. (2010). Data reliability from an instrumented vertical jump platform. *Journal of Strength and Conditioning Research*, 24(10): 2799-2808
51. Chatzinikolaou A, Fatouros I, Gourgoulis V, et al. (2010). Time course of changes in performance and inflammatory response after acute plyometric exercise. *Journal of Strength and Conditioning Research*, 24(5): 1389-1398
52. Chen J, Yeh D, Lee J, et al. (2011). Parasympathetic nervous activity mirrors recovery status in weightlifting performance after training. *Journal of Strength and Conditioning Research*, 25(6): 1546-1552
53. Cheng A and Rice C. (2005). Fatigue and recovery of power and isometric torque following isotonic knee extensions. *Journal of Applied Physiology*, 99: 1446-1452
54. Chiu L, Schilling B, Fry A, et al. (2004). Measurement of resistance exercise force expression. *Journal of Applied Biomechanics*, 20: 204-212

55. Clarkson P, Nosaka K, and Braun B. (1992). Muscle function after exercise-induced muscle damage and rapid adaption. *Medicine and Science in Sports and Exercise*, 24: 512-520
56. Claudino JG, Mezêncio B, Soncin R, et al. (2012). Pre vertical jump performance to regulate the training volume. *International Journal of Sports Medicine*, 33(12): 101-107
57. Clausen T and Nielsen O. (1994). The Na⁺, K⁺ pump and muscle contraction. *Acta Physiologica Scandinavica*, 152: 365-373
58. Cohen J (1988). Statistical Power Analysis for the Behavioral Sciences. 2nd ed. Hillsdale (NJ) Lawrence Erlbaum. 567.
59. Coldwells A, Atkinson G, and Reilly T. (1994). Sources of variation in back and leg dynamometry. *Ergonomics*, 37(1): 79-86
60. Cormack SJ, Newton RU, and Mcguigan M. (2008). Neuromuscular and endocrine responses of elite players to an Australian Rules Football match. *International Journal of Sports Physiology and Performance*, 3(3): 359-374
61. Cormack SJ, Newton RU, Mcguigan M, et al. (2008). Reliability of measures obtained during single and repeated countermovement jumps. *International Journal of Sports Physiology and Performance*, 3: 131-144
62. Cormack SJ, Newton RU, Mcguigan MR, et al. (2008). Neuromuscular and endocrine responses of elite players during an Australian Rules Football season. *International Journal of Sports Physiology and Performance*, 3: 439-453
63. Cormie P, Mccauley G, Triplett T, et al. (2007). Optimal Loading for maximal power output during lower-body resistance exercises. *Medicine and Science in Sports and Exercise*, 39(2): 340-349
64. Cormie P, Mcguigan M, and Newton R. (2010). Changes in eccentric phase contribute to improved SSC performance after training. *Medicine and Science in Sports and Exercise*, 42(9): 1731-1744
65. Coutts A, Reaburn P, Piva T, et al. (2007). Changes in selected biochemical, muscular strength, power, and endurance measures during deliberate overreaching and tapering in rugby league players. *International Journal of Sports Medicine*, 28: 116-124
66. Coutts A, Reaburn P, Piva T, et al. (2007). Monitoring overreaching in rugby league players. *European Journal of Applied Physiology*, 99: 313-324
67. Coutts AJ and Reaburn P. (2008). Monitoring changes in rugby league players' perceived stress and recovery during intensified training. *Perceptual and Motor Skills*, 106(3): 904-916
68. Coutts AJ, Slaterry KM, and Wallace LK. (2007). Practical tests for monitoring performance, fatigue and recovery in triathletes. *Journal of Science and Medicine in Sport*, 10(6): 372-381
69. Crameri RM, Aaggard P, K Q, et al. (2007). Myofibre damage in human skeletal muscle: effects of electrical stimulation versus voluntary contraction. *Journal of Physiology*, 583(1): 365-380
70. Crewther BT, Kilduff LP, Cunningham DJ, et al. (2011). Validating two systems for estimating force and power. *International Journal of Sports Medicine*, 32: 254-258
71. Cronin J, Hing R, and McNair P. (2004). Reliability and validity of a linear position transducer for measuring jump performance. *Journal of Strength and Conditioning Research*, 18(3): 590-593
72. Davies C and White M. (1981). Muscle weakness following eccentric work in man. *European Journal of Applied Physiology*, 39: 168-171

73. Dawson M, Gadian D, and Wilkie D. (1980). Mechanical relaxation rate and metabolism studied in fatiguing muscle by phosphorus nuclear magnetic resonance. *Journal of Physiology*, 299: 465-484
74. Deschenes M, Brewer R, Bush J, et al. (2000). Neuromuscular disturbance outlast other symptoms of exercise-induced muscle damage. *Journal of Neurological Sciences*, 174: 92-99
75. Dowling J and Vamos L. (1993). Identification of kinetic and temporal factors related to vertical jump performance. *Journal of Applied Biomechanics*, 9: 95-110
76. Dressendorfer R, Wade C, and Schaff J. (1985). Increased heart rate in runners: a valid sign of overtraining? *Physician and Sports Medicine*, 27(7): 77-86
77. Drust B, Rasmussen M, Mohr M, et al. (2005). Elevations in core and muscle temperature impairs repeated sprint performance. *Acta Physiologica Scandinavica*, 183: 181-190
78. Dugan E, Doyle T, Humphries B, et al. (2004). Determining the optimal load for jump squats: a review of methods and calculations. *Journal of Strength and Conditioning Research*, 18(3): 668-674
79. Eastwood A, Hopkins W, Bourdon P, et al. (2008). Stability of hemoglobin mass over 100 days in active men. *Journal of Applied Physiology*, 104(4): 982-985
80. Ebbeling C and Clarkson P. (1990). Muscle adaptation prior to recovery following eccentric exercise. *European Journal of Applied Physiology*, 60: 26-31
81. Edwards R, Human muscle function and fatigue, in *Human muscle fatigue: Physiological mechanisms*, Porter, R and Whelen, J, Editors. 1981, Pitman Medical: London. p. 1-18.
82. Edwards R, Hill D, Jones D, et al. (1977). Fatigue of long duration in human skeletal muscle after exercise. *Journal of Physiology*, 272: 769-778
83. Elloumi M, Maso F, Michaux O, et al. (2003). Behaviour of saliva cortisol [C], testosterone [T] and the T/C ratio during a rugby match and during post-competition recovery days. *European Journal of Applied Physiology*, 90: 23-28
84. Enoka R (2002). *Neuromechanics of Human Movement*. Second ed. Champaign, IL: Human Kinetics.
85. Enoka R and Duchateau J. (2008). Muscle function: what, why and how it influences muscle function. *Journal of Physiology*, 586(1): 11-23
86. Faude O, Kellman M, Ammann T, et al. (2011). Seasonal changes in stress indicators in high level football. *International Journal of Sports Medicine*, 32(4): 259-265
87. Faude O, Meyer T, Urhausen A, et al. (2009). Recovery training in cyclists: ergometric, hormonal and psychometric findings. *Scandinavian Journal of Medicine and Science in Sports*, 19: 433-441
88. Faulkner J, Brooks S, and Opitck J. (1993). Injury to skeletal muscle fibres during contractions: conditions of occurrence and prevention. *Physical Therapy*, 73(12): 911-921
89. Filaire E, Bernain X, Sagnol M, et al. (2001). Preliminary results on mood state, salivary testosterone:cortisol ratio and team performance in a professional soccer team. *European Journal of Applied Physiology*, 86: 179-184
90. Filaire E, Legrand B, Lac G, et al. (2004). Training of elite cyclists: effects on mood state and selected hormonal responses. *Journal of Sports Sciences*, 22: 1025-1033
91. Fitts R. (1994). Cellular mechanisms of muscle fatigue. *Physiological Reviews*, 74(1): 49-94

92. Fowles J, Green H, Tupling R, et al. (2002). Human neuromuscular fatigue is associated with altered Na⁺ -K⁺ -ATPase activity following isometric exercise. *Journal of Applied Physiology*, 92: 1585-1593
93. Fowles JR. (2006). Technical issues in quantifying low-frequency fatigue in athletes. *International Journal of Sports Physiology and Performance*, 1: 169-171
94. Fridén J and Lieber R. (2001). Eccentric exercise-induced injuries to contractile and cytoskeletal muscle fibre components. *Acta Physiologica Scandinavica*, 171(3): 321-326
95. Fridén J, Sjöström M, and Ekblom B. (1983). Myofibrillar damage following intense eccentric exercise in man. *International Journal of Sports Medicine*, 4(3): 170-176
96. Fry A, Kraemer W, Lynch J, et al. (1994). Does short-term near-maximal intensity machine resistance training induce overtraining? *Journal of Strength and Conditioning Research*, 8(3): 188-191
97. Fry A, Kraemer W, and Ramsey L. (1998). Pituitary-adrenal-gonadal responses to high-intensity resistance exercise overtraining. *Journal of Applied Physiology*, 85(6): 2352-2359
98. Fry A, Kraemer W, Stone M, et al. (1994). Endocrine responses to overreaching before and after 1 year of weightlifting. *Canadian Journal of Applied Physiology*, 19(4): 400-410
99. Fry A, Kraemer W, Stone M, et al. (1993). Endocrine and performance responses to high volume training and amino acid supplementation in elite junior weightlifters. *International Journal of Sport Nutrition*, 3: 306-322
100. Fry A, Kraemer W, Van Borselen F, et al. (1994). Performance decrements with high-intensity resistance exercise overtraining. *Medicine and Science in Sports and Exercise*, 26(9): 1165-1173
101. Fry A, Morton A, and Keast D. (1991). Overtraining in athletes. An update. *Sports Medicine*, 12: 32-65
102. Fry AC and Kraemer WJ. (1997). Resistance exercise overtraining and overreaching: Neuroendocrine responses. *Sports Medicine*, 23(2): 106-129
103. Fuglevand A, Zackowski K, Huey K, et al. (1993). Impairment of neuromuscular propagation during human fatiguing contractions at submaximal forces. *Journal of Physiology*, 460(1): 549-572
104. Gambetta V (2007). Athletic development. Champaign, IL: Human Kinetics.
105. Gandevia S. (1992). Some central and peripheral factors affecting human motoneuronal output in neuromuscular fatigue. *Sports Medicine*, 13(2): 93-98
106. Gandevia S. (1998). Neural control in human muscle fatigue: changes in muscle afferents, moto neurones and moto cortical drive. *Acta Physiologica Scandinavica*, 162: 275-283
107. Gandevia S. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews*, 81(4): 1725-1789
108. Gastmann U, Peterson K, Bocker J, et al. (1998). Monitoring intensive endurance training at moderate energetic demands using resting laboratory markers failed to recognize an early overtraining stage. *Journal of Sports Medicine and Physical Fitness*, 38: 188-193
109. Gauthier A, Davenne D, Martin A, et al. (2001). Time of day effects on isometric and isokinetic torque developed during elbow flexion in humans. *European Journal of Applied Physiology*, 84: 249-252
110. Gee T, French D, Howaston G, et al. (2011). Does a bout of strength training affect 2,000 m rowing ergometer performance and rowing-specific maximal power 24 h later? *European Journal of Applied Physiology*, 111: 2653-2662

111. Girard O, Lattier G, Micallef J-P, et al. (2006). Changes in exercise characteristics, maximal voluntary contraction, and explosive strength during prolonged tennis playing. *British Journal of Sports Medicine*, 40: 521-526
112. Girard O, Micallef J-P, Noual J, et al. (2010). Alteration of neuromuscular function in squash. *Journal of Science and Medicine in Sport*, 13: 172-177
113. Gore CJ, Hopkins WG, and Burge CM. (2005). Errors of measurement for blood volume parameters: a meta-analysis. *Journal of Applied Physiology*, 99: 1745-1758
114. Green HJ. (1997). Mechanisms of muscle fatigue in intense exercise. *Journal of Sports Sciences*, 15(3): 247-256
115. Grove J and Prappavessis H. (1992). Preliminary evidence for the reliability and validity of an abbreviated Profile of Mood States questionnaire. *International Journal of Sport Psychology*, 23: 93-109
116. Gulbin J and Gaffney P. (2002). Identical twins are discordant for markers of eccentric exercise-induced muscle damage. *international Journal of Sports Medicine*, 23(7): 471-476
117. Hakkinen K. (1993). Neuromuscular fatigue and recovery in male and female athletes during heavy resistance training. *International Journal of Sports Medicine*, 14: 53-59
118. Hakkinen K. (1994). Neuromuscular fatigue in males and females during strenuous heavy resistance loading. *Electromyography and Clinical Neurophysiology*, 34: 205-214
119. Hakkinen K, Pakarinen A, and Alen M. (1988). Daily hormonal and neuromuscular responses to intensive strength in 1 week. *International Journal of Sports Medicine*, 9(6): 422-428
120. Hakkinen K, Pakarinen A, Alen M, et al. (1987). Relationships between training volume, physical performance capacity, and serum hormone concentrations during prolonged training in elite weight lifters. *International Journal of Sports Medicine*, 8: S61-65
121. Halson S, Bridge M, Meeusen R, et al. (2002). Time course of performance changes and fatigue markers during intensified training in trained cyclists. *Journal of Applied Physiology*, 93: 947-956
122. Halson S and Jeukendrup A. (2004). Does overtraining exist? An analysis of overreaching and overtraining research. *Sports Medicine*, 34(14): 967-981
123. Halson S, Lancaster G, Jeukendrup A, et al. (2003). Immunological responses to overreaching in cyclists. *Medicine and Science in Sports and Exercise*, 35: 854-861
124. Halson S, Quod M, Martin D, et al. (2008). Physiological responses to cold water immersion following cycling in the heat. *International Journal of Sports Physiology and Performance*, 3(3): 331-346
125. Hamill J and McNiven S. (1990). Reliability of selected ground reaction force parameters during walking. *Human Movement Science*, 9: 117-131
126. Hamilton D. (2009). Drop jumps as an indicator of neuromuscular fatigue and recovery in elite youth soccer athletes following tournament match play. *Journal of Australian Strength and Conditioning*, 17(4): 3-8
127. Hansen KT, Cronin JB, and Newton MJ. (2011). The reliability of linear position transducer, force plate and combined measurement of explosive power-time variables during a loaded jump squat in elite athletes. *Sports Biomechanics*, 10(1): 46-58
128. Harris G and Atkinson G. (2011). Update - Ethical standards in sport and exercise science research. *International Journal of Sports Medicine*, 32: 819-821

129. Harris G, Stone M, O'byrant H, et al. (2000). Short-term performance effects of high power, high force, or combined weight-training methods. *Journal of Strength and Conditioning Research*, 14(1): 14-20
130. Harris N, Cronin J, Hopkins W, et al. (2008). Relationship between sprint times and the strength/power outputs of a machine squat jump. *Journal of Strength and Conditioning Research*, 22(3): 691-698
131. Harriss DJ and Atkinson G. (2009). International Journal of Sports Medicine – Ethical Standards in Sport and Exercise Science Research. *international Journal of Sports Medicine*, 30: 701-702
132. Hartman M, Clark B, Bemben D, et al. (2007). Comparisons between twice-daily and once-daily training sessions in male weight-lifters. *International Journal of Sports Physiology and Performance*, 2: 159-169
133. Hartmann U and Mester J. (2000). Training and overtraining markers in selected sports events. *Medicine and Science in Sports and Exercise*, 32(1): 209-215
134. Hartwig T, Naughton G, and Searl J. (2009). Load, stress and recovery in adolescent rugby union players during a competitive season. *Journal of Sports Sciences*, 27(10): 1087-1094
135. Hedelin R, Kenetta G, Wiklund U, et al. (2000). Short-term overtraining: effects on performance, circulatory responses, and heart rate variability. *Medicine and Science in Sports and Exercise*, 32(8): 1480-1484
136. Hermansen L and Osnes J. (1967). Blood and muscle pH after maximal exercise in man. *Journal of Applied Physiology*, 32: 304-308
137. Hoffman J, Maresh C, Newton R, et al. (2002). Performance, biochemical, and endocrine changes during a competitive football game. *Medicine and Science in Sports and Exercise*, 34(11): 1845-1853
138. Hoffman JR and Kaminsky M. (2000). Use of performance testing for monitoring overtraining in elite youth basketball players. *Strength and Conditioning Journal*, 22(6): 54-62
139. Hoffman JR, Nussle V, and Kang J. (2003). The effect of an intercollegiate soccer game on maximal power performance. *Canadian Journal of Applied Physiology*, 28(6): 807-817
140. Hooper S, Mackinnon L, Howard A, et al. (1995). Markers for monitoring overtraining and recovery. *Medicine and Science in Sports and Exercise*, 27: 106-112
141. Hopkins W. (2006). A spreadsheet for combining outcomes from several subject groups. *Sportscience*. sportsci.org/2006/wghcom.htm.
142. Hopkins W. (2007). Understanding statistics by using spreadsheets to generate and analyze samples. *Sportscience*. sportsci.org/2007/wghstats.htm.
143. Hopkins WG. (2000). Measures of reliability in sports medicine and science. *Sports Medicine*, 30(1): 1-15
144. Hopkins WG. (2002). Probabilities of clinical or practical significance. *Sportscience*. sportsci.org/jour/0201/wghprob.htm.
145. Hopkins WG, Hawley JA, and Burke LM. (1999). Design and analysis of research on sport performance enhancement. *Medicine and Science in Sports and Exercise*, 31(3): 472-485
146. Hopkins WG, Marshall SW, Batterham AM, et al. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, 41(1): 3-12
147. Hopkins WG, Schabert EJ, and Hawley JA. (2001). Reliability of power in physical performance tests. *Sports Medicine*, 31(2): 211-234

148. Hori N and Andrews WA. (2009). Reliability of velocity, force and power obtained from the Gymaware optical encoder during countermovement jump with and without external loads. *Journal of Australian Strength and Conditioning*, 17(1): 12-17
149. Hori N, Newton R, Andrews W, et al. (2007). Comparison of four different methods to measure power output during the hang power clean and the weighted jump squat. *Journal of Strength and Conditioning Research*, 21(2): 314-320
150. Horne J and Ostberg O. (1976). A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *International Journal of Chronobiology*, 4: 97-110
151. Hortobagyi T, Lambert N, and Kroll W. (1991). Voluntary and reflex responses to fatigue with stretch-shortening exercise. *Canadian Journal of Sport Sciences*, 16(2): 142-150
152. Hubal M, Rubinstein S, and Clarkson P. (2007). Mechanisms of variability in strength loss after muscle-lengthening actions. *Medicine and Science in Sports and Exercise*, 39(3): 461-468
153. Hunter S, Butler J, Todd G, et al. (2006). Supraspinal fatigue does not explain the sex differences in muscle fatigue of maximal contractions. *Journal of Applied Physiology*, 101: 1036-1044
154. Hynynen E, Uusitalo A, Kontinen N, et al. (2008). Cardiac autonomic responses to standing up and cognitive task in overtrained athletes. *International Journal of Sports Medicine*, 29: 552-558
155. Iellamo F, Pigozzi F, Spataro A, et al. (2004). T-wave and heart rate variability changes to assess training in world-class athletes. *Medicine and Science in Sports and Exercise*, 36(8): 1342-1346
156. Israel S. (1958). Die Erscheinungsformen des Übertrainings. *Sportmed*, 9: 207-209
157. James C and Jones D. (1990). Changes in the isometric force and dynamic force of fatigued human quadriceps muscle. *Journal of Physiology*, 429 (Suppl): 59
158. James CR, Herman JA, Dufek JS, et al. (2007). Number of trials necessary to achieve performance stability of selected ground reaction force variables during landing. *Journal of Sports Science and Medicine*, 6: 126-134
159. Jammes Y, Zattara-Hartmann C, Caquelard F, et al. (1997). Electromyographic changes in vastus lateralis during dynamic exercise. *Muscle and Nerve*, 20: 247-249
160. Jeukendrup A, Hesselink M, Kuipers H, et al. (1992). Physiological changes in male competitive cyclists after two weeks of intensified training. *International Journal of Sports Medicine*, 13(7): 534-541
161. Jones C, Allen T, Talbot J, et al. (1997). Changes in mechanical properties of human and amphibian muscle after eccentric exercise. *European Journal of Applied Physiology and Occupational Physiology*, 76: 21-31
162. Jones D, Muscle fatigue due to changes beyond the neuromuscular junction, in *Human Muscle Fatigue: Physiological Mechanisms*, Porter, R and Whelen, J, Editors. 1981, Medical Press: London. p. 178-196.
163. Jones D. (1996). High- and low-frequency fatigue revisited. *Acta Physiologica Scandinavica*, 156: 265-270
164. Jones D, Newham D, and Torgan C. (1989). Mechanical influences on long-lasting human muscle fatigue and delayed-onset pain. *Journal of Physiology*, 412: 415-427
165. Jürimäe J, Mäestu J, Purge P, et al. (2004). Changes in stress and recovery after heavy training in rowers. *Journal of Science and Medicine in Sport*, 7(3): 335-339
166. Kamandulis S, Skurvydas A, Snieckus A, et al. (2011). Monitoring of markers of muscle damage during a 3 week periodized drop-jump exercise program. *Journal of Sports Sciences*, 29(4): 345-353

167. Kargotich S, Keast D, Goodman C, et al. (2007). Monitoring 6 weeks of progressive endurance training with plasma glutamine. *International Journal of Sports Medicine*, 28: 211-216
168. Katch VL, Sady SS, and Freedson P. (1982). Biological variability in maximum aerobic power. *Medicine and Science in Sports and Exercise*, 14(1): 21-25
169. Keeton R and Binder-Macleod S. (2006). Low-frequency fatigue. *Physical Therapy*, 86: 1146-1150
170. Kellman M, Altenburg D, Lormes W, et al. (2001). Assessing stress and recovery during preparations for the World Championships in Rowing. *The Sport Psychologist*, 15: 151-167
171. Kellman M and Gunther K. (2000). Changes in stress and recovery in elite rowers during preparation for the Olympic games. *Medicine and Science in Sports and Exercise*, 32(3): 676-683
172. Kellman M and Kallus W (2001). Recovery-Stress Questionnaire for Athletes. Champaign, IL: Human Kinetics.
173. Kentta G and Hassmen P. (1998). Overtraining and recovery: A conceptual model. *Sports Medicine*, 26(1): 1-16
174. Kindermann W. (1986). Overtraining: expression of a disturbed autonomic regulation [in German]. *Dtsch Z Sportmed*, 37: 238-245
175. Klass M, Guissard N, and Duchateau J. (2004). Limiting mechanisms of force production after repetitive dynamic contractions in human triceps surae. *Journal of Applied Physiology*, 96(4): 1516-1521
176. Knicker A, Renshaw I, Oldham A, et al. (2011). Interactive processes link the multiple symptoms of fatigue in sport competition. *Sports Medicine*, 41(4): 307-328
177. Knudson D. (2009). Significant and meaningful effects in sports biomechanics research. *Sports Biomechanics*, 8(1): 96-104
178. Koutedakis Y, Frischknecht R, Vrbova G, et al. (1995). Maximal voluntary quadriceps strength patterns in Olympic overtrained athletes. *Medicine and Science in Sports and Exercise*, 27(4): 566-572
179. Kraemer W, French D, Paxton N, et al. (2004). Changes in exercise performance and hormonal concentrations over a big ten soccer season in starters and nonstarters. *Journal of Strength and Conditioning Research*, 18(1): 121-128
180. Kraemer W, Fry A, Rubin M, et al. (2001). Physiological and performance responses to tournament wrestling. *Medicine and Science in Sports and Exercise*, 33(8): 1367-1378
181. Kremenec I, Glace B, Ben-Avi S, et al. (2009). Central fatigue after cycling evaluated using peripheral magnetic stimulation. *Medicine and Science in Sports and Exercise*, 41(7): 1461-1466
182. Kuipers H and Keizer H. (1988). Overtraining in elite athletes. Review and directions for the future *Sports Medicine*, 6: 79-92
183. Kuipers H, Verstappen FTJ, Keizer HA, et al. (1985). Variability of aerobic performance in the laboratory and its physiologic correlates. *International Journal of Sports Medicine*, 6(4): 197-201
184. Lambert EV, St Clair Gibson A, and Noakes TD. (2005). Complex systems model of fatigue: integrative homeostatic control of peripheral physiological systems during exercise in humans. *British Journal of Sports Medicine*, 39(1): 52-62
185. Lamberts R and Lambert M. (2009). Day-to-day variation in heart rate at different levels of submaximal exertion: implications for monitoring training. *Journal of Strength and Conditioning Research*, 23(3): 1005-1010

186. Lamberts R, Lemmink K, Durant J, et al. (2004). Variation in heart rate during submaximal exercise: implications for monitoring. *Journal of Strength and Conditioning Research*, 18(3): 641-645
187. Lamberts R, Maskell S, Borresen J, et al. (2011). Adapting workload improves the measurement of heart rate recovery. *International Journal of Sports Medicine*, eFirst
188. Lanza I, Russ D, and Kent-Braun J. (2004). Age-related enhancement of fatigue resistance is evident in men during both isometric and dynamic tasks. *Journal of Applied Physiology*, 97: 967-975
189. Lehmann M, Baumgartl P, and Wiesenack C. (1992). Training-Overtraining: influence of a defined increase in training volumes vs training intensity on performance, catecholamines and some metabolic factors in experienced middle- and long-distance runners. *European Journal of Applied Physiology*, 64(2): 169-177
190. Lepers R, Maffiuletti N, Rochette L, et al. (2002). Neuromuscular fatigue during a long-duration cycling exercise. *Journal of Applied Physiology*, 92: 1487-1493
191. Lieberman H, Kellogg M, and Bathalon G. (2008). Female marine recruit training: mood, body composition, and biochemical changes. *Medicine and Science in Sports and Exercise*, 40(11S): S671-S676
192. Locke S, Osborne M, and O'rouke P. (2009). Persistent fatigue in young athletes: measuring the clinical course and identifying variables affecting clinical recovery. *Scandinavian Journal of Medicine and Science in Sports*, Epub ahead of print
193. Magalhaes J, Inacio M, Oliveira E, et al. (2011). Physiological and neuromuscular impact of beach-volleyball with reference to fatigue and recovery. *Journal of Sports Medicine and Physical Fitness*, 51: 66-73
194. Marcora S. (2009). Perception of effort during exercise is independent of afferent feedback from skeletal muscles, heart, and lungs. *Journal of Applied Physiology*, 106: 2060-2062
195. Marcora S. (2010). Counterpoint: Afferent feedback from fatigued locomotor muscles is not an important determinant of endurance exercise performance. *Journal of Applied Physiology*, 108: 454-456
196. Markovic G, Dizdar D, Jukic I, et al. (2004). Reliability and factorial validity of squat and countermovement jump tests. *Journal of Strength and Conditioning Research*, 18(3): 551-555
197. Maron M, Horvath S, and Wilkerson J. (1977). Blood biochemical alterations during recovery from competitive marathon running. *European Journal of Applied Physiology*, 36: 231-238
198. Martin A, Carpentier A, Guissard N, et al. (1999). Effect of time of day on force variation in human muscle. *Muscle and Nerve*, 22(1380-1387)
199. Martin V, Millet G, Lattier G, et al. (2005). Why does knee extensor muscles torque decrease after eccentric-type exercise? *Journal of Sports Medicine and Physical Fitness*, 45: 143-151
200. Matos N, Winsley R, and Williams C. (2011). Prevalence of nonfunctional overreaching/overtraining in young English athletes. *Medicine and Science in Sports and Exercise*, 43(7): 1287-1294
201. Matveyev L (1981). Fundamentals of sports training. Moscow: Progress Publishers.
202. Maulder P, Bradshaw E, and Keogh J. (2006). Jump kinetic determinants of sprint acceleration performance from starting blocks in male sprinters. *Journal of Sports Science and Medicine*, 5: 359-366
203. McBride J, Tripplett-McBride T, Davie A, et al. (2002). The effect of heavy-vs. light-load jump squats on the development of strength, power, and speed. *Journal of Strength and Conditioning Research*, 16(1): 75-82

204. Mclean BD, Coutts AJ, Kelly V, et al. (2010). Neuromuscular, endocrine, and perceptual fatigue responses during different length between-match microcycles in professional rugby league players. *International Journal of Sports Physiology and Performance*, 5: 367-383
205. McLellan CP, Lovell DI, and Gass GC. (2011). Markers of postmatch fatigue in professional rugby league players. *Journal of Strength and Conditioning Research*, 25(4): 1030-1039
206. McLellan TM, Cheung SS, and Jacobs I. (1995). Variability of time to exhaustion during submaximal exercise. *Canadian Journal of Applied Physiology*, 20(1): 39-51
207. McNair D, Lorr M, and Dopplemann L (1992). Profile of mood states manual. San Diego: Educational and Industrial Testing Service.
208. Meeusen R, Duclos M, Gleeson M, et al. (2006). Prevention, diagnosis and treatment of the Overtraining Syndrome. *European Journal of Sport Science*, 6(1): 1-14
209. Meeusen R, Dulcos M, Foster C, et al. (2013). Prevention, diagnosis and treatment of the overtraining syndrome: Joint consensus statement of the European College of Sport Science (ECSS) and the American College of Sports Medicine (ACSM). *European Journal of Sport Science*, 13(1): 1-24
210. Meeusen R, Piacentini M, Busschaert B, et al. (2004). Hormonal responses in athletes: the use of a two bout exercise protocol to detect subtle differences in (over)training status. *Journal of Applied Physiology*, 91: 140-146
211. Meister S, Faude O, Ammann T, et al., *Indicators for high physical strain and overload in elite football players*, in *Scandinavian Journal of Medicine and Science in Sports* 2011. p. Early view.
212. Millet G and Lepers R. (2004). Alterations of neuromuscular function after prolonged running, cycling and skiing exercises. *Sports Medicine*, 34(2): 106-116
213. Millet G, Lepers R, Maffiuletti N, et al. (2002). Alterations in neuromuscular function after an ultramarathon. *Journal of Applied Physiology*, 92: 486-492
214. Moir G, Sanders R, Button C, et al. (2005). The influence of familiarization on the reliability of force variables measured during unloaded and loaded vertical jumps. *Journal of Strength and Conditioning Research*, 19(1): 140-145
215. Moir GL, Garcia A, and Dwyer GB. (2009). Inter-Session reliability of kinematic and kinetic variables during vertical jumps in men and women. *International Journal of Sports Physiology and Performance*, 4: 317-330
216. Montgomery P, Pyne D, Cox A, et al. (2008). Muscle damage, inflammation, and recovery interventions during a 3-day basketball tournament. *European Journal of Sport Science*, 8(5): 241-250
217. Moore CA and Fry AC. (2007). Nonfunctional overreaching during off-season training for skill position players in collegiate American Football. *Journal of Strength and Conditioning Research*, 21(3): 793-800
218. Morgan W, Brown D, Raglin J, et al. (1987). Psychological monitoring of overtraining and staleness. *British Journal of Sports Medicine*, 21(3): 107-114
219. Morrison S, Sleivert G, and Cheung S. (2004). Passive hyperthermia reduces voluntary activation and isometric force production. *European Journal of Applied Physiology*, 91: 729-736
220. Mullineaux D, Bartlett R, and Bennett S. (2001). Research design and statistics in biomechanics and motor control. *Journal of Sports Sciences*, 19: 739-760
221. Neville M, Bogdanis G, Boobis L, et al., Muscle metabolism and performance during sprinting, in *Biochemistry of Exercise IX*, Maughan, R and Shireffs, S, Editors. 1996, Human Kinetics: Champaign. p. 243-260.

222. Newham D, Jones D, Ghosh G, et al. (1988). Muscle fatigue and pain after eccentric contractions at long and short length. *Clinical Science*, 74: 553-557
223. Nindl B, Leone C, Tharion W, et al. (2002). Physical performance responses to 72 h of military operational stress. *Medicine and Science in Sports and Exercise*, 34(11): 1814-1822
224. Nitsch J, Die Eigenzustandsskala (EZ-Skala) - Ein Verfahren zur hierarch-mehrdimensionalen befindlichkeitsskalierung, in *Beanspruchung im Sport*, Nitsch, J and Udris, I, Editors. 1976, Bad Homburg: Limpert.
225. Noakes TD. (2007). The central governor model of exercise regulation applied to the marathon. *Sports Medicine*, 37(4-5): 374-377
226. Noakes TD, St Clair Gibson A, and Lambert EV. (2005). From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans: summary and conclusions. *British Journal of Sports Medicine*, 39(2): 120-124
227. Nosaka K, Abbiss C, Watson G, et al. (2010). Recovery following an Ironman triathlon: A case study. *European Journal of Sport Science*, 10(3): 169-165
228. Nosaka K and Clarkson P. (1995). Muscle damage following repeated bouts of high force eccentric exercise. *Medicine and Science in Sports and Exercise*, 27: 1263-1269
229. Nosaka K and Clarkson P. (1996). Variability in serum creatine kinase after eccentric exercise of the elbow flexors. *International Journal of Sports Medicine*, 17: 120-127
230. Nuzzo J, McBride J, Cormie P, et al. (2008). Relationship between countermovement jump performance and multi-joint isometric and dynamic tests of strength. *Journal of Strength and Conditioning Research*, 22(3): 699-707
231. Parrado E, Cervantes J, Pintanel M, et al. (2010). Perceived tiredness and heart rate variability in relation to overload during a field hockey world cup. *Perceptual and Motor Skills*, 3: 699-713
232. Parry-Billings M, Budgett R, Koutedakis Y, et al. (1992). Plasma amino acid concentrations in the overtraining syndrome: possible effects on the immune system. *Medicine and Science in Sports and Exercise*, 24(12): 1353-1358
233. Pate E, Bhimani M, and Cooke R. (1995). Reduced effect of pH on skinned rabbit psoas muscle mechanics at high temperatures: implications for fatigue. *Journal of Physiology*, 486: 689-694
234. Perrey S, Smirmaul BDPC, Fontes EB, et al. Comments on Point:Counterpoint: Afferent feedback from fatigued locomotor muscles is/is not an important determinant of endurance exercise performance. *Journal of Applied Physiology*, 108(2): 458-468
235. Perrey S, Smirmaul BDPC, Fontes EB, et al. (2010). Comments on Point:Counterpoint: Afferent feedback from fatigued locomotor muscles is/is not an important determinant of endurance exercise performance. *Journal of Applied Physiology*, 108(2): 458-468
236. Petersen K, Hansen C, Aagaard P, et al. (2007). Muscle mechanical characteristics in fatigue and recovery from a marathon race in highly trained runners. *European Journal of Applied Physiology*, 101: 385-396
237. Pichot V, Roche F, Gaspoz J, et al. (2000). Relation between heart rate variability and training load in middle-distance runners. *Medicine and Science in Sports and Exercise*, 32(10): 1729-1736

238. Place N, Lepers R, Deley G, et al. (2004). Time course of neuromuscular alterations during a prolonged running exercise. *Medicine and Science in Sports and Exercise*, 36(8): 1347-1356
239. Place N, Yamada T, Bruton J, et al. (2010). Muscle fatigue: from observations in humans to underlying mechanisms studied in intact single muscle fibres. *European Journal of Applied Physiology*, 110: 1-15
240. Pyne D. Interpreting the results of fitness testing. in *International Science and Football Symposium*. 2003. Victorian Institute of Sport.
241. Raastad T and Hallen J. (2000). Recovery of skeletal muscle contractility after high- and moderate-intensity strength exercise. *European Journal of Applied Physiology*, 82: 206-214
242. Racinais S, Blonc S, and Hue O. (2005). Effects of active warm-up and diurnal increase in temperature on muscular power. *Medicine and Science in Sports and Exercise*, 37(12): 2134-2139
243. Racinais S, Hue O, and Blonc S. (2004). Time-of-day effects on anaerobic muscular power in a moderately warm environment. *Chronobiology International*, 21(3): 485-495
244. Raglin J, Koceja D, Stager J, et al. (1996). Mood, neuromuscular function, and performance during training in female swimmers. *Medicine and Science in Sports and Exercise*, 28(3): 372-377
245. Ramanathan N. (1964). A new weighting system for mean surface temperature of the human body. *Journal of Applied Physiology*, 19: 531-533
246. Ratatunga K. (1987). Effects of acidosis on tension development in mammalian skeletal muscle. *Muscle and Nerve*, 10: 439-445
247. Refinetti R and Menaker M. (1992). The circadian rhythm of body temperature. *Physiology and Behaviour*, 51(3): 613-637
248. Reilly T and Brooks G. (1986). Exercise and the circadian variation in body temperature measures. *International Journal of Sports Medicine*, 7: 358-362
249. Reilly T and Down A. (1992). Investigation of circadian rhythms in anaerobic power and capacity of the legs. *Journal of Sports Medicine and Physical Fitness*, 32: 346-347
250. Reijtens G, Kuipers H, Adam J, et al. (2005). Physiological, biochemical and psychological markers of strenuous training-induced fatigue. *International Journal of Sports Medicine*, 26: 16-26
251. Rhea M. (2004). Determining the magnitude of treatment effects in strength training research through the use of the effect size. *Journal of Strength and Conditioning Research*, 18(4): 918-920
252. Rietjens G, Kuipers H, Adam J, et al. (2005). Physiological, biochemical and psychological markers of strenuous training-induced fatigue. *International Journal of Sports Medicine*, 26: 16-26
253. Robson-Ansley P, Gleeson M, and Ansley L. (2009). Fatigue management in the preparation of Olympic athletes. *Journal of Sports Sciences*, 27(13): 1409-1420
254. Rodacki ALF, Fowler NE, and Bennett SJ. (2001). Multi-segment coordination: fatigue effects. *Medicine and Science in Sports and Exercise*, 33(7): 1157-1167
255. Rodano R and Squadrone R. (2002). Stability of selected lower limb joint kinetic parameters during vertical jump. *Journal of Applied Biomechanics*, 18: 83-89
256. Roelands B and Meeusen R. (2010). Alterations in central fatigue by pharmacological manipulations of neurotransmitters in normal and high ambient temperature. *Sports Medicine*, 40(3): 229-246

257. Ronglan L, Raastad T, and Borgeson A. (2006). Neuromuscular fatigue and recovery in elite female handball players. *Scandinavian Journal of Medicine and Science in Sports*, 16(4): 267-273
258. Ross E, Gregson W, Williams K, et al. (2010). Muscle contractile function and neural control after repetitive endurance cycling. *Medicine and Science in Sports and Exercise*, 42(1): 206-212
259. Ross E, Middleton N, Shave R, et al. (2007). Corticomotor excitability contributes to neuromuscular fatigue following marathon running in man. *Experimental Physiology*, 92(2): 417-426
260. Rowsell G, Coutts A, Reaburn P, et al. (2009). Effects of cold-water immersion on physical performance between successive matches in high-performance junior male soccer players. *Journal of Sports Sciences*, 27(6): 565-573
261. Rushall B. (1990). A tool for measuring stress tolerance in elite athletes. *Journal of Applied Sport Psychology*, 2: 51-66
262. Rushall B and Pyke F (1990). Training for sports and fitness. Melbourne: McMillan Company of Australia.
263. Sahlin K. (1992). Metabolic factors in fatigue. *Sports Medicine*, 13(2): 99-107
264. Sahlin K and Ren J. (1989). Relationship of contraction capacity to metabolic changes during recovery from a fatiguing contraction. *Journal of Applied Physiology*, 67(2): 648-654
265. Saltin B, Radegran G, Koskolou M, et al. (1998). Skeletal muscle blood flow in humans and its regulation during exercise. *Acta Physiologica Scandinavica*, 162: 421-436
266. Santhiago V, Da Sliva A, Papoti M, et al. (2011). Effects of 14-week swimming training program on the psychological, hormonal, and physiological parameters of elite women athletes. *Journal of Strength and Conditioning Research*, 25(3): 825-832
267. Schmidt V and Bruck K. (1981). Effect of a precooling maneuver on body temperature and exercise performance. *Journal of Applied Physiology*, 50: 772-778
268. Schmikli S, Brink M, De Vries W, et al. (2011). Can we detect non-functional overreaching in young elite soccer players and middle-long distance runners using field performance tests? *British Journal of Sports Medicine*, 45: 631-636
269. Sedilak M, Finni T, Cheng S, et al. (2008). Diurnal variation in maximal and submaximal strength, power and neural activation of leg extensors in men: Multiple sampling across two consecutive days. *International Journal of Sports Medicine*, 29: 217-224
270. Sheppard J, Cormack S, Taylor K, et al. (2008). Assessing the force-velocity characteristics of the leg extensors in well-trained athletes: The incremental load power profile. *Journal of Strength and Conditioning Research*, 22(4): 1320-1326
271. Sheppard J, Hobson S, Barker M, et al. (2008). The effect of training with accentuated eccentric load counter-movement jumps on strength and power characteristics of high-performance volleyball players. *International Journal of Sports Science and Coaching*, 3(3): 355-363
272. Siff M and Verchošanskij V (2003). Supertraining.
273. Škof B and Strojnik V. (2006). Neuromuscular fatigue and recovery dynamics following prolonged continuous run at anaerobic threshold. *British Journal of Sports Medicine*, 40: 219-222
274. Škof B and Strojnik V. (2007). The effect of two warm-up protocols on some biochemical parameters of the neuromuscular system of middle distance runners. *Journal of Strength and Conditioning Research*, 21(2): 394-399

275. Skurvydas A, Dudoniene V, Kalvenas A, et al. (2002). Skeletal muscle fatigue in long-distance runners, sprinters and untrained men after repeated drop jumps performed at maximal intensity. *Scandinavian Journal of Medicine and Science in Sports*, 12: 34-39
276. Skurvydas A, Jascscaninas J, and Zachovajevas P. (2000). Changes in height of jump, maximal voluntary contraction force and low-frequency fatigue after 100 intermittent or continuous jumps with maximal intensity. *Acta Physiologica Scandinavica*, 169: 55-62
277. Skurvydas A, Kamandulis S, and Masiulis N. (2010). Two series of fifty jumps performed within sixty minutes do not exacerbate muscle fatigue and muscle damage. *Journal of Strength and Conditioning Research*, 24(4): 929-935
278. Skurvydas A, Mamkus G, Dudoniene V, et al. (2007). The time-course of voluntary and electrically evoked muscle performance during and after stretch-shortening exercise is different. *Journal of Science and Medicine in Sport*, 6: 408-416
279. Slinde F, Suber C, Suber L, et al. (2008). Test–retest reliability of three different countermovement jumping tests. *Journal of Strength and Conditioning Research*, 22(2): 640-644
280. Smith D and Norris S, Training load and monitoring an athlete's tolerance for endurance training, in *Enhancing recovery: Preventing underperformance in athletes*, Kellman, M, Editor. 2002, Human Kinetics: Champaign, IL. p. 81-101.
281. Smith DJ and Norris SR. (2000). Changes in glutamine and glutamate concentrations for tracking training tolerance. *Medicine and Science in Sports and Exercise*, 32: 684-689
282. Smith TB, Hopkins WG, and Lowe TE. (2011). Are there useful physiological markers for monitoring overload training in elite rowers? *International Journal of Sports Physiology and Performance*, 6: 469-484
283. Snyder A, Kuipers H, and Cheng B. (1995). Overtraining following intensified training with normal muscle glycogen. *Medicine and Science in Sports and Exercise*, 27(7): 1063-1070
284. Sogaard K, Gandevia S, Todd G, et al. (2006). The effect of sustained low-intensity contractions on supraspinal fatigue in human elbow flexor muscles. *Journal of Physiology*, 573(2): 511-523
285. St Clair Gibson A, Lambert M, and Noakes T. (2001). Neural control of force output during maxiaml and submaximal exercise. *Sports Medicine*, 31(9): 637-650
286. St Clair Gibson A and Noakes TD. (2004). Evidence for complex system integration and dynamic neural regulation of skeletal muscle recruitment during exercise in humans. *British Journal of Sports Medicine*, 38(6): 797-806
287. Stewart R, Duhamel T, Rich S, et al. (2008). Effects of consecutive days of exercise and recovery on muscle mechanical function. *Medicine and Science in Sports and Exercise*, 40(2): 316-325
288. Stray-Gundersen J, Viderman T, and Snell P. (1986). Chnges in selected parameters during overtraining. *Medicine and Science in Sports and Exercise*, 18: S54-55
289. Strojnik V and Komi P. (1998). Neuromuscular fatigue after maximal stretch-shortening cycle exercise. *Journal of Applied Physiology*, 84(1): 244-350
290. Taylor J and Gandevia S. (2008). A comparison of central aspects of fatigue in submaximal and maximal voluntary contrctions. *Journal of Applied Physiology*, 104(2): 542-550
291. Taylor K, Chapman DW, Cronin JB, et al. (2012). Fatigue monitoring in high performance sport: A survey of current trends. *Journal of Australian Strength and Conditioning*, 20(1): 12-23

292. Taylor K, Cronin JB, Gill ND, et al. (2011). Sources of variability in iso-inertial jump assessments. *International Journal of Sports Physiology and Performance*, 5(4): 546-558
293. Thorlund J, Michalsik L, Madsen K, et al. (2008). Acute fatigue-induced changes in muscle mechanical properties and neuromuscular activity in elite handball players following a handball match. *Scandinavian Journal of Medicine and Science in Sports*, 18: 462-472
294. Thuma J, Gilders R, Verdun M, et al. (1995). Circadian rhythm of cortisol confounds cortisol responses to exercise: implications for future research. *Journal of Applied Physiology*, 78(5): 1657-1664
295. Tomazin K, Dolenc A, and Strojnik V. (2008). High-frequency fatigue after alpine skiing. *European Journal of Applied Physiology*, 103: 189-194
296. Tomlin D and Wenger H. (2001). The relationship between aerobic fitness and recovery from high intensity intermittent exercise. *Sports Medicine*, 31: 1-11
297. Umeda T, Suzukawa K, Takahashi I, et al. (2008). Effects of intense exercise on the physiological and mental condition of female university judoists during a training camp. *Journal of Sports Sciences*, 26(9): 897-904
298. Urhausen A, Gabriel H, and Kindermann W. (1995). Blood hormones as markers of training stress and overtraining. *Sports Medicine*, 20(4): 251-276
299. Urhausen A, Gabriel H, and Weiler B. (1998). Ergometric and psychological findings during overtraining: a long-term follow-up study in endurance athletes. *International Journal of Sports Medicine*, 19(2): 114-120
300. Urhausen A and Kindermann W. (1992). Biochemical monitoring of training. *Clinical Journal of Sport Medicine*, 2: 52-61
301. Urhausen A and Kindermann W. (2002). Diagnosis of overtraining. What tools do we have? *Sports Medicine*, 32(2): 95-102
302. Urhausen A, Kullmer T, and Kindermann W. (1987). A 7-week follow-up study of the behaviour of testosterone and cortisol during the competition period in rowers. *European Journal of Applied Physiology*, 56: 528-533
303. Verges S, Maffiuletti N, Kerhervé H, et al. (2009). Comparison of electrical and magnetic stimulations to assess quadriceps muscle function. *Journal of Applied Physiology*, 106: 701-710
304. Viru A and Viru M (2001). Biochemical Monitoring of Sport Training. Human Kinetics Publishers.
305. Vøllestad N, Sejersted I, and Saugen E. (1997). Mechanical behaviour of skeletal muscle during intermittent voluntary isometric contractions in humans. *Journal of Applied Physiology*, 83(5): 1557-1565
306. Wakeling JM, Blake OM, and Chan HK. (2010). Muscle coordination is key to the power output and mechanical efficiency of limb movements. *Journal of Experimental Biology*, 213: 487-492
307. Waldeck M and Lambert M. (2003). Heart rate monitoring during sleep: implications for monitoring training status. *Journal of Science and Medicine in Sport*, 2: 133-138
308. Walloe L and Wesche J. (1988). Time course and magnitude of blood flow changes in the human quadriceps muscles during and following rhythmic exercise. *Journal of Physiology*, 405: 257-273
309. Warren BJ, Stone MH, Kearney JT, et al. (1992). Performance measures, blood lactate and plasma ammonia as indicators of overwork in elite junior weightlifters. *Internal Journal of Sports Medicine*, 13(5): 372-376

310. Warren G, Ingallas C, Lowe D, et al. (2001). Excitation-contraction uncoupling: major role in contraction-induced muscle injury. *Exercise and Sport Science Reviews*, 29(2): 82-87
311. Welsh TT, Alemany JA, Montain SJ, et al. (2008). Effects of intensified military field training in jumping performance. *International Journal of Sports Medicine*, 29: 45-52
312. Westerblad H, Allen D, Bruton J, et al. (1998). Mechanisms underlying the reduction of isometric force in skeletal muscle. *Acta Physiologica Scandinavica*, 162: 253-260
313. Westerblad H, Bruton J, and Lannergren J. (1997). The effect of intracellular pH on contractile function of intact, single fibres of mouse declines with increasing temperature. *Journal of Physiology*, 500: 193-204
314. Wilson G, Murphy A, and Walshe A. (1997). Performance benefits from weight and plyometric training: effects of initial strength level. *Coaching and Sport Science Journal*, 2(1): 3-8
315. Wittert G, Livesey J, Espiner E, et al. (1996). Adaptation of the hypothalamopituitary adrenal axis to chronic exercise stress in humans. *Medicine and Science in Sports and Exercise*, 28(8): 1015-1019
316. Wolf W. (1957). A contribution to the questions of overtraining. *Sportmed*, 2: 35
317. Wyse J, Mercer T, and Gleeson N. (1994). Time-of-day dependence of isokinetic leg strength and associated interday variability. *British Journal of Sports Medicine*, 28(3): 167-170
318. Yu J, Carlsson L, and Thornell L. (2004). Evidence for myofibril remodeling as opposed to myofibril damage in human muscles with DOMS: an ultrastructural and immunoelectron microscopic study. *Histochemistry and Cell Biology*, 121: 219-227

APPENDIX A

Reprints of published manuscripts

Peer Review

FATIGUE MONITORING IN HIGH PERFORMANCE SPORT: A SURVEY OF CURRENT TRENDS

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ABSTRACT

Research has identified a plethora of physiological, biochemical, psychological and performance markers that help inform coaching staff about when an athlete is in a state of fatigue or recovery. However use of such markers in the regular high performance training environment remains undocumented. To establish current best practice methods for training monitoring, 100 participants involved in coaching or sport science support roles in a variety of high performance sports programs were invited to participate in an online survey. The response rate was 55% with results indicating 91% of respondents implemented some form of training monitoring system. A majority of respondents (70%) indicated there was an equal focus between load quantification and the monitoring of fatigue and recovery within their training monitoring system. Interestingly, 20% of participants indicated the focus was solely on load quantification, while 10% solely monitored the fatigue/recovery process. Respondents reported that the aims of their monitoring systems were to prevent overtraining (22%), reduce injuries (29%), monitor the effectiveness of training programs (27%), and ensure maintenance of performance throughout competitive periods (22%). A variety of methods were used to achieve this, based mainly on experiential evidence rather than replication of methods used in scientific publications. Of the methods identified for monitoring fatigue and recovery responses, self-report questionnaires (84%) and practical tests of maximal neuromuscular performance (61%) were the most commonly utilised.

Keywords - training monitoring, neuromuscular fatigue, overtraining, overreaching.

INTRODUCTION

Athlete fatigue is a difficult concept to define, making its measurement equally problematical (1, 18). Muscle physiologists often describe fatigue simply as an acute exercise-induced decline in muscle force (17). Within applied exercise science research, fatigue is most commonly referred to as a reduced capacity for maximal performance (31). Given this characterisation, it would seem that the most relevant way to measure fatigue would be directly, via a maximal test of performance in the athlete's competitive event. There are of course a number of difficulties associated with this approach. Most significantly, repeated maximal performance efforts are likely to contribute to a fatiguing effect, which is impractical, especially during a competitive season. Additionally, accurately defining maximal performance in a number of sporting pursuits, particularly team sports, is challenging if not impossible at this point in time. As well, such a "blunt force" approach to monitoring performance does not indicate the underlying physiological changes associated with performance fluctuations (4). Therefore, monitoring performance and functional capacity during athletic training is generally reliant on indirect markers of maximal performance or relevant physiological and/or psychological characteristics (25, 31, 43).

A multitude of such markers are available to assist in informing coaching staff when an athlete is in a state of fatigue or recovery, and while the research in this area is plentiful, no single, reliable diagnostic marker has yet been identified (4, 31). Also, while numerous markers of fatigue have been identified and studied in relation to the diagnosis of overreaching and overtraining syndromes (see (23, 33, 51) for reviews), less work has been published using such markers during regular training and competition in high performing athletes. Despite a lack of scientific confirmation in the use of such markers for fatigue monitoring and predicting non-functional overreaching in athletes involved in

regular training and competition schedules, anecdotal evidence suggests that most coaches and support staff involved in high performance sport programs have adopted monitoring systems that rely on a range of these markers to provide insight into their athlete's state of fatigue and readiness for training and/or competition.

As there is a paucity of information in the scientific literature on the current training monitoring methods being employed in high performance sports programs, the purpose of the current research was to gather information on the type of training monitoring systems that are considered current best practice. Specifically, information pertaining to the purpose of the monitoring systems, data collection methods, and their perceived effectiveness were examined via an online survey sent to a variety of coaching and support staff within the Australian and New Zealand high performance sport sector.

METHODS

Subjects

This descriptive study utilised an online survey electronically mailed to 100 individuals identified via their employment within high performance programs across a variety of sports. The survey response rate was 55%. The majority of respondents who affirmed their use of training monitoring systems were employed as the head strength and conditioning coach within their program ($n=30$), with other respondents identifying themselves as sports scientists ($n=12$), high performance managers/sports science co-ordinators ($n=9$), head coach ($n=3$) or other ($n=1$). Of the 55 respondents, five indicated that they do not use any form of training monitoring and were thereafter excluded from the analyses. The respondents all worked with elite/non-professional athletes or professional athletes across a variety of sports (see Figure 1). Ethical approval was granted by the Institutional Human Research Ethics Committee.

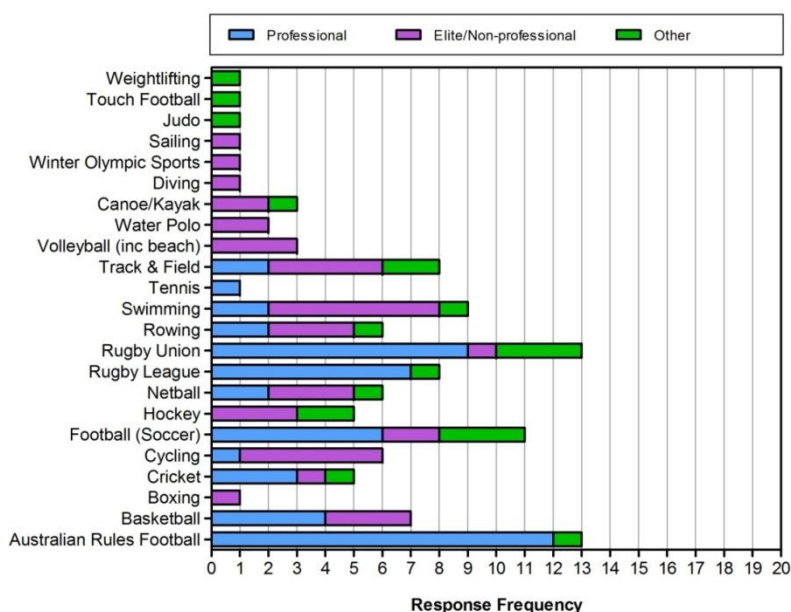


Figure 1 - Number of respondents representing various sports, with colours differentiating the level of performance. This figure represents the 55 respondents, 53% of whom reported being involved with multiple sports.

Survey

The survey (Appendix A) divided the topic of 'training monitoring' into two distinct areas; a) the quantification of training load, and b) monitoring of the fatigue/recovery responses to training or competition loads. The results presented herewith primarily relate to methods employed for monitoring athlete fatigue. Participants completed the online survey in three parts; (A) demographic questions including whether or not a training monitoring system was utilised, (B) items assessing the purpose and perceived value of the training monitoring system and how the data was collected and analysed, and (C) details of which methods are used for quantifying training load and for monitoring fatigue. Questions were based on methods identified within the scientific literature surrounding fatigue monitoring, training load quantification and the modelling of fitness-fatigue responses. In addition personal communications with

coaches in the high performance sport arena about their current practices provided a further basis for the construction of the questionnaire.

Procedures

Subjects were contacted electronically whereby the purpose of the survey was explained and a link to the online survey provided. They were informed that by completing and returning the survey that their consent to use the information was assumed. Upon completion of the survey all respondents were asked to indicate their availability for providing greater detail on selected responses if required by the principal researcher. Of the 50 respondents who indicated the use of a training monitoring system, 39 indicated their willingness to participate in follow-up questioning. Of these 39 participants, 28 were successfully reached via email correspondence with 17 responses received, permitting a subset of responses to be collated. Follow up questions included details concerning; the protocols used for performance testing, items included in custom designed self-report forms, the performance indicators used for tracking performance changes in training/competition, reasons for the (non) use of hormonal profiling, and the magnitude of change typically considered important for each of the parameters monitored.

Statistical Analysis

Frequency analysis for each question was conducted with results presented as absolute frequency counts or percentages of those in agreement or disagreement. Only one question used a Likert scale, where respondents were asked to rate the value of their training monitoring system to the overall performance of their athletes on a 5 point scale (1=minimal value; 5=extremely valuable). In addition to a frequency analysis, the mean response \pm standard deviation is presented for this item.

RESULTS

When asked to rate the value of their training monitoring system to the overall performance of their athletes, 38% rated it extremely valuable, with a mean response of 3.9 ± 1.1 . Respondents indicated that the most important purpose of their training monitoring systems were injury prevention (29%), monitoring the effectiveness of a training program (27%), maintaining performance (22%) and preventing overtraining (22%). The majority of respondents indicated that there was an equal focus on load quantification and the monitoring of fatigue and recovery within the training monitoring system (70%), while others indicated the focus was solely on load quantification (20%) or solely the monitoring of fatigue/recovery (10%).

Most respondents spend between 0-4 hours per week collecting training monitoring data, while approximately 30% require 4 hours or more per week to collect their data. Approximately 75% of respondents indicated that the analysis of their data generally takes between 1-6 hours per week, while approximately 20% of respondents spent greater than 6 hours weekly on data analysis. Generally, results are fed-back to the athletes and/or other staff on the day of assessment, with 50% of respondents requiring less than 1 hour and 42% getting results processed in less than one day.

Of the methods identified for monitoring fatigue responses to training and competition, self-report questionnaires were most common (84%), with 11 respondents relying solely on self-reported measures in their monitoring systems. Fifty-five per cent of respondents indicated that they collected self-report information on a daily basis (22% every session; 33% once per day), while others used the forms multiple times per week (24%), weekly (18%), or monthly (2%) (Figure 2A). The type of self-report forms most commonly used were custom designed forms (80%), with the Recovery-Stress Questionnaire for Athletes (30) (13%), Profile of Mood States (37) (2%) and Daily Analysis of Life Demands (2%) in minor use. Follow-up responses from 14 respondents who indicated the use of custom designed forms revealed their forms typically included 4-12 items measured on Likert point scales typically ranging from either 1-5 or 1-10. Perceived muscle soreness was most frequently signified as an important indicator of an athlete's recovery state. Sleep duration and quality, and perceptions of fatigue and wellness were also identified as highly important components of the custom designed forms. When asked their reasons for not employing one of the self-report questionnaires frequently reported in the scientific literature, a common theme in the responses was that they were too extensive, requiring too much time for athletes to complete (influencing compliance and adherence) and for support staff to analyse, and that they lacked sport specificity.

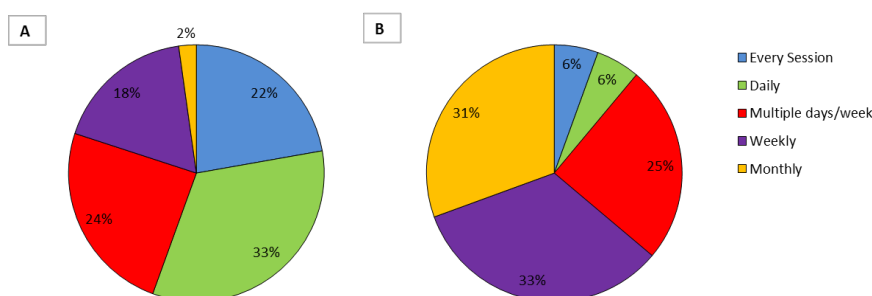


Figure 2 - Frequency of administration of (A) self-report questionnaires and (B) performance tests.

After the use of questionnaires for the monitoring of fatigue, 61% of respondents indicated the use of some form of performance test within their monitoring system. Practical tests of performance included maximal jump and/or strength assessments, overground sprints, submaximal cycling or running tests, and sports specific performance tests (Figure 2). These tests were commonly implemented on a weekly or monthly basis (33% and 30%, respectively), although more frequent testing was performed by 36% of respondents (Figure 1B). Within this category of performance tests, jump tests were most popular, used by 54% of respondents. Follow up questioning revealed a variety of equipment used by respondents in the assessment of jump performance, including linear position transducers, force plates, contact mats, and vertical jumping apparatus (e.g. Vertec or Yardstick). Of the 11 follow-up respondents who reported using jump assessments, all used a counter-movement jump (CMJ) for maximum height, with one respondent also using a broad jump, and another using a concentric-only squat jump in addition to the CMJ. Six practitioners assessed CMJ performance in an unloaded condition (hands on hips or holding a broomstick across the shoulders), and five assessed loaded CMJ performance using a 20kg Olympic bar.

In the performance test category, the next most popular performance tests were sport specific test protocols (20%), strength tests (16%), and submaximal running or cycling tests (14%), with a range of other tests identified that didn't fit into any of the above categories.

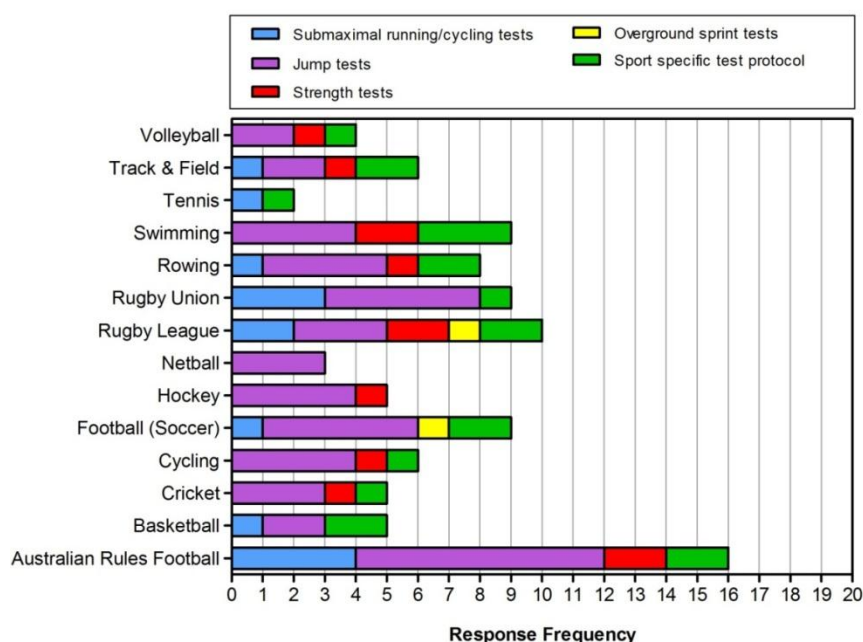


Figure 3 - Frequency of use of performance tests by sport.

Other than self-report questionnaires and performance tests, tracking performance in sporting activity was another popular method for monitoring fatigue and recovery, with 43% of respondents indicating this as a component of their fatigue monitoring system. This method is most popular in Australian Rules Football (n=9), Football (Soccer) (n=4), Rugby League (n=4), Rugby Union (n=3), Swimming (n=3) and Cycling, Rowing and Track and Field (n=2 each). Follow-

up responses were received from seven survey respondents. Those involved in field based sports (n=6) all indicated the use of global positioning system (GPS) units to measure a large range of performance indicators from their athletes both in training and competition. Most common were measures of work rate (e.g. metres covered per minute), time spent in high intensity work ranges, and total distance, although numerous other variables were mentioned including the coaches rating of performance, number of tackles performed and other game statistics. One respondent also indicated the use of a measure of “body load”, based on data obtained from an accelerometer.

A variety of other forms of fatigue monitoring were suggested by survey respondents. Four participants indicated that they use hormonal profiling as a component of their training monitoring system, and other respondents reported the use of musculoskeletal screenings (n=1), resting heart rate (n=1), and a commercially available athlete monitoring system (restwise.com)(n=1). Two other respondents indicated they relied on asking the athlete how they felt, either at rest or during high intensity training efforts.

DISCUSSION

The cumulative fatigue associated with successive overload training and/or frequent competition is an accepted part of modern coaching practice. While anecdotal evidence suggests that a wide variety of methods for monitoring fatigue are practiced in high performance sports programs, the details of what is considered best practice in these environments is not yet detailed in the literature. The results from this survey describe this landscape, and present evidence that a number of methods historically investigated in the scientific literature, such as resting heart rate indices and biochemical monitoring, are not popularly employed at the coal face of high performance sport.

In the population surveyed a high usage of self-report questionnaires for monitoring fatigue was indicated across a wide variety of sports and levels of performance. Support for such instruments and methods for monitoring fatigue and/or overtraining is provided by a large body of scientific investigations showing mood disturbances coinciding with increased training loads (7, 19, 22, 28, 29, 35, 39) and reduced performance (13, 42). It is likely that the popularity of self-report questionnaires for monitoring fatigue in high performance athletic settings is largely due to the simplicity of data collection and analysis which is then reflected in the regularity of the data collection, with 55% of respondents collecting this information on a daily basis. A large percentage of those surveyed opted to rely on their own custom designed self-report forms rather than those that have been used in scientific investigations. Further questioning highlighted the need for self-report forms to be concise and targeted to the monitoring situation, which the established versions reported in the literature are not. Accordingly respondents have designed their own forms, generally consisting of 5-12 items using 1-5 or 1-10 point Likert scales, or by modifying existing questionnaires by placing greater emphasis on ratings of muscle soreness, physical fatigue and general wellness. A dearth of experimental data exists investigating the effectiveness of such self-designed forms for monitoring fatigue, with few published reports available questioning the effectiveness of modified versions of existing questionnaires. Despite this lack of empirical evidence validating the modified forms, follow up respondents indicated they were confident that their modified self-report items provided them valid information, and that in their opinion scientific confirmation is unnecessary.

When asked what types of changes prompt the coaching or support staff to adjust an athlete's training or competition load based on their responses to the self-report questionnaires, a number of methods were identified. The majority of respondents indicated a reliance on visually identifying trends in individual data (decline for successive days/sessions); however another common method involved the use of individual “red flags” to identify meaningful changes in responses. The determination of a “red flag” was often based on arbitrary cut-off values or thresholds considered important by the coaching or support staff. One respondent provided a value for this arbitrary cut-off value (5% below the mean value); with others only stating that a “significant” drop below the athletes mean score is flagged as important. In relation to muscle soreness scores in particular, multiple respondents reported the use of the intra-individual standard deviation (SD) values to highlight changes outside of the individual's normal variation. Respondents utilising this quantitative approach for identifying “red flags” typically used values of ± 1 SD in relation to the mean, although the magnitude of these values were not reported. To our knowledge such methods for identifying unusual changes in regular performance due to fatigue are yet to be reported in the scientific literature.

Fatigue was also commonly assessed by respondents via tests of functional performance, with maximal jump assessments most popular within this category. Vertical jumping in particular has been touted as a convenient model to study neuromuscular function and has been used in a multitude of studies investigating the time course of recovery from fatiguing training or competition (3, 8, 11, 15, 21, 27, 32, 36, 41, 44, 47, 53). The utility of vertical jumps as a

practical measure of neuromuscular fatigue is reflected by the adoption of such testing procedures in the high performance sporting environment. However, a wide variety of protocols and equipment are available for measuring a range of outcome variables associated with vertical jumping performance, and little consensus exists as to the optimal methods or variables of interest for accurately measuring the state of fatigue or recovery in individual athletes. Vertical jump performance during periods of heavy loading has been monitored using vane jump and reach apparatus (9, 14, 15, 20, 38), contact or switch mats (24, 53), and force platforms (11, 32, 36, 40, 44). Within the population surveyed respondents also indicated the use of the above equipment; with the most popular being linear position transducers, or force plates in combination with linear position transducers. The use of force plates in combination with linear position transducers is not a regularly reported method for monitoring changes in performance due to fatigue in overreaching or overtraining studies, but is used widely for the assessment of vertical jump performance in numerous other settings and interventions (e.g. (12, 16, 45, 46)). Cormack et al., (10) monitored changes in vertical jump performance performed on a force plate following an Australian Rules Football match and reported that only six of the 18 force-time variables analysed during single and 5-repetition jumps had declined substantially following the match. In particular there was a lack of sensitivity of jump height to fatigue which supported the earlier work of Coutts and colleagues (15). Of further interest was that the pattern of response in these parameters varied greatly during the recovery period (from 24h to 120h post match) (10). This research highlights the considerable differences in changes in vertical jump performance based on the performance variable of interest. The responses to further questions regarding jump assessment protocols indicated that jump height remained popular among the variables being assessed in fatigue monitoring systems, however numerous other kinetic and kinematic variables, such as peak and mean velocity, peak and mean power, and peak force were also monitored. Many of the respondents indicated that they were still unsure of which parameter(s) are most useful, and thus continued to monitor numerous variables in the hope of gaining a better understanding of how they changed in relation to each other, as well as attempting to establish their relationship with changes in performance. Similar to the self-report questionnaires, the magnitude of change in these variables considered important was often based on visual analysis of trends or arbitrary threshold values (± 5 -10%), with two respondents indicating the use of individual SD values (± 1 SD) to identify changes outside of normal intra-individual trends.

Longer-term negative adaptations to training stress often involve changes in the autonomic nervous system which may be reflected in concomitant alterations in resting heart rate (HR), heart rate variability (HRV) measures and heart rate responses to maximal or submaximal exercise (2, 5). Results from the current survey indicated that heart rate monitoring during submaximal tests are popular, while resting heart rate indices, including heart rate variability, are less commonly monitored. Follow-up questioning regarding custom designed self-report forms did however reveal that resting heart rate was commonly included as an item on these self-report forms, suggesting that its popularity may not have been truly represented in responses during the initial survey. The continued use of HR and HRV measures is in contrast to reported opinion in that although there are significant modifications after short-term fatigue (in resting heart rate and HRV), long-term fatigue (HR during a submaximal workloads) or both (maximal HR), the moderate amplitude of those alterations limits their clinical usefulness since the expected differences fall within the day-to-day variability of those measures (6).

It is interesting that although a large number of scientific investigations have explored the effectiveness of biochemical monitoring for assessing fatigue and/or adaptive states (for extensive reviews see (49, 50, 52)), only four survey participants indicated that this is a component of their training monitoring system. Follow-up questioning suggested that the limited popularity is likely due to the large time, cost and expertise required for the analysis, as well as perceived difficulties in linking changes in biochemical parameters to performance outcomes. In addition, time of day, diet, and presence of injury influence biochemical concentrations, requiring well standardised sampling conditions which are often difficult to realise in the training environment (48, 49). There also exists considerable variation within and between individuals, influencing the reliability of measures and the availability of reference values indicating a "normal" exercise tolerance (49). These methodological issues, along with the inconvenience of collecting samples make this method difficult to implement on a regular basis, which is supported by the findings of the current study.

For all types of assessment, where decisions about an athlete's state of fatigue or recovery are made on the basis of changes in an outcome variable that isn't the performance itself, there is a need to identify a threshold at which negative changes in performance are considered large enough to be meaningful. Commonly this threshold value referred to as the smallest worthwhile change (SWC) in performance. These SWC values for each test parameter change from population to population. However, the reporting of these values in the literature by the people

implementing such tests is not widespread. If this reporting practice can be encouraged it will add greatly to the knowledge base and assist in gaining an understanding of what changes are practically important based on the type of sporting performance involved. It is also important that these values fall outside of the typical error of the assessed variable in order for changes to be confidently interpreted (26). Currently data on the relationship between SWC and typical error has been presented for vertical jumps on a force platform (10) and heart rate values during submaximal running tests (34). To our knowledge few data exist describing the practically important changes associated with item analyses on self-report questionnaires, limiting the ability to make decisions using critical thresholds based on changes in these parameters. Instead coaches and practitioners rely on these self-report questionnaires as a tool to highlight possible problems in an athlete's fatigue or recovery state, with only a few employing statistical methods to quantify what they consider practically important changes within an individual. To date, changes in these values have only anecdotally been linked with reductions in performance.

Based on the current findings that significant time investment is allocated to training monitoring and that the respondents place a high value on their systems for ensuring maximal performance of their athletes, it seems that more research in this popular area will assist in enhancing current best practice. While there appears to be plentiful research focused on the development of training monitoring systems and their validation in high performance sports environments, the current results suggest that the protocols adopted by coaches and support staff at the coal face of elite sport do not entirely reflect the most current evidence available in the scientific literature. A more focused research approach on the development and validation of methods for monitoring fatigue and recovery via practical tests of maximal neuromuscular performance is warranted, given the wide variety of methods and protocols currently employed.

PRACTICAL APPLICATIONS

It is critical for coaches of high performing athletes to have a training plan, yet it is also highly important to be able to adjust the plan based on how the athlete is adapting or coping with the imposed training and competition demands. To do this effectively the coach requires information based on each individual athlete's recovery abilities in response to various training stressors. In high performance sporting environments, self-report questionnaires identifying perceived changes in muscle soreness, feelings of fatigue and wellness, sleep quality and quantity and a variety of other psychosocial factors are relied upon for "flagging" athletes in a state of fatigue. Results from the survey indicate that custom-designed forms are preferred to those existing in the scientific literature because of the time required for completion. This concern is understandable given the time pressures in high performance environments, however shortened versions of the REST-Q are available. Use of a shortened REST-Q would provide a more scientifically valid method for collecting such information and provide support staff with a more reliable cross-reference to broader exercise applications.

Vertical jump tests are also frequently used to assess neuromuscular function, using a variety of equipment and assessment protocols. While limited data are available, unpublished observations from our research group suggests that unloaded jumps are more useful for monitoring fatigue than loaded variations. Similarly we have observed that eccentric displacement in a CMJ is most sensitive to fatigue induced by periods of high loading. Mean power, peak velocity and peak force are also useful variables to monitor. Within the population surveyed CMJs are most popularly employed, however there may also be value in monitoring a variety of different types of jumps (e.g. static-, countermovement- and drop- jumps), since experimental evidence suggests differential responses depending on the fatiguing stimulus.

While only a few practitioners reported using physiological parameters measured during submaximal exercise tasks to monitor training responses, feedback from these respondents along with recent research suggests that such tasks may provide a useful monitoring tool. In contrast, limited evidence exists supporting the use resting heart rate indices for these purposes due to large day-to-day variability.

Biochemical monitoring is not a popular form of athlete monitoring in the population surveyed, mostly due to the high costs associated as well as the extended time required to process results. There is however plentiful research supporting its use in monitoring athletes susceptible to non-functional overreaching or overtraining, and therefore may be useful in circumstances where the practical limitations can be worked around.

Lastly, when deciding on any assessment method, careful consideration should be given to the magnitude of change considered important for each of the measurement variables. Respondents indicated arbitrary thresholds of 5-10% or $\pm 1SD$, but the consequence of changes beyond these thresholds is unknown. The reporting of typical variation in these values during normal training and periods of high stress may assist practitioners in determining the most appropriate monitoring protocols and threshold levels. With this concept at the forefront of decision making, the authors believe that practitioners seeking to effectively monitor the fatigue state of their athletes should at least be using a shortened version of the REST-Q while monitoring changes in eccentric displacement, mean power, peak velocity or peak force in unloaded CMJs. Each of these variables should be consistently monitored during a period of low intensity training determine an individual's normal variation so as to effectively determine "red flag" thresholds.

APPENDIX A – Copy Of Survey

TRAINING MONITORING IN HIGH PERFORMANCE SPORT

PART A – Demographics

1. What is your position?

- ☐ Head Coach
- ☐ Head Strength & Conditioning Coach/Trainer
- ☐ High Performance Manager or Sport Science Coordinator
- ☐ Sport Scientist
- ☐ Other (please specify)

2. Does your employment require you to work with:

- ☐ one team/squad only (single sport)
- ☐ more than one team/squad (multiple sports)

3. Do you mostly work with team sport or individual athletes?

- ☐ Team sports
- ☐ Individual events
- ☐ Both

4. What level of sports performance are you involved in?

- ☐ Professional
- ☐ Elite/nonprofessional
- ☐ Semi-professional
- ☐ State level
- ☐ Other (please specify)

5. Which sport(s) do you work with on a daily/weekly basis?

- ☐ Australian Rules Football
- ☐ Basketball
- ☐ Boxing
- ☐ Cricket
- ☐ Cycling
- ☐ Football (Soccer)
- ☐ Hockey
- ☐ Martial Arts
- ☐ Netball
- ☐ Rugby League
- ☐ Rugby Union
- ☐ Rowing
- ☐ Swimming
- ☐ Tennis
- ☐ Track & Field

- ☐ Volleyball
- ☐ Other (please specify)

6. What is the age range of the athletes you work with?

- ☐ <15 years
- ☐ 15-20 years
- ☐ 21-25 years
- ☐ >25 years

7. Do you have a training monitoring system in place to quantify training load and/or monitor fatigue?

- ☐ Yes
- ☐ No

PART B - Monitoring Practices

8. What is the main purpose of your training monitoring system? (one response only)

- ☐ Reduce injuries
- ☐ Maintain performance
- ☐ Prevent overtraining
- ☐ Monitor the effectiveness of a training program

9. What is the main focus of the system?

- ☐ Load quantification
- ☐ Monitoring fatigue/recovery
- ☐ Equal focus on load quantification and fatigue monitoring

10. How many hours per week do you (or your colleagues) spend COLLECTING training monitoring data?

- ☐ < 1
- ☐ 1-2
- ☐ 2-4
- ☐ 4-6
- ☐ >6

11. How many hours per week do you (or your colleagues) spend ANALYSING training monitoring data?

- ☐ < 1
- ☐ 1-2
- ☐ 2-6
- ☐ 6-10
- ☐ > 10

12. How is your data collected?

- ☐ Using specialist software
- ☐ Via a custom web interface
- ☐ Entered directly into excel
- ☐ Pen and paper
- ☐ Other (please specify)

13. After collecting data, how long does it take to get feedback to the athletes and/or other staff?

- ☐ Less than 1 hour
- ☐ Less than 1 day
- ☐ 1-2 days
- ☐ 1 week
- ☐ More than 1 week

14. Do you monitor your athletes remotely or do you have daily face-to-face contact with them?

- ☐ Remotely
- ☐ Face-to-face (daily)
- ☐ Face-to-face (weekly)
- ☐ Other (please specify)

15. Rate the value of your monitoring system to the overall performance of your athletes

- ☐ 1 = Minimal value
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5 = Extremely valuable

PART C – Methods

16. Which of the following do you use to quantify training load?

- ☐ Sessional RPE
- ☐ External workload calculation (e.g. distance, time, kg lifted)
- ☐ Heart rate trimp
- ☐ GPS data
- ☐ Sport specific workload measurement device (e.g. SRM)
- ☐ None of the above
- ☐ Other (please specify)

17. Which of the following do you use to monitor athlete fatigue/recovery?

- ☐ Self-report questionnaires
- ☐ Performance tests (e.g. jumps, 20m sprint etc)
- ☐ Hormonal profiling
- ☐ Tracking performance in their sporting activity
- ☐ Other (please specify)

18. If applicable, how frequently do you use each of the following to monitor athlete fatigue/recovery?

	Every Session	Daily	Multiple days/week	Weekly	Monthly
Self-report questionnaires	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Performance tests (e.g. jumps, 20m sprint etc)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Hormonal profiling	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Tracking performance in their sporting activity	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Other (specified above)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

19. If you use self-report questionnaires, which do you currently use?

- ☐ RESTQ
- ☐ DALDA
- ☐ TQR
- ☐ POMS
- ☐ Custom designed forms
- ☐ Other (please specify)

20. If applicable, which type of performance test(s) do you use to monitor fatigue/recovery?

- ☐ Submaximal running/cycling test
- ☐ Jump tests
- ☐ Strength tests
- ☐ Overground sprint tests

- ☐ Sport specific test protocol
- ☐ None of the above
- ☐ Other (please specify)

21. When an athlete is identified as being fatigued, how do you modify their training?

- ☐ Prescribe fewer training sessions
- ☐ Modify the length/intensity of prescribed sessions
- ☐ Make recommendations to the head coach that training load be reduced
- ☐ Prescribe extra recovery sessions
- ☐ Other (please specify)

22. Do you modify training based only on individual fatigue responses or do you also look at the team/squad trends?

- ☐ Only individual trends
- ☐ A mixture of team/squad and individual trends
- ☐ Team/squad trends only
- ☐ Not applicable, I only monitor individual athletes
- ☐ Other (please specify)

PART D - Thank you and Follow-up

Thank you once again for taking the time to answer the above questions.

Would you agree to be contacted for a follow-up telephone call regarding your responses?

- ☐ No
- ☐ Yes via telephone
- ☐ Yes via email

If you answered yes, please supply your name, organisation and the most convenient contact telephone number or email address below.

REFERENCES

1. Abiss, C. & Laursen, P. Is part of the mystery surrounding fatigue complicated by context? **Journal of Science and Medicine in Sport**. 10: 277-279. 2007.
2. Achten, J. & Jeukendrup, A. Heart rate monitoring. Applications and Limitations. **Sports Medicine**. 33: 517-538. 2003.
3. Andersson, H., Raastad, T., Nilsson, J., Paulsen, G., Garthe, I., & Kadi, F. Neuromuscular fatigue and recovery in elite female soccer: effects of active recovery. **Medicine and Science in Sports and Exercise**. 40: 372-380. 2008.
4. Bishop, P., Jones, E., & Woods, K. Recovery from training: a brief review. **Journal of Strength and Conditioning Research**. 22: 1015-1024. 2008.
5. Borresen, J. & Lambert, M. Autonomic control of heart rate during and after exercise. **Sports Medicine**. 38: 633-646. 2008.
6. Bosquet, L., Merkari, S., Arvisais, D., & Aubert, A. Is heart rate monitoring a convenient tool to monitor over-reaching? A systematic review of the literature. **British Journal of Sports Medicine**. 42: 709-714. 2008.
7. Bresciani, G., Cuevas, M., Molinero, O., Almar, M., Suay, F., Salvador, A., De Paz, J., Marquez, S., & Gonzalez-Gallego, J. Signs of overload after an intensified training. **International Journal of Sports Medicine**. 32: 338-343. 2011.
8. Byrne, C. & Eston, R. The effect of exercise-induced muscle damage on isometric and dynamic knee extensor strength and vertical jump performance. **Journal of Sports Sciences**. 20: 417-425. 2002.
9. Callister, R., Callister, R., Fleck, S., & Dudley, G. Physiological and performance responses to overtraining in elite judo athletes. **Medicine and Science in Sports and Exercise**. 22: 816-824. 1990.
10. Cormack, S., Newton, R., & McGuigan, M. Neuromuscular and endocrine responses of elite players to an Australian Rules Football match. **International Journal of Sports Physiology and Performance**. 3: 359-374. 2008.
11. Cormack, S., Newton, R., McGuigan, M., & Cormie, P. Neuromuscular and endocrine responses of elite players during an Australian Rules Football season. **International Journal of Sports Physiology and Performance**. 3: 439-453. 2008.
12. Cormie, P., Mccauley, G., Triplett, T., & McBride, J. Optimal Loading for maximal power output during lower-body resistance exercises. **Medicine and Science in Sports and Exercise**. 39: 340-349. 2007.
13. Coutts, A. & Reaburn, P. Monitoring changes in rugby league players' perceived stress and recovery during intensified training. **Perceptual and Motor Skills**. 106: 904-916. 2008.
14. Coutts, A., Reaburn, P., Piva, T., & Murphy, A. Changes in selected biochemical, muscular strength, power, and endurance measures during deliberate overreaching and tapering in rugby league players. **International Journal of Sports Medicine**. 28: 116-124. 2007.
15. Coutts, A., Reaburn, P., Piva, T., & Rowsell, G. Monitoring overreaching in rugby league players. **European Journal of Applied Physiology**. 99: 313-324. 2007.
16. Dugan, E., Doyle, T., Humphries, B., Hasson, C., & Newton, R. Determining the optimal load for jump squats: a review of methods and calculations. **Journal of Strength and Conditioning Research**. 18: 668-674. 2004.
17. Edwards, R. Human muscle function and fatigue, in Human muscle fatigue: Physiological mechanisms, R. Porter and Whelen, J., eds. London. Pitman Medical, 1981. pp. 1-18.

18. Enoka, R. & Duchateau, J. Muscle function: what, why and how it influences muscle function. **Journal of Physiology (Lond)**. 586: 11-23. 2008.
19. Faude, O., Meyer, T., Urhausen, A., & Kindermann, W. Recovery training in cyclists: ergometric, hormonal and psychometric findings. **Scandinavian Journal of Medicine and Science in Sports**. 19: 433-441. 2009.
20. Fry, A., Kraemer, W., Lynch, J., Triplett, T., & Perry Koziris, L. Does short-term near-maximal intensity machine resistance training induce overtraining? **Journal of Strength and Conditioning Research**. 8: 188-191. 1994.
21. Girard, O., Lattier, G., Micaleff, J.-P., & Millet, G. Changes in exercise characteristics, maximal voluntary contraction, and explosive strength during prolonged tennis playing. **British Journal of Sports Medicine**. 40: 521-526. 2006.
22. Halson, S., Bridge, M., Meeusen, R., Busschaert, B., Gleeson, M., Jones, D., & Jeukendrup, A. Time course of performance changes and fatigue markers during intensified training in trained cyclists. **Journal of Applied Physiology**. 93: 947-956. 2002.
23. Halson, S. & Jeukendrup, A. Does overtraining exist? An analysis of overreaching and overtraining research. **Sports Medicine**. 34: 967-981. 2004.
24. Hamilton, D. Drop jumps as an indicator of neuromuscular fatigue and recovery in elite youth soccer athletes following tournament match play. **Journal of Australian Strength and Conditioning**. 17: 3-8. 2009.
25. Hoffman, J. & Kaminsky, M. Use of performance testing for monitoring overtraining in elite youth basketball players. **Strength and Conditioning Journal**. 22: 54-62. 2000.
26. Hopkins, W., Marshall, S., Batterham, A., & Hanin, J. Progressive statistics for studies in sports medicine and exercise science. **Medicine and Science in Sports and Exercise**. 41: 3-12. 2009.
27. Hortobagyi, T., Lambert, N., & Kroll, W. Voluntary and reflex responses to fatigue with stretch-shortening exercise. **Canadian Journal of Sport Science**. 16: 142-150. 1991.
28. Jürimäe, J., Mäestu, J., Purge, P., & Jürimäe, T. Changes in stress and recovery after heavy training in rowers. **Journal of Science and Medicine in Sport**. 7: 335-339. 2004.
29. Kellman, M. & Gunther, K. Changes in stress and recovery in elite rowers during preparation for the Olympic games. **Medicine and Science in Sports and Exercise**. 32: 676-683. 2000.
30. Kellman, M. & Kallus, W. **Recovery-Stress Questionnaire for Athletes**. Champaign, IL: Human Kinetics, 2001.
31. Knicker, A., Renshaw, I., Oldham, A., & Cairns, S. Interactive processes link the multiple symptoms of fatigue in sport competition. **Sports Medicine**. 41: 307-328. 2011.
32. Kraemer, W., Fry, A., Rubin, M., Triplett-Mcbride, T., Gordon, S., Koziris, L., Lynch, J., Volek, J., Meuffels, D., Newton, R., & Fleck, S. Physiological and performance responses to tournament wrestling. **Medicine and Science in Sports and Exercise**. 33: 1367-1378. 2001.
33. Kuipers, H. & Keizer, H. Overtraining in elite athletes. Review and directions for the future. **Sports Medicine**. 6: 79-92. 1988.
34. Lamberts, R. & Lambert, M. Day-to-day variation in heart rate at different levels of submaximal exertion: implications for monitoring training. **Journal of Strength and Conditioning Research**. 23: 1005-1010. 2009.
35. Lieberman, H., Kellogg, M., & Bathalon, G. Female marine recruit training: mood, body composition, and biochemical changes. **Medicine and Science in Sports and Exercise**. 40: S671-S676. 2008.
36. Mclean, B., Coutts, A., Kelly, V., McGuigan, M., & Cormack, S. Neuromuscular, endocrine, and perceptual fatigue responses during different length between-match microcycles in professional rugby league players. **International Journal of Sports Physiology and Performance**. 5: 367-383. 2010.
37. McNair, D., Lorr, M., & Dopplemann, L. **Profile of mood states manual**. San Diego: Educational and Industrial Testing Service, 1992.
38. Montgomery, P., Pyne, D., Cox, A., Hopkins, W., Minahan, C., & Hunt, P. Muscle damage, inflammation, and recovery interventions during a 3-day basketball tournament. **European Journal of Sport Science**. 8: 241-250. 2008.
39. Morgan, W., Brown, D., Raglin, J., O'connor, P., & Ellickson, K. Psychological monitoring of overtraining and staleness. **British Journal of Sports Medicine**. 21: 107-114. 1987.
40. Nindl, B., Leone, C., Tharion, W., Johnson, R., Castellani, J., Patton, J., & Montain, S. Physical performance responses to 72 h of military operational stress. **Medicine and Science in Sports and Exercise**. 34: 1814-1822. 2002.
41. Nosaka, K., Abbiss, C., Watson, G., Wall, B., Suzuki, K., & Laursen, P. Recovery following an Ironman triathlon: A case study. **European Journal of Sport Science**. 10: 169-165. 2010.
42. Raglin, J., Kocaja, D., Stager, J., & Harms, C. Mood, neuromuscular function, and performance during training in female swimmers. **Medicine and Science in Sports and Exercise**. 28: 372-377. 1996.
43. Robson-Ansley, P., Gleeson, M., & Ansley, L. Fatigue management in the preparation of Olympic athletes. **Journal of Sports Sciences**. 27: 1409-1420. 2009.
44. Ronglan, L., Raastad, T., & Borgeson, A. Neuromuscular fatigue and recovery in elite female handball players. **Scandinavian Journal of Medicine and Science in Sports**. 16: 267-273. 2006.
45. Sheppard, J., Cormack, S., Taylor, K., McGuigan, M., & Newton, R. Assessing the force-velocity characteristics of the leg extensors in well-trained athletes: The incremental load power profile. **Journal of Strength and Conditioning Research**. 22: 1320-1326. 2008.
46. Sheppard, J., Hobson, S., Barker, M., Taylor, K., Chapman, D., McGuigan, M., & Newton, R. The effect of training with accentuated eccentric load counter-movement jumps on strength and power characteristics of high-performance volleyball players. **International Journal of Sports Science and Coaching**. 3: 355-363. 2008.
47. Thorlund, J., Michalsik, L., Madsen, K., & Aagaard, P. Acute fatigue-induced changes in muscle mechanical properties and neuromuscular activity in elite handball players following a handball match. **Scandinavian Journal of Medicine and Science in Sports**. 18: 462-472. 2008.
48. Thuma, J., Gilders, R., Verdun, M., & Loucks, A. Circadian rhythm of cortisol confounds cortisol responses to exercise: implications for future research. **Journal of Applied Physiology**. 78: 1657-1664. 1995.
49. Urhausen, A., Gabriel, H., & Kindermann, W. Blood hormones as markers of training stress and overtraining. **Sports Medicine**. 20: 251-276. 1995.
50. Urhausen, A. & Kindermann, W. Biochemical monitoring of training. **Clinical Journal of Sport Medicine**. 2: 52-61. 1992.
51. Urhausen, A. & Kindermann, W. Diagnosis of overtraining. What tools do we have? **Sports Medicine**. 32: 95-102. 2002.
52. Viru, A. & Viru, M. **Biochemical Monitoring of Sport Training**: Human Kinetics Publishers, 2001.
53. Welsh, T., Alemany, J., Montain, S., Frykman, P., Tuckow, A., Young, A., & Nindl, B. Effects of intensified military field training in jumping performance. **International Journal of Sports Medicine**. 29: 45-52. 2008.

Sources of Variability in Iso-Inertial Jump Assessments

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Purpose: This investigation aimed to quantify the typical variation for kinetic and kinematic variables measured during loaded jump squats. **Methods:** Thirteen professional athletes performed six maximal effort countermovement jumps on four occasions. Testing occurred over 2 d, twice per day (8 AM and 2 PM) separated by 7 d, with the same procedures replicated on each occasion. Jump height, peak power (PP), relative peak power (RPP), mean power (MP), peak velocity (PV), peak force (PF), mean force (MF), and peak rate of force development (RFD) measurements were obtained from a linear optical encoder attached to a 40 kg barbell. **Results:** A diurnal variation in performance was observed with afternoon values displaying an average increase of 1.5–5.6% for PP, RPP, MP, PV, PF, and MF when compared with morning values (effect sizes ranging from 0.2–0.5). Day to day reliability was estimated by comparing the morning trials (AM reliability) and the afternoon trials (PM reliability). In both AM and PM conditions, all variables except RFD demonstrated coefficients of variations ranging between 0.8–6.2%. However, for a number of variables (RPP, MP, PV and height), AM reliability was substantially better than PM. PF and MF were the only variables to exhibit a coefficient of variation less than the smallest worthwhile change in both conditions. **Discussion:** Results suggest that power output and associated variables exhibit a diurnal rhythm, with improved performance in the afternoon. Morning testing may be preferable when practitioners are seeking to conduct regular monitoring of an athlete's performance due to smaller variability.

Keywords: reliability, smallest worthwhile change, athlete monitoring, diurnal variation, power, training readiness

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The measurement of kinetic and kinematic variables during instrumented vertical jumps are commonly used to examine training effects after various short-term interventions^{1,2} and, more recently, to gain insight into an athlete's state of neuromuscular fatigue via monitoring of performance during intensified training or competition.³⁻⁵ In the regular training environment, especially in high performance sport where training loads are characteristically high, such tests may be useful for coaches and support staff by providing an objective method to assess an athlete's response to training and their recovery between sessions or competitions. However, in order to make informed decisions regarding changes in performance, it is critical that the typical variation or repeatability of the test be known. In this regard, the observation of meaningful changes in performance is reliant on knowing whether the observed change is outside of the variation that can be expected to occur by chance, or due to normal variation in the outcome variable. It follows that the more reliable the measurement is, the easier it will be to quantify real changes in performance.^{6,7}

To enable the estimation of such values, it is necessary to conduct a reliability study using test-retest procedures, where repeated measures are taken from a group of subjects over a time period that is similar to the planned duration between testing sessions.⁷ While a number of authors have established acceptable reliability of loaded and unloaded jump squats and associated kinetic and kinematic variables, comprehensive analyses of variability in athletic populations is limited. Cronin et al⁸ and Hori et al⁹ have reported trial-to-trial reliability, analyzing the change in performance between two consecutive trials, using unloaded and loaded (40 kg) countermovement jumps (CMJ) respectively. Cronin et al⁸ reported acceptable reliability for force related measures (mean force, peak force and time to peak force), using a linear position transducer (LPT) and a force plate with coefficient of variation (CV) values between 2.1 and 7.4%. Hori et al⁹ also reported acceptable trial-to-trial reliability for peak velocity, peak force, peak power and mean power using a variety of measurement devices (LPT, force plate and LPT + force plate), with CVs ranging from 1.2 to 11.1%. Sheppard et al¹⁰ and Cormack et al¹¹ have evaluated the short-term (week-to-week) reproducibility of the CMJ and reported acceptable reliability for a range of variables, with CV values between 2.8 to 9.5%. These studies have presented reliability statistics based on either a single CMJ trial repeated one week apart,¹¹ or three single trials performed seven days apart, where the best trial from each testing session was used in the analysis.¹⁰ While previous work has provided useful information to practitioners in regard to equipment and dependent variable selection, a comprehensive understanding of the typical variation of each of the variables available during instrumented jumps, and the appropriate testing methodologies, requires further investigation.

Cormack et al¹¹ have been the only researchers to consider the reliability statistics in relation to what is considered the smallest worthwhile effect on performance. The smallest worthwhile change (SWC), which is analogous to the minimum clinically important difference in the clinical sciences, is described as the smallest effect or change in performance that is considered practically meaningful.¹² For tests or measurements of athletic performance to be useful in detecting the SWC, the error associated with the measurement needs to be minimal, and ideally less than the SWC.¹³ Hence for the valid interpretation of reliability outcomes, an in-depth analysis of typical variation needs to take into account the relationship between the typical variation of a measurement and the smallest effect that is considered

important, or practically meaningful. Previous research has not addressed this in relation to kinetic and kinematic variables measured via instrumented jumps.

The final consideration is differences between measurements performed on the same day. It has been previously shown that a diurnal variation in maximal neuromuscular performance exists, with findings generally exhibiting morning nadirs and afternoon maximum values^{14–19} indicating that neuromuscular capabilities are influenced by time of day. While authors have typically ensured that time of day was standardized within subjects, the potential differences in typical variation when testing is conducted at differing times of day has not been examined (ie, time of day was generally not standardized between subjects). Hence, along with examining time of day differences in neuromuscular performance, it may also be appropriate to examine loaded CMJs for differences in variability, or reproducibility, between morning and afternoon testing sessions. The present study aimed to (i) evaluate the time of day effect on jump performance and associated kinetic and kinematic variables, (ii) to comprehensively evaluate the reproducibility/variability in performance of highly trained athletes familiar with the testing procedures and (iii) to establish which variables are useful in detecting the smallest worthwhile change in performance.

Methods

Design

To examine the effect of time of day on jump performance, subjects performed six loaded CMJs in the morning (AM; 0800–0900) and afternoon (PM; 1400–1500) after a standardized warm-up. Based on pilot testing, the six jumps were divided into two sets of three, where athletes rested for 2–3 min between sets, to avoid any fatiguing effects across consecutive jumps. Differences in performance between AM and PM sessions were compared using within-subject statistical procedures. All subjects repeated the same procedures 7 d later, to examine differences in intersession reliability between testing conditions (AM and PM).

Subjects

Thirteen professional male rugby union players (mean \pm SD: age 23.7 ± 2.7 y, height 1.86 ± 0.10 m, weight 103.8 ± 10.7 kg) participated in this study as part of their regular preseason training regime. All subjects were free from injury and were highly familiar with the performance test requirements. Written informed consent was obtained from all participants and testing procedures were approved by the Australian Institute of Sport ethics committee.

Procedures

Before each testing session subjects performed a 10 min dynamic warm-up consisting of general whole body movements emphasizing an increase in range of movement, a variety of running patterns and four sets of three practice jumps. Subjects were required to progressively increase the intensity of the exercises until the end of the warm-up period until they felt they were capable of maximal performance.

Jump assessments consisted of each subject performing a CMJ with a load of 20 kg on an Olympic lifting bar (ie, total load of 40 kg), a protocol that has been used extensively with this, and similar populations. The subject stood erect with the bar positioned across his shoulders and was instructed to jump for maximal height while keeping constant downward pressure on the barbell to prevent the bar moving independently of the body. Each subject performed three repetitions, pausing for approx. 3–5 s between each jump. Subjects then rested for 2–3 min before repeating a second set of three jumps. No attempts were made to standardize the starting position, amplitude, or rate of the countermovement. A displacement-time curve for each jump was obtained by attaching a digital optical encoder via a cable (GymAware Power Tool. Kinetic Performance Technologies, Canberra, Australia) to one side of the barbell. This system recorded displacement-time data using a signal driven sampling scheme²⁰ where position points were time-stamped when a change in position was detected, with time between samples limited to a minimum of 20 ms. The first and second derivative of position with respect to time was taken to calculate instantaneous velocity and acceleration respectively. Acceleration values were multiplied by the system mass to calculate force, and the given force curve multiplied by the velocity curve to determine power. Mean values for force (mean force; MF) and power (mean power; MP) were calculated over the concentric portion of the movement and peak values for velocity (peak velocity; PV), force (peak force; PF) power (peak power; PP) and relative power (relative peak power; RPP) were also derived from each of the curves. Jump height was determined as the highest point on the displacement-time curve.

Statistical Analysis

Means and standard deviations (SD) were computed for the kinetic and kinematic variables in the AM and PM conditions for Weeks 1 and 2 independently. Thereafter intraday analyses examining the diurnal effect were conducted using the mean values of six trials from the AM and PM sessions by averaging Weeks 1 and 2 (mean diurnal response). To examine the AM to PM differences in performance, effects were calculated as the mean difference divided by the pooled between-subject SD, and were characterized for their practical significance using the criteria suggested by Rhea²¹ for highly trained participants as follows: <0.25 = trivial, 0.25 – 0.50 = small, 0.51 – 1.0 = moderate, and >1.0 = large. In addition, a substantial performance change was accepted when there was more than a 75% likelihood that the true value of the standardized mean difference was greater than the smallest worthwhile (substantial) effect.²² Thresholds for assigning the qualitative terms to chances of substantial effects were: $<1\%$, almost certainly not; $<5\%$, very unlikely; $<25\%$ unlikely; 25 – 75% , possibly; $>75\%$ likely; $>95\%$ very likely; and $>99\%$ almost certain. The smallest worthwhile effect on performance or SWC from test to test was established as a “small” effect size ($0.25 \times$ between-participant SD) according to methods outlined previously.⁷

When investigating reliability Hopkins⁷ has recommended that the systematic change in the mean, as well as measures of absolute and relative consistency (ie, within-subject variation and retest correlations respectively) be reported. Systematic changes in the mean from AM to AM and PM to PM were examined via the procedures described above for examining the diurnal response. The absolute reliability

or typical within-subject variation was quantified via the CV (%). For trial-to-trial reliability this was calculated as $\sqrt{(\sum SD^2/n)}$, where SD equals the standard deviation for each individual across the six trials, and n is the number of subjects. This value was then divided by $\sqrt{6}$ to give the estimated error in the mean of six trials, which represents the variation in the mean if the six trials were to be repeated without any intervening effects. The AM to PM reliability, calculated as the mean change in AM to PM performance on the same day, was quantified as the SD of the change scores divided by $\sqrt{2}$. Week-to-week reliability was calculated using the same formula, based on the change scores from Week 1 to Week 2 for the two morning trials (AM reliability) and then the two afternoon trials (PM reliability). To examine the influence of the number of trials on the reliability outcomes, we calculated the week-to-week CV using the first trial from Week 1 and Week 2, the mean of trial 1 and 2, the mean of trials 1–3, the mean of trials 1–4 and so on.

Results

Performance characteristics across the AM and PM sessions are presented in Table 1. No substantial systematic change was observed in any variable across the six trials, indicating that learning effects and fatigue did not affect the results within each session. Figure 1 illustrates the mean changes for the AM-PM trials, AM-AM trials, and the PM-PM trials. Small to moderate time of day effects were observed for PP, RPP, MP, PV, PF and jump height, with a mean diurnal response of 4.3–6.1% (Figure 1A). No substantial changes in the mean were observed from week to week in either the AM or PM conditions (Figure 1B and 1C).

Reliability estimates based on the variation within a single session, between sessions within the same day (AM to PM), and from week-to-week are presented in Table 2. Trial-to-trial reliability was good for all variables (range = 1.4–7.7%)

Table 1 Mean ± SD for kinetic and kinematic variables measured during 40 kg CMJ. Results were calculated using the mean of six trials during each session and averaged for Week 1 and Week 2.

Variable	AM	PM
Peak Power (W)	5457 ± 453	5719 ± 424
RPP (W/kg)	53.1 ± 7.8	55.8 ± 8.4
Mean Power (W)	2347 ± 225	2451 ± 189
Peak Velocity (m/s)	2.53 ± 0.17	2.60 ± 0.19
Peak Force (N)	3015 ± 375	3116 ± 363
Mean Force (N)	1435 ± 105	1433 ± 111
Jump Height (cm)	28.9 ± 3.7	30.2 ± 5.5
RFD (kN/s)	20.9 ± 7.7	21.7 ± 8.0

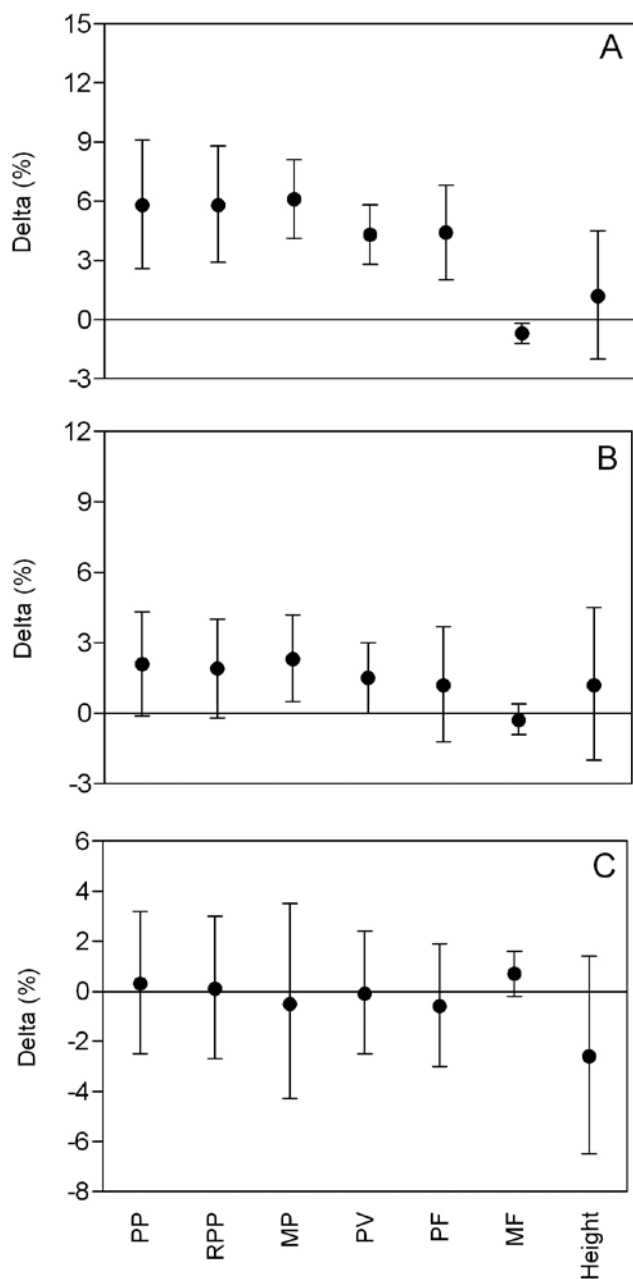


Figure 1 — Mean changes in performance \pm 90% confidence limits for peak power (PP), relative peak power (RPP), mean power (MP), peak velocity (PV), peak force (PF), mean force (MF), jump height (Height). (A) mean change in performance from AM to PM (average of trials for week 1 and 2); (B) mean change in performance from week 1 to week 2 for AM trials; (C) mean change in performance from week 1 to week 2 for PM trials.

Table 2 Coefficients of variation (CV) representing the expected variation from trial-to-trial; for the mean of six trials within a session; between AM and PM sessions; and for the mean of six trials between sessions conducted 1 wk apart. Smallest worthwhile change (SWC) values are also presented for comparisons with the estimates of typical variation.

Variable	Trial-to-trial CV (%) within a session		CV (%) of the mean of the six trials		Within-day CV (%)		Week-to-Week CV (%)		SWC (%)
	AM	PM	AM	PM			AM	PM	
Peak Power	5.5	5.2	2.3	2.1	3.4		2.5	3.4	2.4
RPP	5.6	5.2	2.3	2.1	3.4		2.4	3.4	3.9
Mean Power	5.3	5.0	2.2	2.0	2.9		2.1	4.7	2.5
Peak Velocity	2.6	2.8	1.1	1.1	2.3		1.7	2.9	1.9
Peak Force	5.5	5.3	2.2	2.2	2.7		2.9	2.9	3.2
Mean Force	1.5	1.4	0.6	0.6	0.8		0.8	1.0	1.9
Height	7.0	7.7	2.9	3.2	6.6		4.3	6.2	4.3
RFD	39.4	32.5	16.1	13.3	15.5		22.5	25.9	10.8

except RFD. The reliability based on the mean of six trials was very high, with CVs less than 3.2% for all variables except RFD (13.3–16.6%). In addition to exhibiting excellent absolute reliability, PP, RPP, MP, PV, PF and height yielded typical variation scores less than the SWC.

When the mean of the six trials were used to examine week-to-week test-retest reliability a similar pattern emerged with all variables except RFD exhibiting high reliability coefficients (range = 0.8–6.2%). Only height in the PM condition had a CV exceeding 5%. However, while such values would generally be considered to represent excellent reliability, PP, PF and MF were the only variables where the typical variation was less than the SWC in both conditions. A number of variables (RPP, MP, PV and height) demonstrated CV < SWC in the AM condition only.

Along with changes in AM and PM performance, substantial differences in reliability were observed for a number of variables across the AM and PM conditions (Table 2). Based on the analysis, it is likely to very likely (ie, > 75% likelihood) that the week-to-week variability in the PM sessions was greater than the variability in the AM sessions for RPP, MP and PV. It was unclear if there were substantial differences in variability between AM and PM for all other variables.

Figure 2 illustrates the differences in AM and PM reliability, along with differences in the estimated typical variation as the number of trials included in the analysis increased. For PP, RPP, MP and PV it is evident that PM variability is greater than AM variability, and as the number of trials included in the analysis was increased, the typical week-to-week variation was reduced. A contrasting result was observed for PF with AM variability greater than PM variability. In addition the low variability achieved for PF in the PM session was not noticeably reduced as more trials were included. For MF, which demonstrated the lowest variability in all analyses, AM and PM reliability was similar, and both varied very little with the inclusion of additional trials. Similarly the variability for height between the two PM sessions was minimally reduced when a single trial was compared with the mean of 6 trials (6.2% and 4.8% respectively). RFD displayed trends similar to PP, RPP, MP and PV (ie, greater PM variability and greater reliability with increased trials); however, the CVs are greater than what can be considered of practical value (range = 23 to 37%).

Discussion

To confidently estimate true maximal athletic capacities, and assess real and meaningful changes in performance a greater understanding of how variables are expected to vary both within and between testing sessions is needed. Authors have often reported acceptable reliability for force and power related variables during CMJs, with within-subject variability coefficients ranging from 1.2 to 11.1%.^{8–11,23} Our findings were similar for a number of variables, with all variables except RFD producing CVs between 0.8 and 6.2%, for trial-to-trial and week-to-week reliability. The novelty of our statistical analysis demonstrates that the variability associated with the time of day that testing is performed affects the extent of variation inherent in performance. In addition we have shown that while most variables demonstrated “acceptable” reliability, the relationship between the CV and the SWC signifies that limited variables are capable of detecting practically important changes in performance.

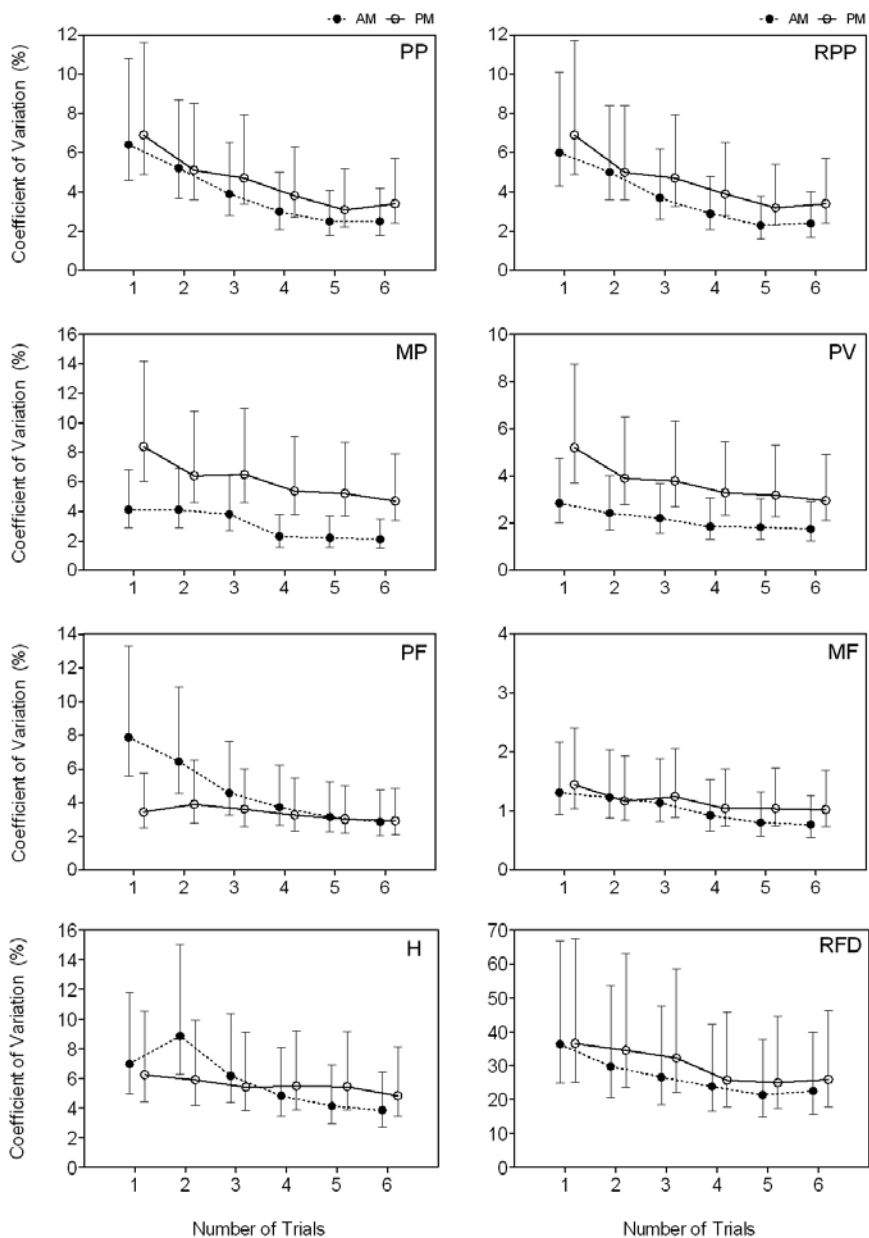


Figure 2 — Mean coefficients of variation \pm 90% confidence limits of for peak power (PP), relative peak power (RPP), mean power (MP), peak velocity (PV), peak force (PF), mean force (MF), jump height (H) and peak rate of force development (RFD) based on the time of day (AM or PM) and the number of trials performed.

It is important to recognize that while both trial-to-trial and short-term (week-to-week) reliability are important, in the context of athletic assessment they serve different purposes. The error estimate associated with trial-to-trial reliability can be attributed to random measurement error, as there is little scope for biological changes.⁷ This value assists the practitioner in estimating the amount of error likely to occur around a single measurement within a single session, thus allowing for an accurate estimation of the true likely range of the outcome variable. Our results indicate that if a single trial protocol is used, the practitioner can expect an approximate 4–8% error for most kinetic and kinematic variables (the error associated with MF was lower at approx. 1.5%, while RFD demonstrated considerably greater random error, ranging from 32 to 40%). When a six-trial protocol was used, the error rate was reduced for all variables, and the variability from trial-to-trial was estimated between 1.1–3.2%; RFD, however, still remained high at approx. 13–16%. Thus the inclusion of six trials in the analysis demonstrated the error associated with each trial was approx. 1–3%, which is similar to the 2–3% reported by Cronin et al⁸ but substantially less than Hori et al⁹ who reported variations of 9.0–11.1% for PF, PP and MP.

When the purpose of testing is to monitor an athlete's response to training and their recovery between sessions or weekly competitions, the focus is on the short-term variability. Such short-term variability includes the random measurement error plus associated "normal" or biological variation that occurs over time. This type of reliability is most commonly reported and is useful for estimating the magnitude of error associated with test-retest designs, where subjects are tested before and after an intervention, or when performance tests are used for regular athlete monitoring. Our results indicate that when testing was repeated 7 d later, additional biological error was present for all variables. For example, PP demonstrated a typical trial-to-trial error of approx. 2%, which increased to approx. 3.5% when week-to-week variability was included. While no previous studies have examined week-to-week reliability using similar instrumentation, the range of 0.8–6.2% would satisfy the criteria for acceptable reliability reported in the literature.

Although there is no preset standard for acceptable CV values, many researchers have set a criteria of <10% for "good" reliability.^{6,10,11} Upon meeting this requirement, authors have generally recommended that their test protocols can be used to confidently assess changes in a range of neuromuscular parameters. However, knowing that a change is "real" (ie, outside of the expected measurement error), does not provide the practitioner with information regarding the meaningfulness of the change. To identify meaningful or worthwhile changes in performance, knowledge of the SWC is needed.¹² It has been suggested that if the typical variation (CV) of a test or variable is less than the SWC, then the test/variable is rated as "good," while a variable with a CV that is considerably greater than the SWC would signify marginal practicality of that variable.¹³ Previously, only Cormack et al¹¹ compared their reported reliability estimates to what was considered the SWC in performance, and while they reported CVs less than their criterion of 10% for a large number of variables, only MF had a typical variation less than the SWC. In our analysis, only MF and PF demonstrated CV < SWC in both AM and PM conditions. While all variables other than RFD easily met the normally accepted criterion of <10%, they were generally not capable of detecting the SWC. Exceptions to this included the AM reliability values for RPP (CV = 2.4%; SWC = 3.9%), MP (CV = 2.1%; SWC = 2.5%) and PV (CV = 1.7%; SWC = 1.9%). Therefore, when implementing a testing program to monitor changes

in neuromuscular performance characteristics, our results suggest that MF and PF would be the most useful variables to monitor. However, confounding issues remain, since it is possible that the most reliable tests are not necessarily the most effective for monitoring performance in athletes.²⁴ When using an assessment of neuromuscular performance to predict changes in performance readiness in team sports, or as an indicator of fatigue, it is important to also consider the relationship of the variable to successful performance. Although MF is very reliable, its stable nature may also mean that it is not able to effectively discriminate between positive and negative performance outcomes. While this is yet to be investigated, preliminary findings by the current authors suggest that even during periods of highly stressful training and competition, MF only tends to fluctuate by approximately 1%. In addition, previous research examining the relationship between kinetic and kinematic variables and dynamic strength tests²⁵ and sprint performance,²⁶ have not identified MF as an important predictor of successful performance. While MF was not included in these previous analyses, PP, MP and PF relative to body mass were reported to be strong predictors of performance.^{25–28} Therefore researchers require the development of methods that allow for other variables that are more informative (ie, a stronger relationship to competitive performance) to be capable of detecting the SWC. This can only be achieved by reducing the typical variation associated with the practiced testing methodologies.

To investigate means for reducing the typical variation, we examined the effect of trial size on the week-to-week variability. Though it is well known that increasing the number of trials from which the reliability statistics are generated reduces the noise associated with the test, the number of trials before the error is reduced to an acceptable level is not well documented. Our results indicate that the inclusion of additional trials (up to six) improved the reliability of PP and RPP by 4–5%. The differences in reliability from the analysis of one to six trials were also practically significant for MP, PV and PF (approx. 1–4%). These findings suggest that the typical variation from week-to-week can be improved by using the average of six trials, rather than a single trial protocol. Numerous other studies have strongly suggested that multiple trial protocols are necessary for obtaining stable results in the assessment of lower limb function in a variety of activities.^{29–31} For example, Rodano and Squadrone³⁰ reported that a 12 trial protocol was needed for establishing stable results for power outputs of the ankle, knee and hip joints during vertical jumping. James et al³¹ indicated that a minimum of four and possibly as many as eight trials should be performed to achieve performance stability of selected ground reaction force variables during landing experiments. We capped the number of trials in our study at six (2 sets \times 3 repetitions) as we considered this a viable number when using such a protocol as a weekly monitoring tool with a large squad of players. By using the average of additional trials, it may be possible to reduce the error further; however, it is felt such a protocol would have limited feasibility in the regular training environment of high performance athletes.

Interestingly we found that AM variability was lower than PM variability for a number of variables (Table 1), which has important implications when the magnitude of variability is compared with SWC. For RPP, MP, PV and height, greater variability in the PM sessions meant that they were rejected on the basis that the estimated typical error was greater than the signal we are interested in measuring (ie, $CV > SWC$). That is, while the $CV < SWC$ in the AM condition, indicating that the variables were in fact capable of detecting worthwhile changes in performance, the

PM condition did not satisfy this criteria. Hence, since greater variability is present when testing was conducted in the afternoon, it appears that it may be more difficult to identify worthwhile changes in performance and therefore limit the utility of such assessments for monitoring training readiness and recovery between sessions.

Practical Applications

Practitioners seeking to conduct regular monitoring of an athlete's performance are recommended to standardize the time of day that assessments occur. If maximal performance is paramount, then afternoon testing is likely to produce better results. However, if monitoring small changes in performance, changes may be more confidently observed if testing occurs in the morning due to smaller week-to-week variability. The use of an optical-encoder to measure a range of kinetic and kinematic variables during CMJs has been shown to be effective for monitoring practical changes in MF and PF, but less practical for monitoring small but meaningful changes in power, velocity and jump height. RFD was shown to be unreliable and cannot be used to confidently assess changes in neuromuscular status. Although MF and PF were the only variables to demonstrate CV less than the SWC, other variables with acceptable reliability may be more related to performance, or have greater sensitivity to change, and require further investigation. Increasing the number of trials included in the analysis is one way to reduce the typical variation in kinetic and kinematic variables and enhances their utility in monitoring small but practical changes in performance across a training week.

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References

1. Adams K, O'Shea J, O'Shea K, Climstein M. The effect of six weeks of squat, plyometric and squat-plyometric training on power production. *J Appl Sport Sci Res.* 1992;6:36–41.
2. McBride J, Triplett-McBride T, Davie A, Newton R. The effect of heavy-vs. light-load jump squats on the development of strength, power, and speed. *J Strength Cond Res.* 2002;16:75–82.
3. Welsh T, Alemany J, Montain S, et al. Effects of intensified military field training in jumping performance. *Int J Sports Med.* 2008;29:45–52.
4. Cormack S, Newton R, McGuigan M. Neuromuscular and endocrine responses of elite players to an Australian Rules Football match. *Int J Sports Physiol Perform.* 2008;3:359–374.
5. Ronglan L, Raastad T, Borgeson A. Neuromuscular fatigue and recovery in elite female handball players. *Scand J Med Sci Sports.* 2006;16:267–273.
6. Atkinson G, Nevill A. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Med.* 1998;26:217–238.
7. Hopkins W. Measures of reliability in sports medicine and science. *Sports Med.* 2000;30:1–15.
8. Cronin J, Hing R, McNair P. Reliability and validity of a linear position transducer for measuring jump performance. *J Strength Cond Res.* 2004;18:590–593.

9. Hori N, Newton R, Andrews W, Kawamori N, McGuigan M, Nosaka K. Comparison of four different methods to measure power output during the hang power clean and the weighted jump squat. *J Strength Cond Res.* 2007;21:314–320.
10. Sheppard J, Cormack S, Taylor K, McGuigan M, Newton R. Assessing the force-velocity characteristics of the leg extensors in well-trained athletes: The incremental load power profile. *J Strength Cond Res.* 2008;22:1320–1326.
11. Cormack S, Newton R, McGuigan M, Doyle T. Reliability of measures obtained during single and repeated countermovement jumps. *Int J Sports Physiol Perform.* 2008;3:131–144.
12. Hopkins W, Hawley J, Burke L. Design and analysis of research on sport performance enhancement. *Med Sci Sports Exerc.* 1999;31:472–485.
13. Pyne D. Interpreting the results of fitness testing. in *International Science and Football Symposium.* 2003: Victorian Institute of Sport.
14. Martin A, Carpentier A, Guissard N, van Hoecke J, Duchateau J. Effect of time of day on force variation in human muscle. *Muscle Nerve.* 1999;10:1380–1387.
15. Sedlak M, Finni T, Cheng S, Haikarainen T, Hakkinen K. Diurnal variation in maximal and submaximal strength, power and neural activation of leg extensors in men: Multiple sampling across two consecutive days. *Int J Sports Med.* 2008;29:217–224.
16. Coldwells A, Atkinson G, Reilly T. Sources of variation in back and leg dynamometry. *Ergonomics.* 1994;37:79–86.
17. Gauthier A, Davenne D, Martin A, Hoecke JV. Time of day effects on isometric and isokinetic torque developed during elbow flexion in humans. *Eur J Appl Physiol.* 2001;84:249–252.
18. Wyse J, Mercer T, Gleeson N. Time-of-day dependence of isokinetic leg strength and associated interday variability. *Br J Sports Med.* 1994;28:167–170.
19. Racinais S, Hue O, Blonc S. Time-of-day effects on anaerobic muscular power in a moderately warm environment. *Chronobiol Int.* 2004;21:485–495.
20. Qaisar S, Fesquet L, Renaudin M. Adaptive rate sampling and filtering based on level crossing sampling. *EURASIP Journal on Advances in Signal Processing.* 2009;7:1-12.
21. Rhea M. Determining the magnitude of treatment effects in strength training research through the use of the effect size. *J Strength Cond Res.* 2004;18:918–920.
22. Hopkins W (2002) Probabilities of clinical or practical significance. *Sportscience 6* sports. sports.org/jour/0201/wghprob.htm.
23. Chiu L, Schilling B, Fry A, Weiss L. Measurement of resistance exercise force expression. *J Appl Biomech.* 2004;20:204–212.
24. Hopkins W, Schabert E, Hawley J. Reliability of power in physical performance tests. *Sports Med.* 2001;31:211–234.
25. Nuzzo J, McBride J, Cormie P, McCaulley G. Relationship between countermovement jump performance and multi-joint isometric and dynamic tests of strength. *J Strength Cond Res.* 2008;22:699–707.
26. Harris N, Cronin J, Hopkins W, Hansen K. Relationship between sprint times and the strength/power outputs of a machine squat jump. *J Strength Cond Res.* 2008;22:691–698.
27. Dowling J, Vámos L. Identification of kinetic and temporal factors related to vertical jump performance. *J Appl Biomech.* 1993;9:95–110.
28. Maulder P, Bradshaw E, Keogh J. Jump kinetic determinants of sprint acceleration performance from starting blocks in male sprinters. *J Sports Sci Med.* 2006;5:359–366.
29. Hamill J, McNiven S. Reliability of selected ground reaction force parameters during walking. *Hum Mov Sci.* 1990;9:117–131.
30. Rodano R, Squadrone R. Stability of selected lower limb joint kinetic parameters during vertical jump. *J Appl Biomech.* 2002;18:83–89.
31. James CR, Herman JA, Dufek JS, Bates BT. Number of trials necessary to achieve performance stability of selected ground reaction force variables during landing. *J Sports Sci Med.* 2007;6:126–134.

Warm-Up Affects Diurnal Variation in Power Output

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Key words

- body temperature
- counter-movement jump
- assessment
- monitoring

Abstract



The purpose of this study was to examine whether time of day variations in power output can be accounted for by the diurnal fluctuations exist-ent in body temperature. 8 recreationally trained males (29.8 ± 5.2 yrs; 178.3 ± 5.2 cm; 80.3 ± 6.5 kg) were assessed on 4 occasions following a: (a) control warm-up at 8.00 am; (b) control warm-up at 4.00 pm; (c) extended warm-up at 8.00 am; and, (d) extended warm-up at 4.00 pm. The control warm-up consisted of dynamic exercises and practice jumps. The extended warm-up incorporated a 20 min general warm-up on a stationary bike prior to completion of the control warm-up, resulting in a whole body

temperature increase of $0.3 \pm 0.2^\circ\text{C}$. Kinetic and kinematic variables were measured using a linear optical encoder attached to a barbell during 6 loaded counter-movement jumps. Results were 2–6% higher in the afternoon control condition than morning control condition. No substantial performance differences were observed between the extended morning condition and afternoon control condition where body temperatures were similar. Results indicate that diurnal variation in whole body temperature may explain diurnal performance differences in explosive power output and associated variables. It is suggested that warm-up protocols designed to increase body temperature are beneficial in reducing diurnal differences in jump performance.

Introduction



Time of day has been repeatedly shown to affect various indices of maximal neuromuscular performance in humans with morning nadirs and afternoon maximum values a common finding in various tests of maximal voluntary strength in both dynamic and isometric conditions [6,9,13,18,28]. Similarly, the current authors have recently shown that a time of day effect is characteristic of performance in a loaded counter-movement jump, with afternoon improvements of 4.3–6.1% in force, peak movement velocity and power output [30].

Although it is possible that the effect of time of day on muscle contractile properties could be attributed in part to intracellular variations in the muscle (e.g. a circadian variation in inorganic phosphate concentration [18]), the more common hypothesis is that performance differences are causally related to the circadian rhythm in body temperature since previous researchers have observed a general parallelism between rhythms of physical performance and core tem-

perature [3,12,25]. The importance of temperature in performance is supported by extensive data from heating and cooling experiments which have demonstrated that maximal anaerobic power declines by 5% for every 1°C drop in muscle temperature [5]. Since body temperature is lowest in the morning (~5.00 am) and rises throughout the day reaching a plateau between 2.00 pm and 8.00 pm [24] it follows that increases in morning temperatures could significantly impact testing results and perhaps dilute the diurnal performance effect previously noted.

Previous authors have extended the pre-assessment warm-up prior to swimming [1] and cycling [4] time trials, with the aim of increasing body temperature before the morning performances to match the body temperature in the afternoon. Findings from these studies lead to the conclusion that time of day differences in performance are not likely mediated by body temperature variation. Conversely Bernard et al., [6] observed that daily variations in anaerobic performance were in phase with the changes in core temperature, and Racinais et al. [22] reported that a pas-

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Bibliography

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sive warm-up which increased morning temperature to afternoon levels blunted the diurnal variation in muscle power by increasing muscle contractility in the morning. Given the conflicting results in the literature to date, and that maximal acyclic tests of power production (such as vertical jumps) occur over a much shorter time period (~300ms) than the activities previously investigated, we aimed to examine the effects of an extended warm-up period on the time of day differences in vertical jump performance.

Methods



Experimental approach to the problem

To examine whether increased whole body temperature gained through an extended warm-up affected the known time of day differences in explosive jump performance, subjects completed 4 separate testing sessions differing in time of day and type of warm-up completed. In a randomised order, jump performance was assessed following: (a) control warm-up at 8.00 am (AM control condition); (b) control warm-up at 4.00 pm (PM control condition); (c) extended warm-up at 8.00 am (AM extended condition); and, (d) extended warm-up at 4.00 pm (PM extended condition). Using a within-subject crossover design, kinetic and kinematic variables measured during loaded counter-movement jumps (CMJs) were compared between conditions.

Subjects

8 recreationally trained males (29.8 ± 5.2 yrs; 178.3 ± 5.2 cm; 80.3 ± 6.5 kg) with a minimum of 6 months resistance training history participated in this study. All subjects were rated intermediate in circadian phase type as determined by the Horne and Östenberg morning-eveningness scale [16]. Subjects were asked to avoid any strenuous lower body exercise as well as refraining from consuming alcohol or caffeine for 48 h prior to all assessments. Additionally they were asked to minimise any alterations in their diet and life style (e.g. sleeping time, etc.) for the entire period, and wake time was standardised between testing days. All procedures were approved by the institutional ethics committee following the principles outlined in Harriss and Atkinson [14], with written informed consent obtained from each participant prior to data collection.

Procedures

The control warm-up consisted of dynamic exercises and practice jumps equivalent to the standard warm-up for strength and power assessment used in our laboratory. This included 2 min of easy self-paced jogging; 2×10 m of walking lunges, high knee skips and heel flicks; $10 \times$ body weight squats; $2 \times$ run-throughs/accelerations (10m easy jog, 10m at ~75% max sprint speed, 10m easy jog); 2 sets of 3 unloaded jumps at ~80–90% of perceived maximal effort; and 1 set of 40 kg jumps (~80–90%). This type of dynamic warm-up is characteristically similar to warm-ups previously used in the investigation of vertical jump performance [7, 10, 17, 19, 31]. The extended warm-up incorporated a more extensive general warm-up period with the aim of increasing body temperature to a value equivalent to the values observed during the afternoon control trials. This was achieved with the subjects cycling on a stationary ergometer for 20 min at 150–200 W. This protocol was established after extensive pilot trials which confirmed that post warm-up body temperature in the morning conditions matched the average afternoon resting

body temperature. The general warm-up period was then followed by the control warm-up, so that the effects of the general warm-up on subsequent performance could be directly examined.

Body temperature was measured using a combination of skin and core temperature to estimate overall body temperature. Skin temperature (Mon-a-therm temperature system cables #502-0400, Mallinckrodt Medical, St. Louis, MO) and core temperature measured using ingestible core temperature pills (CorTemp, HQInc, Palmetto Florida) were recorded prior to the warm-up (baseline) and after the warm-up (immediately prior to the jump assessments). Skin thermistors were placed on the chest, forearm, thigh and calf of each subject, and these values were incorporated in the following equations to provide mean skin temperature [23] and subsequently an estimate of overall body temperature [27]:

$$\text{Mean Skin Temperature: } T_{sk} = (0.3 \times (T_{Chest} + T_{Forearm}) + 0.2 \times (T_{Thigh} + T_{Calf}))$$

$$\text{Total Body Temperature: } T_b = 0.87 T_{core} + 0.13 T_{sk}$$

Jump assessments consisted of each subject performing a CMJ with a load of 20 kg on an Olympic lifting bar (i.e., total load of 40 kg). 5 min after the practice jumps, the subject stood erect with the bar positioned across his shoulders and was instructed to jump for maximal height while keeping constant downward pressure on the barbell to prevent the bar moving independently of the body. Each subject performed 3 repetitions, pausing for ~3–5 s between each jump. Subjects then rested for 2 min before repeating a second set of 3 jumps. No attempts were made to standardise the starting position, amplitude, or rate of the counter-movement. A displacement-time curve for each jump was obtained by attaching a digital optical encoder via a cable (GymAware Power Tool, Kinetic Performance Technologies, Canberra, Australia) to one side of the barbell. This system recorded displacement-time data using a signal driven sampling scheme where position points were time-stamped when a change in position was detected, with time between samples limited to a minimum of 20 ms. The first and second derivative of position with respect to time was taken to calculate instantaneous velocity and acceleration respectively. Acceleration values were multiplied by the system mass to calculate force, and the given force curve multiplied by the velocity curve to determine power. Mean values for power were calculated over the concentric portion of the movement (i.e., from minimum displacement to take-off) along with peak values for velocity, force and power. Jump height was determined as the highest point on the displacement-time curve. High test-retest reliability has previously been established for this assessment protocol (coefficients of variation for all variables <6%) [30], while the validity and accuracy of the data collection procedures have been confirmed using similar methodologies [8, 11].

Statistical analyses

The mean kinetic and kinematic values of the 6 jumps for each subject were used to compare performance between conditions. To examine differences in performance between conditions, effect size statistics (ES) were calculated as the mean difference divided by the pooled between-subject SD, and were characterized for their practical significance using the following criteria: <0.2 = trivial, 0.2–0.6 = small, 0.6–1.2 = moderate, and >1.2 = large. Additionally, a substantial performance change was accepted when there was more than a 75% likelihood that the true value of the standardized mean difference was greater than

the smallest worthwhile (substantial) effect [15]. The smallest worthwhile change in performance from test to test established as a “small” effect size ($0.2 \times$ between-participant SD) according to methods outlined previously [15].

Results

Whole body temperature results for AM and PM at baseline were $36.4 \pm 0.16^\circ\text{C}$ and $36.6 \pm 0.18^\circ\text{C}$ (mean \pm SD) respectively (● Fig. 1). Following the AM extended warm-up, body temperature increased to $36.8 \pm 0.09^\circ\text{C}$ which matched the post warm-up value of $36.8 \pm 0.38^\circ\text{C}$ in the PM control condition. The observed increase in whole body temperature following the extended warm-up in the AM condition was $0.44 \pm 0.14^\circ\text{C}$, which was greater than the $0.26 \pm 0.19^\circ\text{C}$ increase provided by the extended warm-up in the PM condition.

Substantial differences in performance were observed between the AM and PM control conditions across all variables (● Table 1), providing further evidence of diurnal performance variation. Following control warm-up PM performance was 4–6% higher than AM control performance for peak power, mean power and jump height, and 2–3% higher for peak velocity and peak force. All these differences were greater than the smallest worthwhile changes of 2.8% for jump height, 3.3% for peak power, 3.1% for mean power, 1.8% for peak velocity and 1.6% for peak force (ES range = 0.2–0.4). Similar improvements in performance were

observed when the AM control and AM extended conditions were compared (ES range = 0.3–0.5).

● Fig. 2 illustrates the individual responses for mean power across the different conditions, where the shaded area represents the SWC. It is clear that for most individuals, performance was substantially better in the AM extended and the PM control conditions when compared with AM control (● Fig. 2a, b). This trend was maintained across each of the kinetic and kinematic variables analysed.

When the AM extended and PM control conditions were compared, no substantial differences in performance were observed (mean difference < 1%; ES range = 0.0–0.1). The only exception to this trend was peak power, where performance was higher after the extended warm-up (4.8%; ES = 0.3). Interestingly, a variety of individual responses were observed when performance in the PM control and PM extended conditions were compared (● Fig. 2d). For peak velocity, peak force and jump height, the overall effects were trivial (ES < 0.2); however the effect of an extended warm-up in the PM sessions for peak and mean power was unclear due to the variety of individual responses.

Discussion

The results demonstrate that using a short dynamic warm-up routine, as commonly practiced prior to maximal performance testing, results in a substantial 4–6% difference in performance between morning and afternoon testing sessions. The improvements in the afternoon power and jump height are similar to previous research on time of day differences in jumping performance [6, 26, 28, 30]. The novel finding from this study was that incorporating an extended, generalised warm-up period designed to increase body temperature equivalent to a normal whole body temperature experienced in the afternoon reduced the time of day differences in explosive neuromuscular performance.

The influence of temperature on performance was illustrated by the difference in performance between the AM control and the AM extended conditions. Following an increase in body temperature via the extended warm-up we observed a 4–6% improvement in AM jump performance. To our knowledge this is the first study to report this finding. While previous authors have manipulated the pre-event warm-up to remove the diurnal differences in body temperature, their findings contrast our own. Arnett [1] achieved similar morning and afternoon body temperatures by doubling the volume of the morning swim warm-up prior to a 200m time trial, but still observed significant time of day performance differences. Similarly, Atkinson et al. [4] reported significantly greater performances during afternoon cycling time trials despite the performance of a vigorous warm-up prior to morning trials, leading them to conclude that time of day differences in cycling performance were not likely mediated by body temperature variation. It seems reasonable that these conflicting

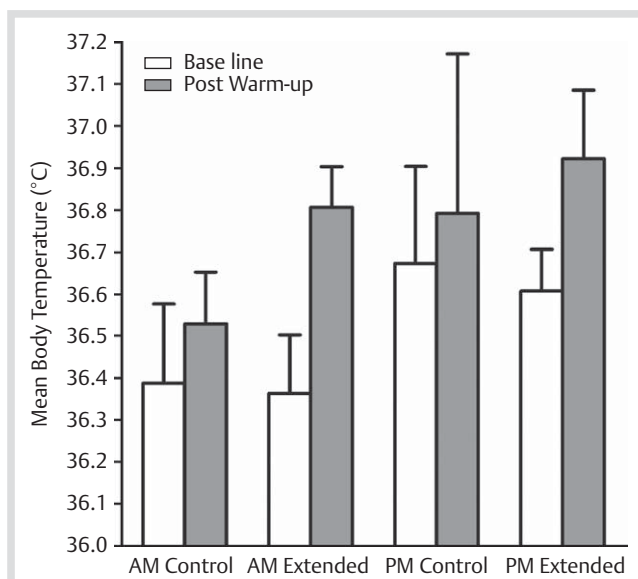


Fig. 1 Mean \pm SD estimated whole body temperature for the AM control condition, the AM extended condition, the PM control condition, and the PM extended conditions prior to warm-up (baseline) and immediately prior to the jump assessments (post warm-up).

Table 1 Mean (\pm SD) for kinetic and kinematic variables measured after the control warm-up in the morning and afternoon (AM Control and PM Control) and after the extended warm-up in the morning and afternoon (AM Extended and PM Extended).

Condition	Peak Power (W)	Mean Power (W)	Peak Velocity ($\text{m}\cdot\text{s}^{-1}$)	Peak Force (N)	Height (cm)
AM control	3747 \pm 636	2054 \pm 329	2.15 \pm 0.21	1697 \pm 152	26.3 \pm 4.5
AM extended	4090 \pm 768	2159 \pm 371	2.24 \pm 0.21	1738 \pm 167	27.9 \pm 4.5
PM control	3899 \pm 543	2152 \pm 312	2.22 \pm 0.16	1733 \pm 149	28.0 \pm 3.7
PM extended	4047 \pm 705	2223 \pm 361	2.25 \pm 0.22	1761 \pm 157	28.5 \pm 4.1

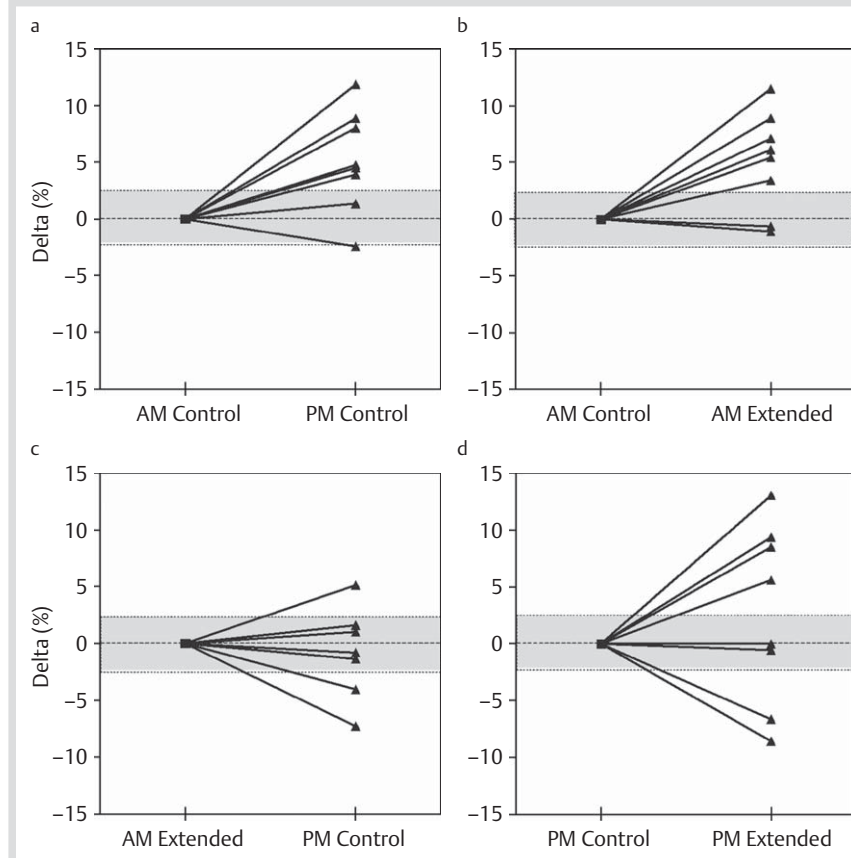


Fig. 2 Individual changes in mean power across conditions where (a) represents the change in performance between the AM control and PM control conditions; (b) change between AM control and AM extended conditions; (c) change between AM extended and PM control conditions; and (d) change between the PM control and PM extended conditions. Shaded areas represent the smallest worthwhile change in performance.

results may be due to the differences in the nature of the performance tasks previously examined, whereby the energetic and neuromuscular performance requirements differed substantially to the loaded CMJs in the present study.

Though we cannot directly prove a cause and effect relationship between temperature and performance with the current data, it seems justifiable that the beneficial effect noted is preponderantly a temperature effect, and that other effects of the control warm-up were minimal. This is supported by previous work demonstrating beneficial effects of passive heating on work output in the absence of any preliminary muscular activity [2,22]. In contrast to this suggestion Škof and Strojnik [29] recommend that the priming of an athlete's neuromuscular system needs to be achieved with both temperature and non temperature dependent processes, since they observed changes in muscle activation independent of changes in temperature. It is clear from the results of this study that the addition of a general whole body warm-up period to increase body temperature added to the warm-up benefits of the dynamic control warm-up, reducing the time of day performance differences. It therefore appears that the addition to a general warm-up period which sufficiently increases body temperature to the normally practiced short dynamic warm-up routine is warranted.

While the results from this experiment suggest that increases in body temperature are necessary for achieving maximal performance in the morning, we also observed some negative effects on performance when a similar warm-up was conducted in the afternoon, with 2 from 8 subjects performing substantially worse in this condition. It is possible that this result is due to inter-subject variations in the temperature response to the extended warm-up since the subjects with the greatest temperature response ($> 37.5^{\circ}\text{C}$) were those that responded negatively.

Morrison et al., [20] reported that maximal voluntary force and central activation during 10s isometric knee extension gradually decreased with an increase in core temperature $> 37.5^{\circ}\text{C}$. Other authors have suggested a "ceiling" above which an increase in body temperature fails to further improve muscular performance in vivo [12,21,22]. It therefore seems important that prior to the adoption of an extended warm-up protocol in afternoon testing sessions that individual optimal temperatures for ensuring maximal performance are identified.

In conclusion, we found that time of day performance differences in the loaded jump squat can be eliminated by manipulating the pre-assessment warm-up to minimise the diurnal differences in body temperature. Current practice of a short dynamic warm-up prior to assessment does not promote an increase in body temperature great enough to compensate for the diurnal difference in body temperature. This results in the persistence of substantial and practically important performance differences in morning and afternoon assessments. The addition of a general whole body warm-up period designed to increase body temperature makes it possible to compare performances at different times throughout the day, although more work is needed to determine the critical temperature above which an individual's performance may be impaired.

Practical applications

Differences exist between AM and PM performance of explosive activities. The results from this study show that maximal vertical jump performance is not likely to be demonstrated if testing is scheduled in the morning, limiting the validity of the assessment. It is therefore necessary to identify methods for maximising performance independent of the time of day that the assessment is conducted. We suggest that warm-up protocols

designed to increase whole body temperature would be beneficial for reducing these differences and ensuring maximal performance. This is also very important for accurate monitoring of performance changes over time where it may be impractical to standardise the time of day that assessments take place.

References

- 1 Arnett M. Effects of prolonged and reduced warm-ups on diurnal variation in body temperature and swim performance. *J Strength Cond Res* 2002; 16: 256–261
- 2 Asmussen E, Boje O. Body temperature and capacity for work. *Acta Physiol Scand* 1945; 10: 1–22
- 3 Atkinson G, Reilly T. Circadian variation in sports performance. *Sports Med* 1996; 21: 292–312
- 4 Atkinson G, Todd C, Reilly T, Waterhouse J. Diurnal variation in cycling performance: Influence of warm-up. *J Sports Sci* 2005; 23: 321–329
- 5 Bergh U, Ekblom B. Influence of muscle temperature on maximal muscle strength and power output in human skeletal muscles. *Acta Physiol Scand* 1979; 107: 33–37
- 6 Bernard T, Giacomoni M, Gavarry O, Seymat M, Falgairette G. Time-of-day effects in maximal anaerobic exercise. *Eur J Appl Physiol* 1998; 77: 133–138
- 7 Carlock J, Smith S, Hartman M, Morris RT, Ciroslan DA, Pierce KC, Newton RU, Harman EA, Sands WA, Stone MH. The relationship between vertical jump power estimates and weightlifting ability: a field-test approach. *J Strength Cond Res* 2004; 18: 534–539
- 8 Chiu L, Schilling B, Fry A, Weiss L. Measurement of resistance exercise force expression. *J Appl Biomech* 2004; 20: 204–212
- 9 Coldwells A, Atkinson G, Reilly T. Sources of variation in back and leg dynamometry. *Ergonomics* 1994; 37: 79–86
- 10 Cormack S, Newton R, McGuigan M. Neuromuscular and endocrine responses of elite players to an Australian Rules Football match. *Int J Sports Physiol Perform* 2008; 3: 359–374
- 11 Cronin J, Hing R, McNair P. Reliability and validity of a linear position transducer for measuring jump performance. *J Strength Cond Res* 2004; 18: 590–593
- 12 Drust B, Rasmussen M, Mohr M, Nielson B, Nybo L. Elevations in core and muscle temperature impairs repeated sprint performance. *Acta Physiol Scand* 2005; 183: 181–190
- 13 Gauthier A, Davenne D, Martin A, Hoecke JV. Time of day effects on isometric and isokinetic torque developed during elbow flexion in humans. *Eur J Appl Physiol* 2001; 84: 249–252
- 14 Harriss D, Atkinson G. International Journal of Sports Medicine – Ethical Standards in Sport and Exercise Science Research. *Int J Sports Med* 2009; 30: 701–702
- 15 Hopkins W. Probabilities of clinical or practical significance. *Sport-science* 2002
- 16 Horne J, Ostberg O. A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *Int J Chronobiol* 1976; 4: 97–110
- 17 Markovic G, Dizdar D, Jukic I, Cardinale M. Reliability and factorial validity of squat and countermovement jump tests. *J Strength Cond Res* 2004; 18: 551–555
- 18 Martin A, Carpentier A, Guissard N, Hoecke JV, Duchateau J. Effect of time of day on force variation in human muscle. *Muscle Nerve* 1999; 22
- 19 Moir G, Sanders R, Button C, Glaister M. The influence of familiarization on the reliability of force variables measured during unloaded and loaded vertical jumps. *J Strength Cond Res* 2005; 19: 140–145
- 20 Morrison S, Sleivert G, Cheung S. Passive hyperthermia reduces voluntary activation and isometric force production. *Eur J Appl Physiol* 2004; 91: 729–736
- 21 Racinais S, Blonc S, Hue O. Effects of active warm-up and diurnal increase in temperature on muscular power. *Med Sci Sports Exerc* 2005; 37: 2134–2139
- 22 Racinais S, Hue O, Blonc S. Time-of-day effects on anaerobic muscular power in a moderately warm environment. *Chronobiol Int* 2004; 21: 485–495
- 23 Ramanathan N. A new weighting system for mean surface temperature of the human body. *J Appl Physiol* 1964; 19: 531–533
- 24 Refinetti R, Menaker M. The circadian rhythm of body temperature. *Physiol Behav* 1992; 51: 613–637
- 25 Reilly T, Brooks G. Exercise and the circadian variation in body temperature measures. *Int J Sports Med* 1986; 7: 358–362
- 26 Reilly T, Down A. Investigation of circadian rhythms in anaerobic power and capacity of the legs. *J Sports Med Phys Fitness* 1992; 32: 346–347
- 27 Schmidt V, Bruck K. Effect of a precooling maneuver on body temperature and exercise performance. *J Appl Physiol* 1981; 50: 772–778
- 28 Sedilak M, Finni T, Cheng S, Haikarainen T, Hakkinen K. Diurnal variation in maximal and submaximal strength, power and neural activation of leg extensors in men: Multiple sampling across two consecutive days. *Int J Sports Med* 2008; 29: 217–224
- 29 Škof B, Strojnik V. The effect of two warm-up protocols on some biochemical parameters of the neuromuscular system of middle distance runners. *J Strength Cond Res* 2007; 21: 394–399
- 30 Taylor K, Cronin J, Gill N, Chapman D, Sheppard J. Sources of variability in iso-inertial jump assessments. *Int J Sports Physiol Perform*, in press
- 31 Wilson G, Murphy A, Walshe A. Performance benefits from weight and plyometric training: effects of initial strength level. *Coaching Sport Sci J* 1997; 2: 3–8

APPENDIX B

Statements of contributions of others

STATEMENT OF CONTRIBUTION OF OTHERS: CHAPTER 3

To Whom It May Concern,

I, *Kristie-Lee Taylor*, contributed the majority of work in the design, data collection, analysis and interpretation of the results, composition and editing the manuscript entitled *Fatigue monitoring in high performance sport: A survey of current trends* published in the *Journal of Australian Strength and Conditioning*, 20(1): 12-23; 2012

(Signature of Candidate)

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Dale W. Chapman

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26/06/12

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Nicholas D. Gill

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STATEMENT OF CONTRIBUTION OF OTHERS: CHAPTER 4

To Whom It May Concern,

I, *Kristie-Lee Taylor*, contributed the majority of work in the design, data collection, analysis and interpretation of the results, composition and editing the manuscript entitled *Sources of variability in iso-inertial jump assessments*, published in the *International Journal of Sports Physiology and Performance*, 5(4): 546-558; 2010.

(Signature of Candidate)

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

<i>John B. Cronin</i>	<i>AUT University</i>	<i>26/06/12</i>
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<i>Dale W. Chapman</i>	<i>Edith Cowan University</i>	<i>26/06/12</i>
<i>Jeremy M. Sheppard</i>	<i>Edith Cowan University</i>	<i>29/06/12</i>

STATEMENT OF CONTRIBUTION OF OTHERS: CHAPTER 5

To Whom It May Concern,

I, *Kristie-Lee Taylor*, contributed the majority of work in the design, data collection, analysis and interpretation of the results, composition and editing the manuscript entitled *Warm-Up Affects Diurnal Variation in Power Output*, published in the *International Journal of Sports Medicine*, 32(3): 185-189; 2011.

(Signature of Candidate)

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

<i>John B. Cronin</i>	<i>AUT University</i>	<i>26/06/12</i>
<i>Nicholas D. Gill</i>	<i>AUT University</i>	<i>27/06/12</i>
<i>Dale W. Chapman</i>	<i>Edith Cowan University</i>	<i>26/06/12</i>
<i>Jeremy M. Sheppard</i>	<i>Edith Cowan University</i>	<i>29/06/12</i>

STATEMENT OF CONTRIBUTION OF OTHERS: CHAPTER 6

To Whom It May Concern,

I, *Kristie-Lee Taylor*, contributed the majority of work in the design, data collection, analysis and interpretation of the results, composition and editing the manuscript entitled *Monitoring neuromuscular fatigue using vertical jumps*, submitted for publication in the *International Journal of Sports Medicine*.

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I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

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<i>Dale W. Chapman</i>	<i>Edith Cowan University</i>	<i>26/06/12</i>
<i>John B. Cronin</i>	<i>AUT University</i>	<i>26/06/12</i>
<i>Michael J. Newton</i>	<i>Edith Cowan University</i>	<i>26/06/12</i>
<i>Stuart J. Cormack</i>	<i>Australian Catholic University</i>	<i>27/06/12</i>
<i>Nicholas D. Gill</i>	<i>AUT University</i>	<i>27/06/12</i>

STATEMENT OF CONTRIBUTION OF OTHERS: CHAPTER 7

To Whom It May Concern,

I, *Kristie-Lee Taylor*, contributed the majority of work in the design, data collection, analysis and interpretation of the results, composition and editing the manuscript entitled *Error of measurement in jump performance is influenced by training phase* submitted for publication in the *Journal of Sports Physiology and Performance*.

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I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

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STATEMENT OF CONTRIBUTION OF OTHERS: CHAPTER 8

To Whom It May Concern,

I, *Kristie-Lee Taylor*, contributed the majority of work in the design, data collection, analysis and interpretation of the results, composition and editing the manuscript entitled *Relationship between changes in jump performance and laboratory measures of low-frequency peripheral fatigue* submitted for publication in the *Journal of Sports Medicine and Physical Fitness*.

(Signature of Candidate)

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

<i>John B. Cronin</i>	<i>AUT University</i>	<i>26/06/12</i>
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<i>Dale W. Chapman</i>	<i>Edith Cowan University</i>	<i>26/06/12</i>
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<i>William G. Hopkins</i>	<i>AUT University</i>	<i>30/06/12</i>
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<i>Michael J. Newton</i>	<i>Edith Cowan University</i>	<i>26/06/12</i>
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