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**NEUROMUSCULAR FATIGUE
AND ENDOCRINE RESPONSES IN
ELITE AUSTRALIAN RULES
FOOTBALL PLAYERS**

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**This thesis is submitted in fulfilment of the requirements for the degree
of Doctor of Philosophy**

March 2008

USE OF THESIS

The Use of Thesis statement is not included in this version of the thesis.

ABSTRACT

Chapter 3 (Studies 1 and 2 – Paper 1)

Purpose: To examine the reliability of a single (CMJ1) and short duration 5 repeated (CMJ5) countermovement jump. **Methods:** Two studies were conducted in which 15 elite Australian Rules Football (ARF) subjects performed AM and PM trials of either a CMJ1 or CMJ5 on two days one week apart. Trials were conducted using a portable forceplate. The Typical Error (*TE*) and Coefficient of variation (*CV%*) were calculated to assess intra-day, inter-day and overall reliability. **Results:** Mean Force (*CV* 1.08%) and Relative mean force (*CV* 1.57%) were the most reliable variables in the CMJ1 and CMJ5 conditions respectively. Only CMJ1 Mean force displayed a *TE* < smallest worthwhile change (*SWC*). **Conclusion:** Selected CMJ1 and CMJ5 variables display levels of reliability acceptable for them to be used in the assessment of the impact of chronic and acute training and competition in elite ARF players.

Chapter 4 (Study 3 – Paper 2)

Purpose: To examine the acute and short term response of reliable CMJ1 and CMJ5 variables in addition to salivary Testosterone (T), Cortisol (C) and T:C to an elite ARF match. **Methods:** Twenty-two elite ARF players provided CMJ and saliva samples from 48h pre match to 120h post match. The magnitude of change in variables was analysed using the effect size (ES) statistic and % difference to pre match and 48h pre match. **Results:** CMJ1 Flight time: Contraction time displayed a substantial decrement (ES -0.65 ± 0.28) from pre to post match. Cortisol (ES ± 1.06) and T:C (ES -0.52 ± 0.42) also displayed large pre to post match changes. CMJ1 Flight time: Contraction time was the only CMJ variable capable of detecting a decrement compared to 48h pre match. Cortisol displayed a clear pattern of response compared to 48h pre match.

Conclusion: CMJ1Flight time:Contraction time appears to be the most useful variable for monitoring neuromuscular status in elite ARF players whilst C may provide the most useful measure of hormonal status.

Chapter 5 (Study 4 – Paper 3)

Purpose: To examine neuromuscular and hormonal responses during a season of elite ARF competition and assess the relationship between these variables and performance, training and competition load. **Methods:** Fifteen elite ARF players performed CMJ1 and CMJ5 trials and provided saliva samples prior to the commencement of the season (Pre) and between matches of the 22 match season. The magnitude of change in variables compared to pre was assessed using the ES statistic and % change. Correlations were conducted to assess relationships between these variables and training and competition load and performance. **Results:** CMJ1Flight time:Contraction time was substantially reduced at 60% of measurement points compared to pre with magnitudes of change up to ES -0.77 ± 0.81 (-17.1%). Cortisol was up to 40% lower in all but one comparison against pre, whilst the response of T was varied. Large increases in T:C (up to ES 2.03 ± 0.76) were evident compared to pre. CMJ1Flight time:Contraction time ($r = 0.24 \pm 0.13$) and C ($r = -0.16 \pm 0.1$) displayed small correlations with performance. **Conclusion:** The response of CMJ1Flight time:Contraction time suggests periods of neuromuscular fatigue. The response evident in hormonal measures indicates subjects were unlikely to have been in a catabolic state during the season. Both CMJ1Flight time:Contraction time and C may be useful monitoring variables in elite ARF athletes.

Declaration

I certify that this thesis does not, to the best of my knowledge and belief:

- (i) incorporate without acknowledgement any material previously submitted for a degree or diploma in any institution of higher education;
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ACKNOWLEDGEMENTS

A large number of people have been important to the completion of this thesis and without their involvement it would not have been possible.

Firstly, the input, support and enthusiasm of my supervisors was amazing. Professor Rob Newton has lent his considerable experience and expertise to all aspects of this research. His ability to critically analyse and interpret data and provide feedback on draft versions was invaluable. The advice, guidance and support of Dr. Mike McGuigan was beyond all expectation. The capacity to reply to emails and phone calls in record time and spend numerous early mornings patiently teaching me the techniques for salivary assays is greatly appreciated. Both Professor Newton and Dr. McGuigan have made a major contribution to the monitoring program undertaken by the West Coast Eagles Football Club through their involvement in this research.

Thanks must also go to Dr. Tim Doyle for his work on the development of software to automate the analysis of countermovement jump data. Without this software, it would have been almost impossible to analyse the huge amount of data generated in the 4 studies. Dr. Doyle's contribution as a co-author on the reliability paper was also important. My fellow PhD student, Prue Cormie provided enormous support and assistance through many long hours conducting salivary assays. Prue was always so enthusiastic about my research and her help in recording well locations for saliva samples while I performed the assays made conducting them simpler and the time go faster. Prue was also a valuable contributor as a co-author on Study 4.

The involvement of the West Coast Eagles Football Club made this research possible. The willingness of such high level athletes to provide saliva samples and perform countermovement jumps throughout the heavy load of a competitive season was outstanding. Their capacity to provide these samples pre and post match and then on a daily basis to allow collection of data for Study 3 showed the professionalism of the group and their willingness to do whatever was required to potentially aid their preparation. In addition to the player group, the support of Head Coach John Worsfold,

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PREFACE

This thesis comprises 4 Experimental studies presented as 3 papers in the form accepted for publication. These papers are supported by Introduction, Review of Literature and Conclusion chapters. Each experiment builds on the previous one in an attempt to understand neuromuscular fatigue and endocrine responses as they relate to elite Australian Rules Football (ARF) athletes.

The first paper comprises Experimental Studies 1 and 2 (Chapter 3).

Cormack, S.J., Newton, R.U., McGuigan, M.R., and Doyle, Tim L. A., Reliability of Measures Obtained During Single and Repeated Countermovement Jumps. *International Journal of Sports Physiology and Performance*, In press.

Chapter 4 contains the second paper (Experimental Study 3).

Cormack, S.J., Newton, R.U., and McGuigan, M.R., Neuromuscular and Endocrine Responses of Elite Players to an Australian Rules Football Match. *International Journal of Sports Physiology and Performance*, In press.

Chapter 5 reflects Experimental Study 4 (Paper 3).

Cormack, S.J., Newton, R.U., McGuigan, M.R., and Cormie, P., Neuromuscular and Endocrine Responses of Elite Players During an Australian Rules Football Season. *International Journal of Sports Physiology and Performance*, In press.

In addition to these papers, the following presentations relate to research conducted contributing to completion of this thesis.

Conference Presentation: Cormack, S. Performance Monitoring – The Use of Repeat Jump Tests. *AIS Team Sport Conference, Canberra 2006*

Poster Presentation: Cormack, S. Reliability of a Repeated Countermovement
Jump Test. *13th Commonwealth International Sport
Conference, Melbourne 2006*

CHAPTER 1

1.0 INTRODUCTION

Australian Rules Football (ARF) is played by two teams of 22 players, with each match lasting between 100 and 120 minutes. At any one time there are 18 players from each team on the field and 4 interchange players. An unlimited number of interchange rotations is allowed. Although specific field positions exist, there is no limitation on where players can move. Typically, players are characterised as forwards, backs and midfielders. Previous work has shown midfield players in the Australian Football League (AFL) cover distances of between 14 and 20km.¹ Average speed has been reported as 6.78 ± 0.94 km·hr with maximums of 29.7 ± 2.2 km·hr.² Distance covered and the amount of sprinting, jogging and walking appears to be influenced by position^{1,2} and during the course of an elite ARF game, players are involved in 52 to 91 game activities that are also generally dependant on position.¹ In addition, players can be involved in large amounts of physical contact such as tackling and bumping during a match and this may also contribute to the fatigue response.

The AFL comprises 16 teams that play in a National competition lasting 22 matches, followed by a 4 week finals series. There are teams based in 5 of Australia's capital cities, although 10 are based in Melbourne, Victoria. The AFL is currently the largest spectator sport in Australia but despite the highly professional nature of this competition, there is limited data available on the potentially fatiguing affects of week to week competition in elite players. Due to the suggestion that overtraining syndrome is a dysfunction of both the nervous and endocrine systems³ it is possible that various measures, such as those related to neuromuscular and hormonal status may be useful monitoring tools in an elite ARF population. Additionally, such variables may have a relationship to performance measures and training or competition loads.

There have been numerous attempts to establish the site of neuromuscular fatigue and determine its influence on muscular performance.⁴⁻⁷ Neuromuscular fatigue is traditionally associated with changes anywhere between the brain and muscle fibre with distinctions made between central and peripheral fatigue based on the specific site of disruption.⁸ A limitation to a number of studies examining the impact of neuromuscular fatigue is the requirement for complex equipment and time consuming protocols.^{4,6,9} These limitations decrease the usefulness of such tests when there is a requirement for rapid assessment of large numbers of athletes. In order to overcome these limitations, some attempt has been made to utilise functional athletic tasks to measure neuromuscular fatigue. However, performance on some of these tasks is likely to be affected by metabolic factors¹⁰⁻¹⁹ which makes it difficult to isolate the role of neuromuscular fatigue in their performance. A further limitation to functional tests of neuromuscular fatigue is the reliability of variables that can be measured in these types of movements. It is important that variables obtained during a functional test are highly repeatable so that any change in performance can be attributed to changes in function. The impact of high level contact team sport participation on these variables is largely unknown and so little data exists to clarify their usefulness as measures of neuromuscular status. Therefore, how these measures respond to changes in workload or how changes in neuromuscular status influence performance in elite ARF players is uncertain.

In addition to the impact of neuromuscular fatigue on performance, the hormonal response to exercise has also been well documented.¹³⁻¹⁹ However, there is little work examining the hormonal response to elite level contact team sport performance,²⁰⁻²⁴ particularly over entire competitive seasons. It is possible that measures such as the Testosterone (T) to Cortisol (C) ratio (T:C) may be useful in assessing the relative anabolic or catabolic state of an athlete and provide a potential marker of the response to training and competition workloads.^{25,26} However, the link between endocrine measures and training or competition load and performance in elite level ARF players is unknown. Due to this, an in depth analysis of endocrine response in elite ARF athletes appears warranted.

1.1 Purpose of the Research

The first purpose of this research was to establish the reliability of numerous measures obtained from a single and short duration repeated countermovement jump (CMJ) utilising a portable forceplate (Experimental Studies 1 and 2). Secondly, the response of reliable CMJ variables and T, C and T:C to a single elite level ARF match was assessed to identify the pattern of response and highlight those measures with the greatest potential for usefulness as monitoring tools across longer periods (Experimental Study 3). Finally, those variables identified as most valuable in Experimental Study 3 in addition to T, C and T:C; were measured throughout a season of elite ARF competition in order to examine the manner of their response and assess the magnitude of change in these variables in relation to performance and training and competition loads (Experimental Study 4).

1.2 Significance of the Research

The development of an easy to administer test of neuromuscular fatigue with high reliability would be useful to both sport scientists and coaches involved in the preparation of high level athletes. An in depth analysis of neuromuscular and hormonal measures obtained during an extended period of training and competition for elite level contact team sport would provide an insight into the long term responses expected in such athletes. It is possible that these variables are capable of detecting various degrees of acute fatigue, overreaching, or overtraining. Specifically, this analysis may shed light on the value of these measures in elite ARF, particularly in relation to issues regarding the impact of training and competition load and performance.

1.3 Research Questions

1. What is the level of intra-day, inter-day and overall reliability in a range of variables that can be obtained from a single and short duration repeated CMJ in elite ARF athletes? What is the ability of these variables to detect the smallest worthwhile change (SWC)?

2. What impact does a single ARF match have on neuromuscular status, as measured by the response of variables identified as reliable in Experimental Studies 1 and 2?
3. As a result, which CMJ variables appear to be the most sensitive and useful indicators of neuromuscular status in elite ARF players?
4. How do the hormones T, C and T:C respond to an elite ARF match and what is the potential value of these endocrine measures for longer term tracking?
5. What is the response of neuromuscular and hormonal measures to a season of elite ARF competition and how do changes in these variables reflect performance and training or competition loads?

CHAPTER 2

2.0 REVIEW OF LITERATURE

2.1 Synopsis

This review begins with an analysis of the concept of fatigue, and specifically with neuromuscular fatigue and its origins. Methods of assessing neuromuscular fatigue are then examined with particular reference to athletic performance and the limitations to the use of various measurement techniques in sporting environments. This is followed by an evaluation of the efficacy of using single and repeated stretch shorten cycle (SSC) movements as indicators of fatigue status in athletic populations, especially those involved in team sports. This section of the review concludes with an assessment of previously reported vertical jump reliability studies and technical issues associated with the measurement and reporting of reliability.

The next section of the review examines the use of endocrine variables as indicators of fatigue status. The measurement of Testosterone (T), Cortisol (C) and their ratio value (T:C) is discussed in addition to the response of these measures in various individual and team sports. This includes previous work assessing the ability of these variables to reflect changes in training volume and intensity or performance. Analysis of the relationship between neuromuscular and hormonal measures has also been included. Finally, an assessment of previous work in which neuromuscular fatigue and hormonal response has been measured in elite ARF players is conducted.

2.2 Fatigue

A commonly accepted principle of training is that a period of loading followed by adequate rest results in improved performance.^{27,28} Due to this; an imbalance between training and recovery can result in fatigue, which if continued, can negatively impact performance.^{27,29} This imbalance has sometimes been referred to as overtraining;^{25,26,30} which is reflected as a combined reduction in performance and altered mood state.³¹ It has been suggested that short term overtraining or overreaching is a reversible occurrence where performance can be recovered within days or weeks, whilst staleness or overtraining syndrome is a longer lasting phenomena where performance continues to be suppressed despite reductions in training stress.^{26,29,32} In situations where athletes have deliberately undergone fatigue inducing training prior to periods of recovery, they are likely to enter a state known as functional overreaching.^{29,33,34} Conversely, where insufficient recovery is allowed following high load training, athletes can suffer from non-functional overreaching.^{29,33,34} It has been suggested that overtraining is a dysfunction of both the nervous and endocrine systems.³ Although this suggests measures of change in these systems could be worthwhile, it is possible that performance measures are the most important criteria for the diagnosis of overreaching and particularly overtraining and it is also conceivable that other systems (eg. muscular) are experiencing dysfunction during times of overtraining.^{29,33,35}

Whilst the concept of an imbalance between training and recovery resulting in fatigue may be widely accepted, the term “fatigue” may have various connotations depending on the context in which it is applied;^{36,37} although it has been consistently defined as a reduction in maximal force generating capacity^{4,38,39} that is thought to involve many factors at various sites within the neuromuscular system.⁴⁰

A number of models have been proposed to describe the factors that contribute to fatigue, including the cardiovascular/anaerobic model, energy supply/depletion model, muscle trauma model, thermoregulatory model, biomechanical model and neuromuscular model.^{36,41} Although all of these models provide some insight into the possible origins of reduced force production capability, the study of neuromuscular

fatigue is potentially one of the most useful for determining both acute and longer term fatigue responses to training and competition in high level athletes.

2.2.1 Neuromuscular Fatigue

Neuromuscular fatigue is traditionally associated with changes anywhere on the pathway between the brain and muscle fibre, with effects at the motor unit level considered peripheral and events occurring in the brain or spinal cord considered central.⁸ The level of force produced by a muscle in a voluntary contraction is determined by the firing frequency and pattern of motor unit recruitment, and increasing either of these aspects plays a role in increasing the force of the contraction.⁴² Fatigued muscle is known to develop tension more slowly than non-fatigued muscle and displays a simultaneous extension of the relaxation phase⁴² in conjunction with a decrease in peak force production capability.⁴³ It has also been suggested that this reversible reduction in efficiency may be present regardless of whether or not a given workload can be maintained.⁵ The exact site on the chain from the Central Nervous System (CNS) (Central Activation Failure) to the contractile tissue (neuromuscular propagation failure) where neuromuscular fatigue is controlled is unclear; and it has been reported that both central and peripheral factors are responsible for reduced force production capability.⁴⁴ Research aimed at determining the site and most appropriate method of measuring neuromuscular fatigue has been pursued quite vigorously.^{4-7,9,38,42-54}

2.2.2 Central Fatigue

Central or supraspinal fatigue,⁵ has been referred to as an “activity induced” inability to fully activate a muscle and as a progressive reduction in voluntary activation during exercise.⁴ It is thought that central fatigue exists as a protective mechanism to guard against irreparable exercise induced muscle damage (EIMD) or systemic failure.^{5,8} During maximum fatiguing contractions, the increase in centrally mediated neural drive is insufficient to compensate for failure at a peripheral level.⁴¹ The precise cause of central fatigue is inconclusive but may be associated with intracortical inhibition. Changes in serotonin, dopamine and acetylcholine concentrations in the brain may reduce neural drive, resulting in decreased fibre recruitment.^{36,41}

The CNS contribution to fatigue is often assumed, based on the comparison of the force of contraction elicited by electrical stimulation of motor axons (which removes the contribution of the CNS to the contraction) to voluntary contractions. If there is no difference in contraction measures between the voluntary and electrically stimulated conditions, it is taken to represent the absence of central fatigue.⁴⁴

2.2.3 Peripheral Fatigue

A contrasting explanation for decreased force production is the contribution of peripheral mechanisms. Peripheral fatigue suggests a decreased ability of the muscle itself to produce force.⁶ The Neuromuscular Propagation Failure Theory suggests that the ability of a muscle to produce force is determined by the muscle's response to an electrical stimulus.⁵³ Inhibition is believed to occur at the sarcolemma or α -motor neuron level where a reflex response from the muscle results in reduced neural activation. The mechanism underlying this response appears related to increased Na^+ and reduced K^+ gradients via less than optimal activation of the Na^+ / K^+ pump. This in turn causes a decrease in action potential and ultimately less Ca^{2+} release from the sarcoplasmic reticulum and/or a total loss of excitability in selected fibres resulting in decreased force production.^{8,36,41} Similarly, the Muscle Power or Peripheral Failure Theory proposes that changes occur at the muscle level. This theory suggests that force production limitations occur as a result of Ca^{2+} release and/or regulation and variations in cross bridge cycling^{36,41} and proposes that individual motor units may experience fatigue.

2.2.4 Central and Peripheral Contributions to Neuromuscular Fatigue

Numerous studies have been conducted in an attempt to quantify the relative contributions of central and peripheral factors to fatigue.⁴⁻⁶ Exercise induced central fatigue can be studied with the use of the twitch interpolation technique which assesses the degree of voluntary activation of a muscle.⁵ Central fatigue can also be analysed by the response of a particular muscle to transcranial electrical or magnetic stimulation.⁵ In

a study where central and peripheral fatigue was induced by electromyostimulation (EMS), subjects were required to complete a battery of neuromuscular tests before and after 13 min of EMS-induced resistance exercise.⁴ The results of this study showed the maximum voluntary contraction (MVC) of the plantar flexor muscles to be significantly decreased after EMS (9.4%, $p < 0.01$). The authors concluded that both central and peripheral factors contributed to the muscular fatigue detected and importantly that the EMS induced reduction in neural drive came in response to decreased motor unit recruitment and/or firing rate within the central nervous system. Whilst this data provides some insight into the mechanisms that may contribute to neuromuscular fatigue, the non-functional nature of the protocol involved raises the question of applicability to sporting tasks. It may also be particularly difficult to utilise these methods of neuromuscular fatigue assessment in athletic settings.

Another study investigating central and peripheral contributions to fatigue examined fatigue during repeated maximal voluntary isometric plantar flexions.⁶ During the fatiguing bouts (9 bouts of 10 MVC), changes in joint torque, level of activation, resting twitch amplitude, electromyography (EMG) signals, and presynaptic inhibition were investigated. These researchers concluded that MVC's induced both peripheral and central fatigue and that only peripheral fatigue was correlated with a decrease in plantar flexor strength ($r^2 = 0.57$). An interesting outcome of this study was that those subjects who had a poor ability to achieve full voluntary activation during the MVC's developed less peripheral fatigue. This suggests that the lack of ability to completely activate a muscle may actually lead to prolonged endurance, however as these results also reflect the response of a small muscle mass, this research may not be representative of the factors important during large muscle mass sporting performance.

A potentially important consideration in understanding neuromuscular fatigue is the distinction between high and low frequency fatigue. High frequency fatigue (> 50 Hz) is characterised by a rapid loss of force production capability at high frequency and an equally rapid recovery when the stimulation frequency is reduced.⁵⁵ However, frequencies in excess of 50 Hz are reportedly uncommon in voluntary activation.⁵⁵ Conversely, low frequency fatigue results in force reduction at low frequency. Reduced Ca^{2+} release in each action potential has been implicated in causing low frequency fatigue after submaximal stretch-shorten cycle (SSC) exercise.^{40,56} In the

case of low frequency fatigue, recovery is slow and occurs over hours or days, which suggests this type of fatigue may have the most important implications for exercise.⁵⁵ Therefore, it may be important to assess neuromuscular fatigue in elite ARF players over an extended post match period to gain an insight into the influence of low frequency fatigue, the pattern of response, and assess the ability of variables to monitor this potentially important phenomenon.

2.3 Assessing Neuromuscular Fatigue

Reduced output of motor neurons is thought to occur as a result of the attempt by the CNS to optimise force output under fatigue conditions. Due to this, various EMG measures are considered effective in quantifying neuromuscular fatigue.³⁶ A study examining EMG signs of neuromuscular fatigue in the vastus lateralis muscle during cycling performance discovered changes in one or more EMG variables in the majority of subjects.⁴⁸ Notably, these investigators reported large individual differences in the pattern of EMG variations in response to the fatiguing exercise. This group concluded that neuromuscular fatigue accompanied ventilatory threshold and that the accumulation of metabolic by-products was potentially responsible.⁴⁸ However, as demonstrated previously, it may be that other fatigue models are able to partly explain the mechanism of neuromuscular fatigue evident in this research.^{36,41} The large inter-individual differences demonstrated in this study may have important implications for the assessment of neuromuscular fatigue and it is likely that individual response patterns, including appropriate baseline data, should be determined prior to assessing neuromuscular fatigue status.

In another study utilising EMG to measure fatigue, Bonato et al.⁴⁹ examined fatigue related changes in the EMG signal of trunk and limb musculature during a repetitive lifting task. They calculated an EMG based fatigue index for dynamic contractions utilising the instantaneous median frequency. This measure showed a significant decrease during a cyclic lifting task ($p < 0.05$) and mean MVC force recorded immediately after the task was also significantly reduced ($p < 0.01$) when compared to baseline measures, but significantly increased again after a 1 minute recovery ($p < 0.05$). This apparently short recovery time may have implications for the

assessment of neuromuscular fatigue.⁴⁹ In the same study, maximum torque of working muscles significantly decreased during the lifting task. As MVC's performed in static situations immediately before and after dynamic fatiguing exercise displayed different patterns from those seen in the dynamically obtained data; these researchers have questioned the validity of previous studies where dynamic fatigue is inferred from performance on static tasks.⁴⁹ As the response and impact of neuromuscular fatigue in athletes is related to dynamic activity, the use of non-functional static tasks appears questionable and it is possible that a movement closely related to that performed in athletic events would produce the most valid assessment of neuromuscular status.

In addition to the use of EMG, the mechanomyogram (MMG) has been suggested as a useful tool in the detection of changes in mechanical properties of muscle due to fatigue. This is because during fatiguing contractions, similar responses in EMG and MMG signals (ie. increased amplitude and decreased frequency) have been reported.⁵⁰ It is assumed that oscillations measured on the surface of the muscle are based on mechanical events within the muscle and therefore changes in motor unit recruitment, firing pattern and synchronisation could be measured via MMG.⁵⁰ However, there is still uncertainty as to which physiological changes due to fatigue are detectable through changes in MMG, although it is possible that MMG may be able to more accurately reflect the decrease in MVC than EMG.⁵⁰ A study examining EMG and MMG responses of the biceps brachii muscle to 30 minutes of isometric elbow flexion, found clear evidence of fatigue after intermittent contractions at extremely low force levels (10% and 30% of MVC).⁵⁰ The fatigue was still detectable after 30 minutes of recovery. Interestingly, this long lasting fatigue was displayed differently in EMG and MMG signals. These results appear to raise questions about the ability of these two methods to be used interchangeably when assessing residual fatigue. There also appears to be similar limitations to the use of MMG in athletic populations that exist with regard to EMG.

Despite the capacity of these studies to indicate the origins and mechanisms associated with neuromuscular fatigue, they are limited by the non-functional nature of the fatigue protocols and the complexity of the measurement equipment and variables.⁵⁷ In addition, the assessment of central activation does not usually occur during the

exercise intervention, and measures of central fatigue are often made using activities that are different from the fatigue task.^{8,57} From this data, it is unclear as to whether fatigue interventions more representative of sporting performance exhibit the same pattern of response in EMG and MMG measures.

2.4 Neuromuscular Fatigue and Athletic Performance

The use of various EMG and MMG parameters in the assessment of neuromuscular fatigue is well established. However, there is less work examining the fatiguing effect of functional athletic activities via EMG, MMG or the use of non-invasive performance oriented tasks. In support of this concept, it has been suggested that a practical test capable of assessing low frequency fatigue in hard training athletes is warranted.⁵⁸ In fact, it has been claimed that the use of a particular fatigue measure can be justified depending on whether the interest is in underlying physiological mechanisms or functional relevance measured via performance outcomes.⁵⁷

In one study utilising athletic performance and a semi-functional assessment task, 9 well trained endurance runners and triathletes completed a treadmill run for 300 min at 55% of previously determined maximal aerobic velocity.³⁸ Each hour, subjects were required to perform neuromuscular tests including 2 x 5s MVC of the knee extensor muscles with 1 min rest between trials. Reductions in MVC were significant after the 4th hour and reached -28% ($p < 0.01$) at the end of exercise. MVC was still significantly depressed after a 30 min recovery period. Whilst the results of this study indicated changes in MVC as a result of athletic activity, it is questionable whether the fatiguing task employed is representative of many sporting events.

Ten kilometre run performance has been used repeatedly as an intervention in fatigue studies.^{59,60} One project⁵⁹ monitored a number of variables including EMG activity, ground reaction forces, MVC and 20m sprint performance. The results showed a decrease in maximal running speed and an increase in contact time during the 20m sprint. These authors concluded that the 10km run negatively affected neuromuscular function, resulting in an impairment of force generating capacity. This project provides evidence of the effect of athletic activity on neuromuscular function and how its

impairment can affect subsequent explosive performance. It may be that high intensity functional tasks such as a 20m sprint or other explosive actions are useful tools for monitoring neuromuscular fatigue.

Further evidence of the impact of athletic activity has been demonstrated via examination of the fatigue effects of marathon performance. The impact of this endurance event were measured via isometric MVC, maximal M waves, Hoffman reflex and stretch reflex during a repeated SSC activity (10 maximal drop jumps from a predetermined optimal height).⁴⁵ Maximal isometric force and maximal rate of force production in the soleus and gastrocnemius muscles were reduced by $29.8 \pm 10.9\%$ and $29.5 \pm 27.1\%$ respectively, immediately after the marathon. Scores obtained 2h after completion had recovered significantly ($p < 0.05$). Values continued to return to pre marathon levels until full recovery was reached 2 days post exercise, however the maximal rate of force production was still significantly lower than pre marathon levels ($p < 0.05$) at this time point. The authors concluded that the most significant changes were seen in landing responses from the SSC activity which did not appear to have improved 6 days post exercise. Push off force and time was significantly ($p < 0.05$) reduced resulting in a decreased takeoff velocity. These findings lend support to the notion that SSC activities, particularly those measurement variables reflecting force-time parameters, may be capable of detecting long lasting low frequency neuromuscular fatigue resulting from athletic events.

The results of EMG research suggest that a number of parameters may be useful in assessing both the level and site of fatigue in athletic populations, however there appear to be numerous limitations to use of these measurement techniques. Part of this limitation lies in the regular use of MVC's, which although able to assist in the assessment of total muscle fatigue, are distinctly different from dynamic movements where contractions often involve less than 50% of total muscle mass activated concurrently.⁵⁷ Importantly, the use of isokinetic contractions is unrepresentative of normal movements that have regular velocity changes and the protocols used often involve contraction velocities well below those seen in dynamic activity.⁵⁷ Some authors have also raised methodological concerns related to surface EMG which suggests results should be viewed with caution.⁸

Although determining the precise origin of decreased force production capability as a result of neuromuscular fatigue is important from a mechanistic perspective, it is potentially less important from a practical viewpoint. It is arguable that the choice of model for examining neuromuscular fatigue depends on the specific purpose of the assessment.⁵⁷ In the case of elite ARF players, the detection and impact of neuromuscular fatigue may be the most critical aspect, and a simple athletic task may be more useful than complex methods of assessment considering the limitations involved with complicated equipment, a large number of athletes and the requirement for prompt feedback. Given the results of previous work,^{45,59} SSC activities may be capable of detecting neuromuscular fatigue resulting from athletic performance.

2.4.1 Stretch Shorten Cycle Assessment of Neuromuscular Fatigue

Consistent with this notion, previous studies suggest that SSC activities may be useful in the study of neuromuscular fatigue.^{46,61,62} This is related to the fact that in such movements; metabolic, mechanical and neural elements are taxed in conjunction with disturbances of stretch-reflex activation.⁴⁶ Recovery from SSC exercise occurs in two phases that are characterised by an initial large drop in performance, followed by a transient recovery and then a further drop that generally peaks 48 to 72h post exercise.⁴⁶ The initial decline in the ability to produce force has been attributed to metabolic processes and the secondary reduction to inflammatory processes,⁴⁶ although as suggested earlier this may be considered a simplification of the mechanisms responsible for low frequency neuromuscular fatigue.^{36,41}

Various forms of vertical jump (VJ) have been used widely in the assessment of athletic performance^{10-12,22,33,63-72} and it has been proposed that assessing repetitive VJ power may also be important.¹¹ It is interesting that the elastic behaviour of muscles has been shown to be similar in VJ and running, suggesting VJ may be highly relevant for assessing various parameters important in sport.⁷³ Significantly, a number of factors have been identified as critical in the performance of a VJ including the contribution of arm swing, sequencing and timing of segmental actions, and speed and amplitude of the countermovement.⁶³ Any assessment in which a version of a single or repeated VJ is

utilised should ensure a technique is chosen that limits the potential for change in, and therefore influence of these factors. A distinction of vertical jump type can be made on the basis of the inclusion or absence of an arm swing and/or countermovement in the performance. For the purpose of this review, a VJ with no preparatory countermovement has been defined as a Squat Jump (SQJ) and a VJ with a preceding countermovement phase is referred to as a CMJ.

Countermovement jump peak force, power and jump height have been used to assess the impact of both SSC and isometric contractions.⁶⁹ Interestingly, there was no difference in jump height decrease (15.8 v 17.3%) between the two fatigue protocols. Kinematic analysis revealed no change in concentric phase duration maximal hip flexion (i.e. squat depth) following the fatigue protocol. Importantly, the fatigue protocol produced a significant decrease ($p < 0.05$) in work at the knee joint during the concentric phase of the CMJ and a decrease ($p = 0.03$) in knee joint stiffness during the eccentric phase (as measured by the eccentric and transition phases in the SSC fatigue group). The decreased jump performance was attributed to a reduction in the ability of the knee extensors to generate force via a decrease in muscle-tendon stiffness. This group suggested that the mechanisms involved in decreased performance in high stretch-no impact movements were different to high stretch-high impact performance. If this is the case, single and repeated CMJ protocols may assess quite different fatigue mechanisms and possibly follow a different recovery timeline.

In a similar study to investigate the segmental coordination of a CMJ, subjects were required to perform a maximal CMJ with and without fatigue.⁷⁴ In this case, fatigue was induced via maximal knee flexion and extension movements at 50% of the subject's body weight. The results of this research revealed no change in jump height due to the fatigue protocol, however reductions were noted in peak joint angular velocity and power at the knee joint and these peak values occurred earlier when compared to the non fatigued state. These authors concluded that neural input during the fatigued performance may have played a role in the changes noted and speculated training programs aiming to increase jump height should avoid severe fatigue, as this may result in the adoption of sub optimal and non specific coordination patterns. In conjunction with previous research,⁶⁹ this suggests that whilst CMJ height may be minimally effected by fatigue interventions, the possibility exists for changes in other

mechanical variables or technique during CMJ performance under fatigue. If this is the case, an examination of changes in variables other than height appears warranted and results of previous work^{69,74} suggest a variable capable of reflecting technique alterations could be useful.

Whilst the preceding research has utilised various CMJ parameters to assess neuromuscular fatigue, the protocols utilised have been largely unrepresentative of sporting performance. Therefore, studies involving realistic sporting fatigue protocols may be the most relevant. One attempt to utilise such a protocol was a study aimed at assessing the fatigue response to 180min of tennis match play which was also assessed with the use of a SQJ, CMJ and 15s of repeated CMJ's.⁷⁰ Countermovement jump peak power post match was significantly different to pre ($p < 0.05$) whilst both SQJ and CMJ peak power continued to be depressed 30min post game compared to pre ($p < 0.001$ and $p < 0.05$ respectively). Interestingly there was no change to leg stiffness as measured via the repeated CMJ test.

In another realistic fatigue intervention study utilising 10km run performance, the authors hypothesized that any muscular force reduction evident immediately post race would be due to acute fatigue from the exercise and that changes that continued long after the event would be the result of chronic fatigue within the contractile unit.⁶⁰ This research utilised various isokinetic strength measures, a treadmill test of aerobic power and a CMJ. Results showed a significant reduction in knee flexion peak torque and CMJ peak force immediately post race ($p < 0.05$). Countermovement jump rate of force development was also significantly reduced ($p < 0.05$) post race but there was no significant change in peak power at any post race point. The results of this research provide further support for the role of functional SSC activities in measuring fatigue from athletic events; however the lack of reliability data for the CMJ measures suggests the results should be viewed with some caution. It is interesting to note the contrasting response of power measures (assuming they are reliable) seen in this study and 180min of tennis match play.⁷⁰ It could be that the response and sensitivity of variables is affected by the dominant movement patterns of the event. The constant requirement to accelerate, decelerate, and change direction and consequent high eccentric loading experienced in an intermittent sport such as tennis; may exceed that required for more

steady state activities and specifically impact the fatigue response as measured via CMJ variables.

The preceding research has primarily utilised various forms of single CMJ to assess the impact of athletic performance. In addition to this, multiple jump and hop performance has also been used to investigate the neuromuscular response to exercise.^{10,61,62,75} In one study, subjects performed a single leg horizontal hop onto a forceplate in fatigued and non-fatigued states.⁶² The results of this study showed an increase in knee range of motion during landing when in a fatigued state ($p = 0.012$). Peak horizontal and vertical ground reaction forces were not different from those prior to the fatigue intervention.⁶² A study by Augustsson et al.⁶¹ involving horizontal hops for maximal distance showed decreased hip and knee angles and ground reaction forces during take-off in the fatigued hop condition. As previously described, it appears that critical technique manipulations might occur with neuromuscular fatigue that may result in functional measures with an ability to reflect altered technique proving useful.

A potentially confounding influence in the use of multiple jumps or hops is the impact of metabolic limitations on performance. Despite this, numerous works have utilised such protocols. For example, Bosco et al.¹⁰ compared performance on a 60s continuous jump test to performance on a modified Wingate cycle test, Margaria stair climb test and 60m sprint. These authors suggested that the results of their study demonstrated a close relationship between the 60s jumping test and Wingate test. Blood lactate levels recorded after the 60s jump test averaged 8.1 mmol/l, whilst the Wingate and Margaria tests produced blood lactate means of 15.4 and 14.3 mmol/l respectively. The high levels of blood lactate produced by all three tests suggest that metabolic limitations are most detrimental to their performance.¹⁰ Further evidence of metabolic limitations to long duration protocols exists in work involving completion of 40 repeated CMJ's at 1 Hz with and without femoral artery cuff occlusion.¹¹ In this study, power output decreased by approximately 20% regardless of condition, leading the authors to conclude that performance was limited by metabolic capacity.

In another protocol likely to be limited by metabolic factors, 60s of continuous jumping was used to establish the relationship between power, fibre type distribution and fatigue.⁶⁶ In this study, well trained long jumpers were required to utilise a

standardised knee bend of approximately 90 degrees. The results indicated that average mechanical power for the first 15s period of the 60s test was significantly related to fast twitch fibre % of the vastus lateralis muscle ($r = 0.69, p < 0.05$). This finding led the authors to the conclusion that such a test may be a useful discriminator of fibre type distribution. It is questionable whether a protocol similar to that employed in this study would be useful for assessing neuromuscular fatigue in elite ARF footballers. In addition to the potential metabolic constraints on performance, it may be difficult to illicit a maximum response throughout competitive seasons if such a test was to be used for monitoring purposes because of its length and physically taxing nature. Furthermore, a test of this duration would take considerable time to implement with large squads of athletes which may therefore make it impractical.

Although repeated CMJ protocols may be useful for assessing different capacities than single jump protocols, their ability to detect neuromuscular fatigue, as opposed to fatigue limited by metabolic factors, appears to depend on their duration. In addition, as the positional error of repeated jumps has been shown to be approximately 6%,¹² it is possible that this error may be decreased by the performance of less repetitions in a shorter duration test. Despite the limitations of previously examined protocols, the potential exists for repeated jump tests to be useful in the assessment of low frequency neuromuscular fatigue.⁵⁸

Further to earlier research relying on repeated CMJ protocols of extended duration, some attempt has been made to utilise repeated SSC activities of relatively short duration. In a study aimed at establishing the usefulness of practical tests for monitoring performance, fatigue and recovery in 16 male triathletes, Coutts et al.⁷⁵ examined numerous variables including a 5 single leg bound for distance. Subjects were divided into normal and intensified training groups. The performance of the intensified training group was significantly ($p = 0.04$) reduced during the 4 week overload training period and returned to pre training levels following a 2 week taper. The 5 bound distance remained unchanged across the study period in the normal training load group. These results may provide evidence that short duration repeated SSC movements are sensitive to neuromuscular changes brought about by increases in training load, or at least those loads deliberately increased above normal. Whether these results apply to different repetitive SSC tasks, different training protocols or a variety of sports is

unclear. Furthermore, the level of neuromuscular fatigue (sensitivity) required to illicit reductions in performance on this type of test is also unknown.

2.4.2 Team Sport and Stretch Shorten Cycle Assessment of Neuromuscular Fatigue

The use of CMJ or SQJ protocols to study the fatiguing effect of team game performance is limited. A study by Hoffman et al.⁶⁸ examined the effect of a soccer game on maximal performance whilst changes during a competitive college football game have also been analysed.²² The impact of handball training and match play has been assessed with various performance tests including a CMJ⁷² and the influence of a season of collegiate big ten soccer on numerous parameters including CMJ has also been evaluated.⁷⁶ In addition, the impact of simulated soccer match play on SQJ and CMJ performance has also been investigated.⁷⁷

In an examination of the impact of soccer performance, subjects completed a SQJ and CMJ 24h pre match, immediately pre match, 15 minutes post match and again 24h post match.⁶⁸ Analysis was made comparing starters and non-starters. Results showed no significant differences between starters and non starters in SQJ performance at any time point. Starters showed a significant ($p \leq 0.05$) decline in peak power from pre to post match in the CMJ and there was a significant difference in this measure between starters and non-starters at 24 hrs post match. Peak force declined significantly in both jump conditions from immediately pre match to 24h post match in the starting group. Significant correlations were found between playing time and a number of variables including CMJ and SQJ peak power immediately post game ($r = -0.49$ and -0.57 respectively). Playing time and SQJ peak force was significantly correlated ($r = -0.47$) 24 hours post game. The authors of this study pointed to the interesting fact that there was no correlation between playing time and change in jump performance measures. Although speculative, it may be that in some cases performance of a single jump does not allow a significant distinction between pre and post event scores and this limitation may apply more to some variables (eg. height) than others. Multiple jumps or the measurement of alternative variables from a single CMJ may allow greater scope for

the appearance of contrasting scores. Different sports may also elicit unique responses in the same variables or highlight the value of alternative measures.

The impact of simulated soccer match play on SQJ, CMJ and drop jump performance has been evaluated with a protocol using a non-motorised treadmill in which fatigue was induced with 42min of intermittent soccer specific activity.⁷⁷ In this study SQJ and CMJ height was significantly ($p < 0.05$) decreased after the treadmill protocol. Interestingly the authors noted a tendency for greater performance reductions in the jumps that utilise the SSC. It may be that intermittent and continuous fatigue protocols induce different neuromuscular responses and it would seem logical to investigate neuromuscular fatigue in team sport athletes with the use of contraction modes that most closely mimic performance requirements.

The performance of starters and non-starters on various SQJ and CMJ measures pre and post match and at the end of each quarter of play (Quarter 1 – Quarter 4) was analysed in collegiate American football subjects.²² The results of this study showed a significant decline in SQJ peak force (19% and 16%) at Quarter 1 for starters and non-starters respectively. Squat jump peak power decreased by 22% at Quarter 1 in the non-starters group, and 18% in the starters group at Quarter 2. There was no significant difference in SQJ maximum rate of force development at any measurement point. The CMJ revealed a significantly lower (20%, $p < 0.05$) peak force in the starters group at Quarter 2 compared to pre match. It was concluded that fatigue in jumping movements occurs within the first quarter of play during a football match. The authors hypothesised that elevated lactate levels may precede neurological fatigue and that such central fatigue may have a greater effect on performance. This hypothesis may have important applications to ARF, as fatigue due to metabolic factors is probably transient, whilst centrally generated neuromuscular fatigue may have longer lasting implications. In addition, if the aim is to examine neuromuscular fatigue independently of metabolic factors, it is likely that sufficient recovery time should be allowed between completion of intense performance and maximum jump testing.

The preceding work examining neuromuscular fatigue in team sport athletes with the use of SSC tasks provides an important insight into the potential value of these measurements in real world athletic settings. However, the majority of team sport

competitions involve more than single matches and an understanding of longer term, tournament or season long responses seems important. A number of researchers have attempted to address this issue.^{33,71,72,76}

An evaluation of responses in starters and non-starters in collegiate soccer players involved in a big ten season of 19 games over 11 weeks showed significant changes.⁷⁶ In this study, starters displayed a significant ($p < 0.05$) decrease in jump height at the end of the competition season compared to baseline scores. Jump height of non-starters was higher ($p < 0.05$) than starters at the end of the season and non-starters displayed no change in jump height across the season. The authors of this study suggested the force decrements responsible for the reduced CMJ performance were brought about by a catabolic physiological status. The results of this study suggest that jump height, as measured with a Vertec device, is sensitive to a season of high level soccer performance. Whether this response occurs in other team sport athletes, particularly those at the elite level is yet to be determined. It is also unclear as to whether jump height, due to limited resolution in such a test apparatus, lacks the level of sensitivity to detect and track smaller changes that may be functionally important in high performance subjects.

Neuromuscular fatigue in elite female handball players during a training camp and tournament has been assessed via isokinetic knee extension, 20m sprint and CMJ.⁷² These researchers revealed reductions of $6.9 \pm 1.3\%$ in CMJ height on the second and third day of a training camp. Over the course of 3 matches in 3 days there was a $6.7 \pm 1.3\%$ reduction in CMJ height. This report indicated the average jump score to be 6% lower than baseline on day 5 of the training camp. Interestingly this test had been preceded by 48h of recovery. The authors concluded that players developed neuromuscular fatigue during the training camp and the international tournament and that recovery periods during these events were insufficient to allow return to baseline levels. The fact that CMJ performance had not recovered to baseline after 48h rest adds further support to the notion of SSC tasks being sensitive to disturbance from high training and competition loads and therefore useful for monitoring purposes in team sport subjects as measures of low frequency neuromuscular fatigue.

In addition to competition responses in team sport players, the response of this type of athlete to deliberate overreaching training protocols has also been analysed with a CMJ.^{33,71} In one study, Coutts et al.³³ compared responses in semi-professional rugby league players to 6 weeks of normal or deliberately intensified training. Numerous variables including CMJ height were measured but no significant difference in CMJ performance between groups was found. In another study using semi-professional rugby league players as subjects, CMJ height was unchanged after an overload training phase followed by a taper.⁷¹

There appears to be some variation in the ability of SSC tasks to detect changes in neuromuscular status as a result of team game performance. This may be related to the sensitivity of the variables utilised or the impact of particular team sports. It is also possible that an examination of responses over periods longer than single matches may provide insight into the relationships between CMJ measures and training and competition load and performance. It could therefore be valuable to assess the response of numerous single and repeated CMJ variables to elite team sport performance with a view to determining those that are most useful for identifying changes due to specific activities.

2.4.3 Influence of Exercise Induced Muscle Damage

The influence of exercise induced muscle damage (EIMD) resulting in delayed onset muscle soreness (DOMS) on performance measures has received considerable attention.⁷⁸⁻⁸⁷ Defined as muscular discomfort or pain resulting from unaccustomed activity, particularly of the type involving eccentric contractions,^{78,79} it is generally accepted that DOMS peaks 24 -72h after exercise.⁸¹ The exact mechanism responsible for DOMS is yet to be identified; although it is thought that disruption to the contractile mechanism may play a role⁸⁰ in conjunction with various inflammatory responses,⁷⁸ including increases in serum levels of creatine kinase (CK). Some studies have shown EIMD to result in a decrease in force production capability^{81,82,84,87} whilst others have shown no decrement in concentric strength scores in response to EIMD.⁸⁰

In a study using isometric elbow flexor strength to measure the influence of previous intense eccentric exercise, a decrease was found to have occurred immediately after exercise ($p < 0.01$).⁸² Strength scores were lowest (46% lower than baseline score $p < 0.01$) at 24h post exercise. A 20% ($p < 0.01$) deficit remained 11 days post intervention. A study by Harrison and Gaffney⁸⁴ examined performance on a number of variables after a fatiguing exercise involving performance on 7 sets of 10 maximal eccentric knee extensions. The authors of this study concluded that this protocol produced temporary muscle damage and decrements in performance as evidenced by decreases in SQJ, CMJ and drop jump performance. They also suggested that jump performance may be an early indicator of muscle damage. Similar results were obtained by Smith et al.,⁸¹ who discovered the greatest loss of 1RM concentric strength to have occurred at 48h post exercise ($p < 0.0001$). This strength loss followed completion of 3 sets of 12 repetitions of eccentric bench press at 80% of concentric 1RM. Studies utilising isokinetic strength measures have produced comparable results with decreased force at various angular velocities following fatiguing eccentric contractions.⁸⁸

In contrast to the results of these studies, no change was found in concentric elbow flexor strength after performance of 7 sets of 10 bicep curls at 70% of 1RM, although the authors suggested this may have been due to a lack of sensitivity in the concentric strength measure (ie. minimum increment for assessment of 1RM concentric strength was 2.5 kg).⁸⁰ This finding highlights the importance of high reliability and sensitivity in measures that are being utilised where EIMD and subsequent DOMS are potential outcomes.

An interesting occurrence associated with EIMD is known as the repeated bout effect. The repeated bout effect suggests that a prior bout of eccentric exercise provides protection against damage from subsequent bouts.^{79,83,89-92} It appears that even low volumes of eccentric exercise confer this protective effect as it has been demonstrated prior exposure to 2 and 6 maximal eccentric contractions provided a blunting of responses such as decrements in isometric strength, increases in plasma CK and muscle soreness to a subsequent bout of 24 maximal eccentric contractions.⁸⁹ In agreement with this finding, a 46% decrease in maximal isometric force ($p < 0.05$) was discovered immediately after an initial eccentric exercise bout.⁹² Force then gradually recovered despite the application of subsequent eccentric exercise 3 and 6 days after the initial

bout. Further evidence of the existence of the repeated bout effect exists in a study where maximal isometric force measured immediately post exercise in a second and third bout was significantly less ($p < 0.05$) than after the original bout of damaging exercise.⁷⁹ An important conclusion of this study was that muscle soreness was not an indicator of the extent of muscle damage.

The results of muscle damage studies may have important implications for the training and testing of high performance athletes as it is likely that they will sometimes be required to perform in the presence of DOMS. The repeated bout effect is likely to influence the response to eccentric exercise in the majority of high level athletic, particularly field team sport settings, as athletes in these programs undergo regular training with exposure to repeated eccentric contractions. Due to this regular, and usually progressive loading, it is likely that some protective effect is conferred on athletes in these environments. Therefore, it may be particularly important to utilise tests of neuromuscular fatigue, rather than rely on reports of muscle soreness levels alone. These reports may underestimate the degree of muscle damage, whereas an objective performance measure capable of assessing low frequency fatigue might provide a more useful indication of the degree of EIMD. The existence of the repeated bout effect is also likely to be of some benefit in discriminating between decrements to performance resulting from EIMD or other causes of neuromuscular fatigue (eg. reduced Ca^{2+} release). Those familiar with a particular program and group of athletes may be able to identify whether any unaccustomed exercise is likely to have resulted in muscle damage and a resultant change in measurement variables, or sufficient previous loading has conferred a protective effect against EIMD. This may suggest alternate sources of neuromuscular fatigue are responsible for performance decrements.

2.5 Countermovement Jump Reliability

Although VJ measurement has been described as a key component in any training study,^{93,94} limited data exists detailing the reliability of variables other than jump height and power obtained during performance of these movements in elite team sport athletes. This is despite the suggestion that reliability in physical tests is a critical

factor in the ability of tests to determine changes in athletic capacity⁹⁴⁻⁹⁷ and the fact that VJ scores may be dependent on the method of assessment.⁹³

Assessment of the protocols and usefulness of various methods used to calculate test reliability has received considerable attention.^{95,97-100} These methods include the Intraclass correlation, Regression analysis, Technical Error of Measurement (TEM), Limits of Agreement and Coefficient of Variation ($CV\%$).^{95,97,98,100} In simple terms, reliability reflects the variation of a subjects score on repeated tests.⁹⁷ This variation arises from both biological and technological sources.^{95,97} Although numerous calculations exist for the determination of reliability, it has previously been suggested that $CV\%$ may be the most appropriate expression of reliability in sports science as it is a dimensionless measure.^{97,99} In addition, calculation of the TEM and smallest worthwhile change (SWC) important to athletes in a performance setting has also been advocated.⁹⁵ This approach allows classification of the sensitivity of tests in line with their capacity to detect the smallest magnitudes of change important to high level athletes and determine with more certainty whether a change of biological origin has occurred.^{95,97} In elite athlete settings, it seems paramount that changes in performance can be attributed to improved or decreased capacity. Due to this, calculation of reliability is critical and this may be particularly important in the assessment of changes in variables reflecting variation in neuromuscular status.

Whilst a number of methods exist for examining CMJ and SQJ performance, it has been suggested that the most accurate method is to calculate the change in height of the centre of mass utilising high speed video technology.^{93,101} The utility of this methodology may be limited where large numbers of athletes are required to be tested in a short period of time or access to expensive equipment is difficult. Other methods include the use of linear position transducers to directly measure jump height and excellent reliability has been reported with this technology.¹⁰²

Although the use of such technology may be an option, the use of methods involving mathematical assumptions to calculate values for variables such as power have been developed⁹³ and these equations has received considerable attention.^{64,101} It has been demonstrated that significant differences exist between jump height measured via change in centre of mass and jump height calculated using assumptions such as

flight time or take-off velocity⁹³. However although each method is claimed to possess excellent reliability (*CV%* 13.4-18.3),⁹³ it may be argued that such values do not represent high reliability. The reliability of variables in addition to height measured during single and relatively high repetition CMJ performance has been assessed previously^{10,103} and these variables have also been used to examine the impact of athletic performance.^{11,22,65,68}

Power measured during 60s of a repeated maximal CMJ has been shown to be reliable (*ICC* = 0.95)¹⁰ and continuous CMJ's conducted for 30s on a force plate showed mean jump height to be a reliable measure (*r* = 0.97) although peak height scores were less reliable.¹⁰³ The authors of this study concluded that this may have been partially due to the requirement to achieve a minimum 90° knee angle during each countermovement. This suggests that a protocol where a self selected knee angle is utilised, may provide higher reliability and that a shorter test duration may minimise the error if multiple jumps are being assessed.

Another study involving a high number of repetitions¹⁰⁴ investigated the reliability of mean power, peak power, mean velocity, peak velocity, and work during 30s of continuous bench throws and SQJ's using 30% of 1 repetition maximum. Results revealed *ICC*'s of between 0.80 and 0.96 with *CV* of between 3.0% and 7.6%. The results of this research suggest that numerous variables obtained during repetitive jump performance have the potential to display high reliability; however it is questionable whether a test of duration similar to the one in this study is capable of isolating the contribution of neuromuscular fatigue to performance.

In a study to establish the influence of familiarization on reliability in SQJ,CMJ and sprinting, Moir et al.⁹⁴ tested male recreational athletes in a SQJ and CMJ performed on a timing mat at body weight and loaded with a 10kg jacket. Subjects were tested on 5 separate days over a 3 week period with a minimum of 48h separating test occasions. The results of this study showed CMJ height during body weight jumps to be highly reliable with a *CV* of 2.4% and an *ICC* of 0.93. In a similar protocol, displacement of the centre of gravity in the SQJ and CMJ performed on a timing mat proved to be a reliable measure across 6 days of testing, with *CV* of 5.4% and 6.3% respectively.¹⁰⁵ Further research using a contact mat to determine CMJ reliability has

reported *ICC* and *TE* values of 0.98 and 2.8% respectively.¹⁰⁶ Interestingly, the use of a contact or timing mat requires the application of mathematical assumptions to substitute for the fact that no force measures are obtainable with this type of equipment. It would seem feasible that reliability may be enhanced by the utilisation of equipment that limits the requirement for mathematical assumption to determine variable values even though such calculations may be useful providing appropriate technique is maintained. Alternatively, the use of variables that are measured directly by particular apparatus may improve reliability.

Little data is available describing the reliability of an extensive number of variables obtained during a short duration (~5s) repeated CMJ or a single CMJ in an elite team sport population. In a study examining the influence of vibration on jumping performance Bosco et al.¹⁰⁷ utilised a 5s repeated countermovement jump. In this protocol subjects were required to produce a maximum jump effort with minimal knee bend. They reported power variables to have a reliability of $r = 0.95$. Technical restrictions imposed on subjects such as minimising knee bend may make implementation of such a protocol difficult in the elite athlete setting. It may be advantageous to limit technical requirements to ensure maximum subject compliance and reliability. In a protocol of similar duration, an alternate left and right leg 5 bound for distance has also been used to assess fatigue and recovery in triathletes.⁷⁵ The authors reported that the position of the heel of the rear foot after the 5th jump had a *TE* of 0.25 m or 2.3%. Whilst the authors of this study rated this reliability level as good, it is possible that such a test is a comparatively gross performance measure. Variables obtained from more precise measurement devices such as force plates or timing mats may increase the likelihood of not only high reliability but also allow investigation of numerous parameters from a single performance.

For valid conclusions to be drawn regarding changes in pre and post scores, the reliability of the variables in question must first be established. There appears to be no reported data available that provides *TE* or *CV%* data for a wide range of variables that can be obtained in single or repeated CMJ's in elite team sport athletes. It may be of particular importance to examine the reliability of these variables in relation to their ability to detect the *SWC* that is of importance to athletic performance.⁹⁵

2.6 Neuromuscular Fatigue Summary

There is a substantial body of work that has attempted to describe the mechanisms and relative contributions of central and peripheral factors to neuromuscular fatigue. In addition, previous research has utilised EMG, MMG and functional movements such as a CMJ to assess the impact of athletic performance on neuromuscular status. Despite this, little work has investigated the impact of elite level team sport on a wide range of reliable CMJ jump variables in an attempt to determine their expected pattern of response or their suitability for both acute and longer term monitoring of neuromuscular fatigue. The typical pattern of response and the impact of change in measured variables on performance in elite ARF players is unknown. Therefore, clarification of these issues appears warranted.

2.7 Endocrine Variables as Indicators of Fatigue Status

The influence of exercise on the levels of various hormones, particularly T, C and their ratio value T:C, has been studied extensively in both laboratory^{13-19,108-112} and field settings.^{20,21,23,24,30,33-35,71,113-126} Cortisol is a major glucocorticoid and has an important role in both metabolism and immune function.¹¹⁰ Release of C is stimulated by adrenocorticotrophic hormone (ACTH) which is over secreted as a response to the increased sensitivity of the hypothalamo-pituitary axis (HPA) to stress, and the rise in C occurs approximately 15-30mins after ACTH release.¹²⁷ Cortisol stimulates gluconeogenesis which results in the sparing of blood glucose and protein stores.¹¹⁰ In metabolism, C causes increases in protein degradation in muscle and connective tissue, amino acid transport into the liver, liver glycogen synthesis, gluconeogenesis and lipolysis.¹²⁷ In contrast, reductions are caused to muscle protein synthesis, amino acid transport to muscle and glucose uptake and utilisation.^{110,127} Cortisol is considered an important stress hormone and its presence is said to indicate the neuroendocrine system's response to exercise.^{14,25,128} There is believed to be an intensity threshold for C secretion that is close to the lactate threshold but further increases in C are not dependant on an equivalent increase in exercise intensity.¹²⁹ Cortisol response is also

likely to be related to exercise duration and increased by sprint interval training.¹²⁹ In addition, C is influenced by circadian rhythms with values higher in the morning and decreasing across the day.¹⁵

Testosterone is anabolic in nature, important in muscle hypertrophy and increasing muscle glycogen synthesis,^{117,130} and has also been implicated in aggressive behaviour.¹³¹ Testosterone synthesis and secretion increases due to the effects of catecholamines, and plasma concentrations of T increase in response to acute exercise of a moderate or higher intensity.¹²⁷ Testosterone response appears inverse to exercise duration, with levels declining with increases in duration, whilst increases in intensity beyond 60-80% VO₂max are not associated with increased T concentration.¹²⁹ Like C, T follows a diurnal pattern with levels decreasing by 30-40% between early morning and late evening.^{23,132}

2.7.1 Hormonal Measurement

As mentioned earlier, an imbalance between training stress and recovery can lead to overreaching or overtraining syndrome^{25,26} and it appears possible that various hormonal measures may assist in assessing the response to training.^{25,26} Cortisol and T vary in opposite directions in response to exercise and this may represent an imbalance between anabolic and catabolic hormones resulting in a decreased T:C when training and performance loads are increased.¹³³ However, the results of studies analysing the response of T, C and T:C in relation to training and competition and performance are varied.^{15,18,30,35,109,114,116,117,121,122,125,134-136}

A potential limitation for analysis of the hormonal response to exercise has been the need for a blood sample.¹⁴ In an examination of the efficacy of obtaining C values via salivary samples Neary et. al.,¹⁴ compared blood and saliva values. This group reported an ICC of $r = 0.995$ between serum and salivary C values, suggesting that salivary C accurately reflects free (unbound) C. This result has been confirmed in other work reporting a strong relationship between salivary and serum unbound C both at rest ($r = 0.93$) and during exercise ($r = 0.90$).¹³⁷ It has also been reported that salivary measures of C and T concentrations are independent of saliva flow rate.¹³⁸ The use of

saliva samples for monitoring hormonal responses to exercise greatly increases the opportunity to obtain data in athletic populations as the procedure is less invasive.

2.7.2 Hormonal Response to Exercise

In an attempt to quantify the hormonal response to exercise, a number of laboratory based experiments have been conducted with varying results.^{13-19,108-112} A study using recreationally trained males who performed 1h cycle ergometer efforts at various intensities (44.5 – 76% VO₂ peak), determined that C concentrations were significantly higher ($p < 0.004$) during high intensity than low intensity exercise or rest.¹¹⁰ These researchers further concluded that there was no change in C at any intensity with durations of less than 40 minutes.

Tremblay et al.¹¹¹ evaluated the effect of endurance exercise duration on post-exercise hormone response. This group required trained male volunteer's complete 40, 80, and 120min runs at 50 - 55% of VO_{2max}. Results of this study revealed C levels were higher during the 120min run compared to all other durations and that C decreased across time in all efforts apart from the 120min. The increase in C during the 120min run, despite its low intensity, was suggested to have resulted from reaching a threshold work volume. In the same study, T was significantly higher ($p < 0.05$) in the 80min run compared to the 40min run. Testosterone:Cortisol ratio was greater ($p < 0.05$) at rest than during the 80min and 120min runs. A major conclusion was that at a constant intensity, exercise duration influences the endocrine response to endurance exercise in trained males. This finding may have important implications for manipulating the training volume and intensity for athletes throughout different phases of the training cycle, although the results of this study do not clarify whether chronic variations are likely to mimic acute responses.

Research on the influence of periodised versus high monotony cycle training provides some interesting insights into their relative influence on hormonal and performance responses over the longer term.¹⁰⁹ One study demonstrated a 51% increase in T in a periodised training group and a 55% decrease in the monotony training group.¹⁰⁹ There was also an 11.5% increase in maximum power output in the periodised

group (ES = 0.91). Whilst neither group displayed changes in C; T:C increased by 19% in the periodised group and fell by 64% in the monotony group. It may be concluded from this research that a manipulation in training load that provides for periods of high volume or intensity interspersed with periods of relatively lighter load results in a more favourable endocrine response.

In a study examining the effect of high intensity cycle training on a number of endocrine parameters, there was no significant effect of the training program on hormonal measures at rest; although T was 20% lower after the high intensity training intervention.¹¹² Cortisol:Testosterone (as opposed to T:C) increased by approximately 35%, however this was also not considered important. It was concluded that there is a stimulatory effect of T on immune parameters in recreational cyclists but this is lost with an increase in training volume. The impact of changes in levels of T on immune function may have important implications for team sport environments. If the results of this study apply to other sports environments, periods of training and competition resulting in chronic reductions of T may expose large numbers of athletes to potential illness. It is also possible that the changes found in T and C:T were practically important despite the fact that the results were not considered statistically significant.

In addition to a large body of work that has examined the hormonal response to endurance exercise in laboratory settings; the hormonal response to strength training has also been investigated. Bosco et. al.¹⁶ researched the hormonal response of male sprinters to a strength training session and found both T and C were significantly lower ($p < 0.05$) after the session. It has been hypothesised that the specific organisation of the strength training stimulus may affect the hormonal response.¹⁰⁸ The acute and long term (12 week) hormonal responses of untrained men to 3-5 sets of 10 repetitions with and without a 30s intra-set rest found no differences in T concentrations between the regimens.¹⁰⁸ At 30min post activity, T was significantly higher ($p < 0.05$) in both groups after the period of training. It was concluded that although the two regimens produced markedly different lactate responses, the similarity in T response suggested that this marker is unaffected by metabolic acidosis. In the longer term, no difference was seen in the resting concentration of T and C between the two strength training groups. As the volume was equated in this study, it may be that total volume and/or intensity are more important from a hormonal response point of view than individual set configuration. It

is also possible that athletes with a high training status may respond differently, particularly over periods longer than 12 weeks. This may be important for long term adaptations, similar to those that may occur in season long team sport environments, where athletes are exposed to a regular strength training stimulus in conjunction with other training modalities.

One study has examined the impact of multiple training stimuli via the response of various hormones to a block of training in power trained athletes.¹⁸ This work involved subjects completing 5 weeks of strength, speed, and plyometric training. Results of this study showed an increase (17.6 – 23.3 nmol/l, $p < 0.01$) in the fasting level of T after the 5 week training period. Fasting levels of C and T:C were not different from pre test levels. Following a set of short repeated sprints (3 x 4 x 60m) there was no change in hormonal levels, although a set of repeated 20s sprints to exhaustion caused significant increases in T ($p = 0.02$), C ($p = 0.006$) and T:C ($p = 0.006$). These researchers concluded that the participants were in an anabolic state during the 5 week training period. Although providing some evidence that an anabolic status can be maintained for a relatively short period of time, the effect of multiple training stimuli over extended training and competition phases on relative anabolic and catabolic status is unclear.

The hormonal response to resistance training under the influence of DOMS has also been evaluated.¹⁷ In this study, subjects performed 7 sets of bilateral knee extensions at 40% of 1RM which they repeated 48h later. Testosterone increased after both the first and second bouts whilst C decreased in the same way. The results of this study did not suggest any alteration to increases in C or T as a result of the influence of DOMS. This may be important for analysing the response to training loads in a sport such as ARF as it suggests that hormonal responses are not affected by DOMS.

2.7.3 Hormonal Response in Athletic Environments

Despite providing an important platform for the study of hormonal responses to exercise, results obtained in laboratory studies can be limited in terms of their applicability to elite training and competition environments. Numerous researchers have attempted to address the limitations associated with laboratory based projects by examining hormonal response in athletic settings.^{20,21,23,24,30,34,113-119,123,124,133-136} The hormonal response to sports such as swimming, rowing and running has been extensively evaluated.^{30,113-116,119,135} Even though a large number of studies have been conducted previously, the response of hormonal measures to this type of exercise in individual sport athletes is not universal. A large body of research raises doubts about the efficacy of hormonal variables such as T, C or T:C^{15,30,35,114,116,121,122,125,134} including the possibility that increased C is an early marker of intensified training and overreaching whilst decreased C may be a late marker¹³⁹. Other work^{117,135,136} indicates potential value for regular sampling of hormonal variables.

An analysis of the influence of a taper in competitive swimmers on hormonal responses found that levels of T, C, and T:C did not differ from other times in training. Despite this, changes in T:C mirrored performance changes.¹¹⁴ As a result, T:C may be a useful measure of the relationship between hormonal status and performance. In another study conducted using swimmers, there was no difference between levels of C when comparing stale and non-stale athletes.³⁰ In this study, a period of tapering was insufficient to allow stale swimmers to recover their level of performance. From the results of a further swimming study¹¹⁶ where performance, psychological and blood markers were analysed; it was concluded that T and C were not reliable markers of overreaching or overtraining. This conclusion was reached because the swimmers performance did not change in response to a two week taper period. The results of these swimming studies suggest that hormonal markers such as T and C may not be useful as monitoring variables. However, it may be premature to rule out the use of these variables for measuring the response to training for a number of reasons. It could be that longer training and taper periods are required to cause meaningful changes, or that sports involving different muscle actions (eg. higher eccentric loads) may produce

markedly different responses. The potential relationship between T:C and performance appears worthy of detailed long term investigation in a team sport environment.

In another study using elite level swimmers as subjects, saliva samples were collected 30min and 15min post treadmill run to exhaustion and these were compared to samples collected pre and post swim competition.¹⁵ Samples were also collected on a rest day to serve as a comparison. The treadmill test resulted in C rising from a pre test mean of 4.44 nmol/l to a post test mean of 8.46 nmol/l ($p < 0.0001$) and this was not influenced by time of day. Cortisol concentrations after the swimming competition rose from a mean of 6.59 nmol/l to 9.65 nmol/l ($p < 0.0025$). These findings suggest that the psychological stress related to competition caused a greater rise in C. The results of this study would have been even more interesting and applicable to elite sport if values had been obtained for an out of competition swim test rather than a treadmill test and compared to those obtained in competition.

The influence of a period of intensified training followed by a taper in well trained middle distance runners found T correlated with a low intensity taper ($r = -0.78$).¹²² Testosterone was also related to high intensity running distance during the taper period ($r = 0.68$) and percentage change in T during the taper as well as high intensity distance during the 3 weeks prior to the taper ($r = 0.73$). A similar study measured the impact of training frequency during a taper in well trained middle distance runners.¹⁴⁰ After 18 weeks of a training season, subjects were assigned to either a high frequency taper where loads were progressively decreased each day, or moderate frequency taper where loads were also progressively reduced and in addition subjects rested every third day. Results showed an increase in total T and free T to total T ratio after the taper period. However, this response was not different between groups. Cortisol and free T:C were unaffected by either taper. The authors hypothesised that the post taper increase in total T may have been a response to the preceding intense training. Although it was concluded that high frequency taper was more effective, the performance changes could not be explained by any of the blood measures. This study also raises questions regarding the ability of hormonal measures to reflect variations in performance, however the change noted in T after the taper highlights the potential for this measure and therefore anabolic processes to be influenced by training and recovery cycles.

Similar results were noted in a study to determine the effects of cross training on well trained runners, where participants were assigned to a run only or cross training group.¹²¹ The run only group completed their normal run training load and an additional 3 run sessions per week whilst the cross training group completed their normal run training load plus 3 additional bicycle ergometer sessions. Cortisol, T and T:C were not different between the run only and cross training groups.

The change in C over ten months of training in untrained men and triathletes, has been assessed in relation to training load and fatigue.¹³⁴ Subjects in this study provided samples on 3 occasions during different phases of the training period. Samples were collected at each occasion on waking at 0700h and at 0730h. Cortisol was significantly effected by training period ($p = 0.04$). This seasonal variation in hormonal response may be highly important in designing effective long term training programs. In addition, where urinary C excretion was similar between the untrained group and triathletes, overnight urinary cortisone excretion was significantly higher ($p = 0.003$) in the trained group, suggesting an enhanced ability of the triathletes to inactivate C into cortisone. This has been proposed as a protective mechanism against prolonged increase in C secretion.¹³⁴ A potentially important finding of the research was the increase in C response noted in the untrained group between November and June (prior to competition commencing) that did not occur in the triathletes. In both groups, a 24h rest period resulted in similar urinary C excretion. Within this study, a sub-group of triathletes who were considered to be overtrained exhibited the same salivary C pattern as the other triathletes. This suggests that neither waking nor morning salivary C are effective markers of overtraining, however this conclusion may not apply to athletes in different sports, particularly those involved in high level weekly competitions.

A study by Coutts et al.;³⁵ examined hormonal response to intensified training in experienced male triathletes. They found no change in T or C between the normal training and intensified training groups during the 4 weeks of the study. However T:C ratio significantly increased and C significantly decreased in the intensified group during the taper period compared to the post training measure, indicating an increase in anabolic:catabolic balance. The researchers concluded that performance measures are the only definitive measure of overreaching in endurance athletes and that a decrease in physiological state occurs with increased training load. Whilst such a conclusion seems

appropriate, the response of endocrine measures in this study suggest they may be capable of providing an early indication of relative anabolic:catabolic status that in turn could allow manipulation of the training stimulus to avoid unplanned fatigue.

Changes in C have been analysed in relation to 6 days of increased training volume (approximately 50% more than the weekly volume during the preceding month) in international canoeists in order to determine whether these changes were reflective of overreaching indicated by decreased performance.¹²⁵ The authors concluded that the subjects decreased performance was evidence of a state of overreaching, however C was significantly lower ($p < 0.05$) after the camp than in the baseline measure. It may have been expected that C would increase in response to an increased load, however 6 days may be an insufficient period to cause such an increase. It is also possible that the baseline measure was actually an elevated result due to psychological stress about the impending training camp and therefore the post camp measure appeared lower. Alternatively, different modes of exercise may produce different C responses. These results pose interesting questions about the response of C to increased training loads. It may be that responses differ according to exercise mode and in the case of this particular study, that 6 days of loading or the volume of overload may have been insufficient to cause an increase in C.

Analysis of the hormonal response in elite speed skaters over an 8 month period showed T:C to be significantly different ($p < 0.05$) after periods of heavy training and competition.¹³⁵ Importantly, this study showed variations in performance followed fluctuations in T:C. These researchers concluded that free T:C was a reliable marker for the study of training and recovery during a season of speed skating. A unique study examining hormonal responses to a 36 hole golf competition revealed significant increases in C ($p < 0.05$) during competition, whilst T did not change during competition compared to baseline. Testosterone:Cortisol fell during competition and there were high correlations between T ($r = 0.71$) and T:C ($r = 0.82$) measured prior to competition and score at the end of 36 holes.¹²⁰

Although analysis in a variety of sports provides important data on the potential value and mechanisms associated with changes in endocrine status, their non-contact nature is in contrast to many team sports and ARF in particular. Due to this, studies

involving combat sport athletes may provide important insights, and responses in this type of athlete have been studied on multiple occasions.^{117,136} A study using Judo players found that the duration of attacks in a competition were related to pre fight T levels ($p < 0.04$).¹¹⁷ In another study using Judo players, Filaire et al.¹³⁶ discovered C levels measured on the day of a competition to be significantly higher ($p < 0.01$) than rest day scores. The researchers also found C levels to be higher before the first fight of an inter-regional competition than before the first fight of a regional competition. This suggests a psychological component to the rise in C associated with the more important competition. Interestingly these researchers concluded that the mean fight time was too short to cause a high post competition C response. If there is a critical duration required to elicit such a response in a highly physical and aggressive sport, it is worth considering whether contact team sport athletes are also prone to a variation in response linked to performance duration.

It is arguable that the major conclusion to be drawn from previous work examining endocrine response in individual athletes is that a large variation in response is possible. This may be due to the variety of training load interventions utilised and the length of study periods. It is also possible that changes in the endocrine measures studied do not reflect modifications to training load or performance. Therefore, it may be critical to evaluate the usefulness of these measures via analysis of results from sports similar to the one of interest and ultimately, research in specific environments may be the only method of obtaining valid and practically meaningful results to make definitive conclusions regarding the value of endocrine measures for monitoring training and performance.

2.7.4 Hormonal Response in Team Sport

A number of researchers have examined the influence of team sport competition on endocrine response to both single matches and extended training and competition periods.^{20,21,23,24,33,34,71,123,124,133} Elloumi et. al.¹³³ examined the behaviour of T, C and T:C during and after a rugby match. Both T and C values were lower at 2000h on a rest day than at 0800h on the same day and competition day values for these hormones were comparable to rest day levels. Samples taken immediately post game revealed T had

decreased by 16% ($p < 0.05$) and C increased by 148% ($p < 0.001$). In the days following the match, T was higher ($p < 0.05$) than the rest day and C levels decreased from the first to the fourth rest day ($p < 0.05$). Whilst 8am T:C on match day was similar to rest day values, post match values dropped by 62 % ($p < 0.001$) compared to the rest day. Testosterone:Cortisol values at 8am were higher in the four days post-match than at 8am on the rest day. These researchers concluded that the high T:C was associated with fatigue from the match. This finding is extremely interesting and raises a number of issues. It may be that T:C in rugby players is elevated in response to high workloads and is a reflection of the body's anabolic state. Conversely, T:C response in this case may not be indicative of cellular level responses and the subjects may have in fact been in a catabolic state. It may also be possible that the rest day values in this study do not reflect a true fatigue free baseline, therefore confounding the results and subsequent conclusions.

Another study in rugby league found no correlation between C levels and results from an overtraining questionnaire.²³ Coutts et al.;³³ came to a similar conclusion after discovering no significant difference between T and T:C in normal or intensive training groups of semi professional rugby league players. Although in this case, both measures were significantly decreased ($p < 0.05$) by overload training. A further study using semi-professional rugby league players found a significant reduction in T:C following a 6 week period of increased training.⁷¹ The researchers suggested that the change in T:C was due to inadequate recovery between training sessions. The apparent interaction between T:C and training loads and periods of recovery in team sport athletes warrants further investigation. If a decrease in T:C is able to reflect periods of hard training and/or inadequate recovery in this type of team sport athlete, this measure may be extremely valuable in assisting the identification of those athletes who have responded differently than expected. Therefore, T:C may be helpful in early diagnosis of various fatigue states in athletes involved in contact team sports.

Further work in a high contact football code examined the hormonal response to an American Football training camp and in-season period, and reported C levels to be elevated during the competition phase but within normal ranges.²¹ These researchers found a 20% reduction in C ($p < 0.05$) and a lowered T:C ($p < 0.05$) at the end of the 10 day training camp. Testosterone:Cortisol was lower at the end of the season ($p < 0.05$),

although the authors suggested its effect was benign as levels were still within a normal range. Testosterone levels remained at baseline throughout the season. It may have been expected that C would have increased after the training camp, although the specific organisation of the training stimulus may have an influence on endocrine response. Interestingly, this study showed large changes ($p < 0.05$) in blood CK when comparing measures taken at the start and end of the training camp, however levels remained static across the competitive season. This was interpreted to be a reflection of a “contact” adaptation to the pre season training camp. If such an adaptation occurs it could have important implications for the training of ARF, particularly in terms of manipulating periods and loads of contact stress in training.

Another study in American Football analysed responses in collegiate level skill position players.³⁴ This group found T levels to be within normal ranges following 4 weeks of strength training only, however a significant ($p < 0.05$) decline was evident 5 weeks later following a period of combined strength training and conditioning. Testosterone then returned to baseline levels following 4 weeks of football specific practise. Cortisol and T:C remained unchanged from baseline levels throughout the study period, however the authors noted that when individual results were examined, T:C had decreased in 6 subjects by more than 30%, which may suggest a catabolic status. It was concluded that hormone responses measured in this group indicated athletes did not enter an overreaching or overtraining state. A potentially critical result in this study was a non-significant rise in T:C during one period of training that mirrored performance changes. This may provide some evidence of the value of T:C as a marker of training adaptation. In addition, it was suggested that the lack of improvement or decrease in performance measures of sprint speed, VJ and agility were indicative of functional overreaching. As pointed out by the authors of this study, it would be interesting to examine responses in these variables in athletes involved in more physically demanding roles and therefore more intense training programs. The hormonal response noted in this project indicates that T, C and T:C may have a role in assisting the monitoring of adaptations to training and this may particularly be the case with the higher training loads experienced by elite ARF players.

A group of college soccer players served as subjects to examine differences in C response between practice and match situations.¹²³ In this study, C samples were

provided immediately pre and post match and practise. Both starters and non-starters displayed large increases (ES = 1.54) from pre to post match although starters showed greater post match concentrations than non-starters ($p < 0.05$). Interestingly, the results of this study showed no difference in C response between pre practice and pre match values. This suggests there was no anticipatory rise in response to competition which may be considered surprising given previous research,¹³⁶ however the large increases in C provide further evidence of the influence of team sport training and competition on C.

The responses detailed regarding endocrine variation as a result of single matches in team sport athletes suggest these measures are potentially useful for monitoring purposes. However, as the majority of team sport competitions are likely to involve more than single matches, it seems important to assess the usefulness of these same variables over extended training and competition phases.

2.7.5 Hormonal Responses During Extended Competition Seasons

An examination of the influence of a season of professional soccer competition revealed 9 months of training to have no influence on salivary C levels, although samples taken before and after an intensive training block showed a significant decrease in T ($p < 0.01$) at the 11:30am and 5:00pm sample times.²⁴ Testosterone:Cortisol followed a similar pattern. Testosterone was also shown to have significantly decreased ($p < 0.01$) between the start of pre season training and end of competition. The authors of this paper concluded that a decrease in T:C did not lead to decreased performance or overtraining, probably because the ratio remained within normal limits. Despite the authors' conclusion, it is extremely interesting and potentially important that an intensive training block had an impact on levels of T and T:C. It is possible that this pattern of response during periods of "normal" training load could be indicative of an athlete failing to cope with the prescribed load.

Further research in soccer examined the impact of a season of semi-professional soccer competition on both T and C.¹²⁴ This group found C to be increased ($p < 0.001$) by training, with rises 12 weeks after the commencement of training and at the end of the season (24 weeks). Testosterone levels increased ($p < 0.001$) at the 3 week mark, but beyond this time levels were not different from pre training scores. It was concluded

that the increase in T may have been associated with the increased need for glycogen storage and replenishment in response to the training load. The authors further concluded that factors other than physical activity may have been responsible for the continuation of elevated C beyond the high training loads of the pre season phase. Whilst a variety of physical and psychological factors may have contributed to the continued changes noted in C, it is not possible to rule out physical factors as the dominant force. Due to this, regular monitoring of C may be a useful tool over long competition seasons.

The response of numerous hormonal and performance measures in Division 1 collegiate soccer starters and non-starters was studied over a 19 match competitive season with 6 measurement time points.⁷⁶ Testosterone increased ($p < 0.05$) in both starters and non-starters at the completion of the season compared to 3 weeks after the start. The only difference between groups occurred at the 3 week measurement with non-starters displaying higher levels. Interestingly, C was higher ($p < 0.05$) in non-starters than starters at baseline, 1 week prior to the commencement of the season. At week 8, starters showed an increase ($p < 0.05$) in C. Testosterone:Cortisol was elevated in the non-starters group at the end of the season compared to baseline and after 3 weeks of competition. An important finding of this study was that both starters and non-starters suffered performance decrements throughout the season, suggesting that responses are independent of match play. In other words, training may have a larger impact on performance variables and hormonal markers than competition. It was also concluded that T and C represent possible means for monitoring the stress of training and competition. The responses documented in this report lend support to the usefulness of numerous monitoring variables throughout competitive seasons in team sport athletes. Given the non-contact nature of soccer, it appears necessary to investigate changes in contact team sports.

In another study examining responses to a season of soccer match play, 20 professional players were tested on 4 occasions throughout a season after periods of different volumes and intensities of training.²⁸ These authors found resting salivary C to be significantly elevated ($p < 0.05$) at the end of the season after progressively increasing from baseline. Levels had returned to normal by the commencement of the following season and T remained unchanged ($p < 0.05$) throughout the study period.

Testosterone:Cortisol was relatively unchanged except for a non-significant decrease at the end of the season compared to baseline. Whilst the change in T:C was concluded to be non-significant, it may represent further evidence of the potential benefit of this measure for monitoring responses in team sport athletes over long seasons. Coupled with the elevations noted in C at the same time and a non-significant decrease in T, this study provides further evidence of the type of response that may be expected throughout a season of high level team sport competition. It seems that in this study T, C and T:C suggest progression towards a catabolic state in the final phase of the competitive season. This may be related to the extended nature of competitive seasons and the accumulation of periods of less than optimal recovery over time.

2.8 Relationship between Neuromuscular and Endocrine Measures

In addition to the neuromuscular and endocrine responses that have been identified in various settings, there is some suggestion that a relationship exists between the response in these variables.^{71,76} Previous work has identified significant correlations between C and CMJ performance, however this relationship existed only in a group of soccer players considered non-starters.⁷⁶ This study also found significant correlations between T:C and CMJ performance in starters at the end of the season. In contrast, research utilising rugby league players found no significant correlation between endocrine measures and performance, although the authors suggested that the existence of a catabolic state prior to endurance testing negatively influenced performance.⁷¹ It would seem logical that a catabolic state resulting in decreased muscle mass may influence force production capabilities evident in strength dominated activities, however the possibility of influence over endurance capacities may be particularly important in team sports, where both strength and endurance qualities are important. In this case, the existence of a catabolic environment may have a serious impact on performance. The possibility of an association between hormonal and neuromuscular status in elite team sport athletes raises a number of interesting points. It may be expected that endocrine responses indicative of a catabolic environment precede increases in neuromuscular fatigue exhibited in explosive tasks. However, the regularity of loading and unloading and the length of training and competitive seasons experienced by elite ARF athletes

may alter the timing and/or order of this relationship. If changes in either neuromuscular or endocrine status are related to on field performance changes, these measures would assume a high level of importance for regular monitoring.

2.9 Neuromuscular and Endocrine Response in Australian Rules Football

There is limited data examining the fatigue response to ARF match play that attempts to dissociate metabolic causes from other factors. In an effort to evaluate recovery status, one elite ARF club has utilised a moderate intensity treadmill test with measures of blood lactate and blood glucose.¹⁴¹ This protocol produced suppressed post exercise blood glucose, lactate and heart rate responses at 48h post match. At 96h post match, responses to the exercise protocol were normal. The lower blood glucose and lactate responses were thought to be related to a reduction in muscle glycogen levels. Lower heart rates may have been related to a suppression of sympathetic nervous activity. The author of this paper suggested that measuring these variables could provide an indirect measure of metabolic and hormonal status which may allow detection of conditions that would negatively affect performance. Whilst this approach may have merit, the regular measurement of blood glucose and lactate may be somewhat invasive and other methods may provide a more practical option.

In one study, Dawson et al.;¹⁴² conducted ratings to measure perceptions of muscle soreness, energy levels and measured salivary C in elite ARF players. Subjects also completed a repeated CMJ test consisting of 5 efforts with a 3s pause between each jump. In this study, players participated in an 8 game (4 home and 4 away) period of monitoring with testing sessions 24-48h pre match, 48h post match and 6-7 days post match. Results of this study showed no significantly different response to two different recovery protocols for players in home AFL games, away AFL games and that of state level players. Performance on the CMJ test and C were not different between baseline, 48h and 6-7 days post game. However, ratings of muscle soreness and energy ratings 48h after home games were significantly different ($p < 0.01$) to baseline scores. The lack of significant findings in this research may relate to the limited number of subjects in the study who played in the AFL, as some of the 20 subjects participated in the state

league competition. It is also possible that the measurement variables employed were not sensitive enough to detect changes in performance. For example, repeated CMJ performed where height is measured by a chalk mark on a wall board may provide insufficient resolution. It is also possible that jump height percentage decrement over the five jumps may not be the most appropriate variable. Finally, the measurement of C levels in isolation may provide limited information and its relationship to other hormones such as T via the T:C may provide a useful insight into the responses to training, competition and recovery.

2.10 Summary

Considering the professional nature and full time training load of elite team sport athletes, there is minimal data available examining the fatigue response to training and competition in elite ARF players. This is despite the sites and potential mechanisms involved in neuromuscular fatigue being studied extensively. This lack of data applies both acutely (i.e. in response to single matches) and chronically (i.e. across complete seasons) in ARF. One reason for this may be the difficulty associated with determining the level of neuromuscular fatigue due to technical limitations. Therefore, data obtained from a reliable and easy to administer test capable of assessing low frequency fatigue would substantially enhance the understanding of neuromuscular responses to elite team sport performance. These measures could potentially be valuable in avoiding states of non-functional overreaching or overtraining.

The results of previous research examining endocrine responses in elite sport are inconclusive. This could be due to the potential for sport specific responses and it is possible that in some instances, results considered not statistically significant are practically important. Additionally, acquisition of this data has previously occurred primarily in individual sport athletes, single games or simulated athletic settings and much of the data obtained over longer competition periods relates to non-contact team sports. Technical limitations, costs, and specialised equipment associated with collection of samples and performance of salivary assays may partly explain the lack of information available relating to ARF players. The long term response of such measures

may be helpful in advancing training methodology and optimising training loads in ARF.

CHAPTER 3

3.0 EXPERIMENTAL STUDIES 1 & 2

RELIABILITY OF MEASURES OBTAINED DURING SINGLE AND REPEATED COUNTERMOVEMENT JUMPS

3.1 Abstract

Purpose: To establish the reliability of various measures obtained during single and repeated countermovement jump (CMJ) performance in an elite athlete population.

Methods: Two studies, each involving 15 elite Australian Rules Football (ARF) players were conducted where subjects performed two days, separated by one week, of AM and PM trials of either a single (CMJ1) or 5 repeated CMJ (CMJ5). Each trial was conducted on a portable forceplate. The intra-day, inter-day and overall Typical Error (TE) and Coefficient of variation (CV%) was calculated for numerous variables in each jump type. **Results:** A number of CMJ1 and CMJ5 variables displayed high intra-day, inter-day and overall reliability. In the CMJ1 condition Mean force (CV 1.08%) was the most reliable variable. In the CMJ5, Flight time and Relative mean force displayed the highest repeatability with CV of 1.88% and 1.57% respectively. CMJ1 Mean force was the only variable with an overall TE < smallest worthwhile change (SWC). **Conclusion:** Selected variables obtained during CMJ1 and CMJ5 performance can be used to assess the impact of both acute and chronic training and competition. Variables derived from the CMJ5 may respond differently than their CMJ1 counterparts and should provide insights into differential mechanisms of response and adaptation.

3.2 Introduction

Various forms of the vertical jump (VJ) and mechanical components derived from their performance have been studied previously.^{22,63,65,66,68,94,101-103,106,143-145} Although VJ measurement has been described as a key component in any training study,^{93,94} limited data exists on the reliability of variables other than jump height and power obtained during performance of these movements in elite team sport athletes. This is despite the suggestion that reliability in physical tests is a critical factor in the ability of tests to determine changes in athletic capacities⁹⁴⁻⁹⁶ and the fact that VJ scores may be dependent on the method of assessment.⁹³

As the neuromuscular performance qualities of muscles have been shown to be similar in VJ and running, VJ performance may be highly relevant for assessing various parameters important in sport where running is a chief component.⁷³ The use of high speed video technology,^{93,101} linear position transducers¹⁰² and methods involving mathematical assumptions to calculate values for variables such as power have been utilised.⁹³ It has been shown that significant differences exist between jump height measured via change in centre of mass and jump height calculated using assumptions such as flight time or take-off velocity, however each method is claimed to possess excellent reliability (*CV* 13.4 - 18.3%).⁹³ It may be argued that such values do not represent excellent reliability.

In a study to establish the influence of familiarisation on reliability in VJ and sprinting, Moir et al.⁹⁴ tested male recreational athletes in a squat jump (SQJ) and CMJ performed on a timing mat at body weight and with a 10kg load. The results of this study showed CMJ height during body weight jumps to be highly reliable with a *CV* of 2.4% and an *ICC* of $r = 0.93$. In a similar protocol, Arteaga et al.¹⁰⁵ showed displacement of the centre of gravity in the SQJ and CMJ performed on a timing mat to be a reliable measure with *CV* of 5.4% and 6.3% respectively. Markovic et al.¹⁰⁶ also used a contact mat to determine CMJ reliability and reported an *ICC* of $r = 0.98$ and *TE* values of 2.8%.

It has been proposed that assessing repetitive CMJ power may be valuable in sporting performance.¹¹ Interestingly, a number of factors have been identified as important in the performance of a VJ including the contribution of arm swing, sequencing and timing of segmental actions, and speed and amplitude of the countermovement.⁶³ Any assessment in which a version of a repeated CMJ is utilised should ensure a technique is chosen that limits the potential for change in, and therefore influence of, these contributing factors. In another technique related study, Domire and Challis¹⁴³ found that although ground contact time increased with squat depth prior to a VJ, there was no difference in jump heights from a self selected or imposed deeper position.

The reliability of some variables measured during single and relatively high repetition CMJ's has been assessed previously.^{10,103} These variables have also been used to examine the impact of athletic performance.^{11,22,65,68} Power measured during 60s of a repeated maximal CMJ has previously been shown to be reliable ($r = 0.95$).¹⁰ Continuous CMJ conducted for 30s on a force plate has also shown mean jump height to be a reliable measure ($r = 0.97$) although peak height scores were less reliable.¹⁰³ The authors of this study concluded that this may have been partially due to the requirement to achieve a minimum 90° knee angle during each countermovement. This suggests that a protocol, where a self selected knee angle is utilised, may provide higher reliability and that a shorter test duration may minimise the error. In another study involving a high number of repetitions, Alemany and Pandorf et al.¹⁰⁴ investigated the reliability of mean power, peak power, mean velocity, peak velocity, and work during 30s of continuous SQJ's using 30% of 1 repetition maximum. Results revealed *ICC*'s of between $r = 0.80$ and $r = 0.96$ with *CV* of between 3.0% and 7.6%.

Little data is available describing the reliability of an extensive number of variables obtained during short duration (~5s) repeated CMJ performance. Bosco et al.¹⁰⁷, utilised a 5s repeated CMJ requiring subjects to produce a maximum jump effort with minimal knee bend and reported power variables to have a reliability of $r = 0.95$. The potential exists for variables obtained during short duration (ie. short enough not to be restricted by metabolic limitations) repeated CMJ performance to be valuable in assessing the impact of training programs and performance. For valid conclusions to be drawn regarding changes in pre and post scores, the reliability of the variables in

question must first be established. There appears to be no reported data available that provides *TE* or *CV%* data for variables that can be obtained in this type of repeated CMJ performance in elite team sport athletes. Therefore, the purpose of this study was to establish the reliability of a number of variables obtained during the performance of a single and short duration repeated CMJ in an elite athlete population.

3.2 Methods

3.2.1 Subjects

Fifteen elite ARF players (Study 1 Age 23.3 ± 3.8 years, Height 1.91 ± 0.06 m, Mass 93.05 ± 7.7 kg; Study 2 Age 22.5 ± 2.8 years, Height 1.89 ± 0.06 m, Mass 91.2 ± 8.0 kg) participated in each study. All subjects were squad members of a team that participates in the Australian Football League (AFL) competition. Players had a minimum of 2 years full time training experience at the elite level and regularly performed jumping movements as part of their training routine. The study was approved by the University Human Ethics Committee and all subjects signed an informed consent document.

3.2.3 Design

Two studies were conducted with elite ARF players who completed 2 days of testing, separated by 7 days, of AM and PM trials of a CMJ1 (Study 1) or CMJ5 (Study 2).

3.2.4 Methodology

Subjects performed 3 familiarisation sessions followed by an AM (0900 - 0930h) and PM (1530 - 1600h) trial on Day 1, and an AM and PM trial on Day 2. Trial days were conducted one week apart and training in the 48h prior to each trial day and between AM and PM trials was strictly controlled to ensure no influence on performance. Prior to each trial of the CMJ1 or CMJ5, subjects performed a 2 minute dynamic warm up consisting of various running patterns including jogging, high knees,

heel flicks and skipping. Subjects were required to progressively increase the intensity and range of motion in running patterns until the end of the warm up period to ensure they were capable of maximal performance. Subjects then performed 3 submaximal practice CMJ's prior to the measurement trial. A similar warm up protocol has been shown to positively influence CMJ performance.¹⁴⁶

Each trial session consisted of one attempt at either the CMJ1 or CMJ5. In each study, subjects completed the trials on a commercially available forceplate (400 Series Force Plate - Fitness Technology, Adelaide, Australia) connected to computer software (Ballistic Measurement System - Fitness Technology, Adelaide, Australia) capable of recording vertical ground reaction forces (VGRF) at a sample rate of 200 Hz. In both the CMJ1 and CMJ5 conditions, subjects were required to perform a CMJ with hands held in place on the hips. Based on the influence of arm swing on CMJ performance, previous research has also utilised this technique.^{63,65,94,106,147} In the CMJ1, subjects were instructed to jump as high as possible, whilst in the CMJ5, subjects were required to jump as high as possible for 5 consecutive efforts without a pause between jumps. Countermovement depth was self selected by the subject. A self selected countermovement depth was chosen to assess reliability of variables using a technique requiring minimal intervention thereby maximising the potential application to practical settings where time limitations may exist. Each trial was then analysed using custom designed software (Mathworks, Natick, Massachusetts, USA) capable of automatically detecting values for the variables of interest. To identify different segments of the CMJ1 and CMJ5, a number of critical features were identified. The start of the eccentric phase in the CMJ1 was classified as a reduction of 5% in VGRF and in the CMJ5 as peak VGRF after landing from the previous jump (from jump 2 onwards). The end of the eccentric phase was identified as the minimum VGRF prior to values increasing again. This point also served as the marker for the start of the concentric phase. The end of the concentric phase coincided with leave time ($VGRF < 5N$). Land time was calculated as time when VGRF exceeded 50N. Typical CMJ1 and CMJ5 force traces are displayed in Figure 1.

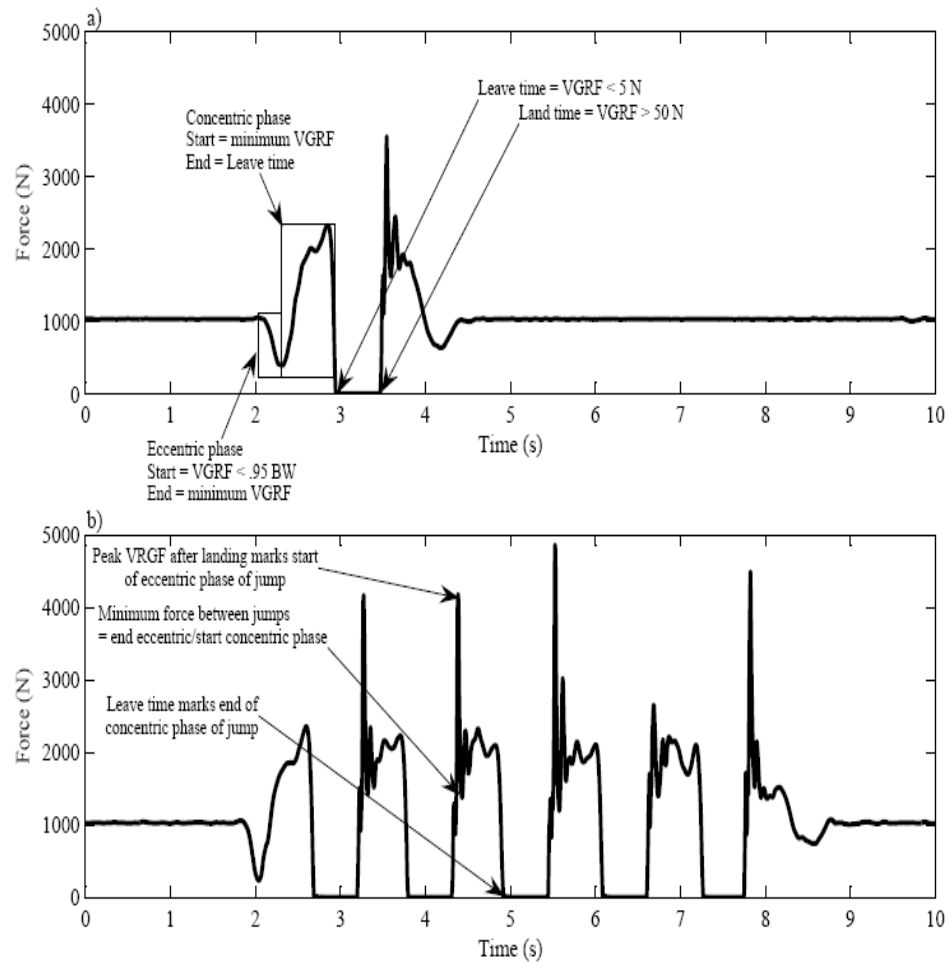


Figure 1. Typical CMJ1 (a) and CMJ5 (b) Force traces with critical features identified.

After identifying these critical features, the following variables were calculated during specific parts of the jump in each trial of the CMJ1 and CMJ5. CMJ5 scores for each variable were calculated as the average score over the 5 jumps of the trial.

Jump height in m: peak height.

Flight time in s: difference between landing and takeoff time.

Peak power in W: highest power generated during the concentric phase.

Relative peak power in w/kg: peak power divided by body mass in kg.

Mean power in W: mean power generated during the concentric phase of the jump.

Relative mean power in w/kg: mean power divided by body mass in kg.

Peak force in N: highest force recorded during the concentric phase.

Relative peak force in N/kg: peak force divided by mass in kg.

Mean force in N: mean force during the concentric phase of the jump.

Relative mean force in N/kg: mean force divided by mass in kg.

Eccentric time in s: length of the eccentric phase measured from the commencement of the countermovement until the commencement of the concentric phase.

Concentric time in s: length of the concentric phase measured from the end of the countermovement phase until the subject leaves the force plate.

Eccentric:Concentric in s: ratio of eccentric time to concentric time.

End eccentric force in N: force at the completion of the eccentric phase.

Flight time:Eccentric time in s: ratio of flight time to eccentric time.

Flight time:Contraction time in s (CMJ1 only): ratio of flight time to contraction time (eccentric + concentric time)

Flight time: Contact time in s (CMJ5 only): ratio of flight time to contact time (eccentric + concentric time).

3.2.5 Statistical Analysis

The Intra-day (AM v PM) and Inter-day (Day 1 v Day 2) reliability of each variable for both the CMJ1 and CMJ5 conditions was calculated to determine *TE* and *CV%* in conjunction with *TE* upper and lower 90% confidence intervals.¹⁴⁸ The average intra-day (Day 1AM v Day 1PM and Day 2AM v Day 2PM) and inter-day (Day 1AM v Day 2AM and Day 1PM v Day 2PM) was then calculated. Overall reliability represents the mean of the intra and inter-day averages. It has been suggested that it is ultimately up to the researcher to decide if a particular variable is reliable enough for its intended use¹⁰⁰. It is also possible that the most reliable tests are not necessarily the most effective for monitoring performance in athletes.⁹⁹ Numerous earlier studies have reported biomechanical variables with *CV* in the vicinity of 10% as reliable.^{61,149-152} As a result, a *CV* of $\leq 10\%$ was set as the criterion to declare a variable as reliable. A 10% *CV* cut off may encourage the examination of variables other than those possessing the highest reliability in future research.

Previous work has suggested that the smallest clinically worthwhile change (*SWC*) represents the smallest change that is of benefit to athletic performance and can be calculated as $0.2 \times$ between-subject *SD*.^{95,96} As a result, variables were considered capable of detecting the *SWC* if the *TE* was \leq *SWC*.⁹⁵

3.3 Results

Intra-day, Inter-day, and Overall Reliability for reliable variables ($CV \leq 10\%$) in CMJ1 and CMJ5 conditions are displayed in Tables 1-4. Tables show Mean, *SD*, *TE* and 90% Lower and Upper Confidence Limits, *SWC*, and *CV%*.

3.3.1 Intra-day reliability

Reliable CMJ1 variables are displayed in Table 1. Mean force had a $TE < SWC$. Eccentric time and Flight time:Eccentric time showed marginal reliability with *CV%* of 11.6 and 11.4 respectively. Concentric time ($CV 17.1\%$) and Concentric time:Eccentric time ($CV 16.5\%$) were less reliable. End eccentric force was the most unreliable CMJ1 variable with a *CV* of 92.6%.

Table 2 shows CMJ5 reliable variables. Height appeared extremely unreliable ($CV 24.7\%$) whilst variables such as Flight time:Contact time ($CV 13.3\%$), Mean power ($CV 11.0\%$), Relative mean power ($CV 11.5\%$) and FLT:ET ($CV 11.4\%$) showed marginal reliability. No CMJ5 variables showed a $TE < SWC$. Mean power and Relative mean power were reliable in the CMJ1 condition but this was not replicated in the CMJ5 condition. However, End eccentric force proved reliable in the CMJ5 despite poor intra-day repeatability in the CMJ1.

Table 1. CMJ1 Intra-day reliable variables. Values are reported as Mean, TE and 90% Lower and Upper CI, SWC and CV%. TE reflects noise in test scores generated from biological and technological sources. SWC represents the smallest change that is of benefit to athletic performance.

	Mean	TE	LOWER 90%CI	UPPER 90%CI	SWC	CV%
Height (m)	0.488	0.024	0.018	0.035	0.007	5.2
Flight time (s)	0.586	0.017	0.013	0.025	0.006	2.9
Peak power (w)	5014	166	127	242	112	3.5
Relative peak power (w/kg)	54	2	1	3	1	3.6
Mean power (w)	765	52	40	78	20	6.9
Relative mean power (w/kg)	8	1	0.5	1	0.2	7.1
Peak force (N)	2163	77	59	115	41	3.5
Relative peak force (N/kg)	23	0.8	0.6	1.2	0.3	3.4
Mean force (N)	1233	13	10	20	20	1.1
Relative mean force (N/kg)	13	0.16	0.12	0.24	0.1	1.2
Flight time:Contraction time (s)	0.807	0.056	0.043	0.082	0.027	6.1

Table 2. CMJ5 Intra-day reliable variables. Values are reported as Mean, TE and 90% Lower and Upper CI, SWC and CV%. TE reflects noise in test scores generated from biological and technological sources. SWC represents the smallest change that is of benefit to athletic performance.

	MEAN	TE	LOWER 90%CI	UPPER 90%CI	SWC	CV%
Flight time (s)	0.519	0.009	0.007	0.014	0.003	2.0
Peak power (w)	4740	210	161	306	77	4.4
Relative peak power (w/kg)	52	2	2	3	1	3.8
Peak force (N)	2121	69	53	101	25	3.3
Relative peak force (N/kg)	23	1	0.5	1.0	0.23	2.8
Mean force (N)	821	18	14	26	9	2.4
Relative mean force (N/kg)	9	0.13	0.10	0.19	0.03	1.5
End eccentric force (N)	1034	92	70	134	23	9.5

3.3.2 Inter-day reliability

CMJ1 inter-day reliable variables are shown in Table 3. They exhibited similar results to the intra-day comparison, however Flight time:Contraction time (*CV* 10.4%) was less reliable than in the intra-day comparison.

Table 3. CMJ1 Inter-day reliable variables. Values are reported as Mean, TE and 90% Lower and Upper CI, SWC and CV%. TE reflects noise in test scores generated from biological and technological sources. SWC represents the smallest change that is of benefit to athletic performance.

	MEAN	TE	LOWER 90%CI	UPPER 90% CI	SWC	CV%
Height (m)	0.488	0.023	0.018	0.034	0.006	5.0
Flight time (s)	0.586	0.020	0.015	0.029	0.005	3.3
Peak power (w)	5014	147	113	214	76	2.9
Relative peak power (w/kg)	54	2	1	2	1	3.0
Mean power (w)	766	42	32	62	15	5.5
Relative mean power (w/kg)	8	0.5	0.4	0.7	0.2	5.7
Peak force (N)	2163	48	36	71	26	2.2
Relative peak force (N/kg)	23	0.5	0.4	0.8	0.2	2.1
Mean force (N)	1233	12	9	18	11	1.0
Relative mean force (N/kg)	13	0.2	0.1	0.2	0.05	1.3

Following a similar pattern, CMJ5 inter-day reliability (Table 4) was comparable to intra-day results; End eccentric force (*CV* 18.4%) demonstrated lower reliability. Height continued to show poor reliability (*CV* 31.3%). No CMJ5 variables appear capable of detecting the *SWC* from an inter-day perspective.

Table 4. CMJ5 Inter-day reliable variables. Values are reported as Mean, TE and 90% Lower and Upper CI, *SWC* and *CV%*. TE reflects noise in test scores generated from biological and technological sources. *SWC* represents the smallest change that is of benefit to athletic performance.

	MEAN	TE	LOWER 90%CI	UPPER 90%CI	SWC	CV%
Flight time (s)	0.519	0.010	0.008	0.015	0.002	1.9
Peak power (w)	4740	278	214	406	56	6.1
Relative peak power (w/kg)	52	3	2	4	0.53	5.2
Peak force (N)	2121	86	66	125	17	4.2
Relative peak force (N/kg)	23	1	0.6	1.2	0.2	3.5
Mean force (N)	821	18	14	27	4	2.4
Relative mean force (N/kg)	9	0.14	0.1	0.2	0.03	1.6

3.3.3 Overall reliability

Overall CMJ1 reliability was identical to the pattern shown in the intra-day analysis. Mean force (*CV* 1.1%) displayed an overall $TE < SWC$ despite Mean force being incapable of detecting the smallest worthwhile change in the inter-day comparison. Relative mean force was the next most overall reliable variable with a *CV* of 1.2%. Peak force (*CV* 2.8%) and Relative peak force (*CV* 2.7%) were also highly reliable. CMJ1 Height and Flight time had overall *CV%* of 5.1 and 3.1 respectively. Peak power and Relative peak power (*CV* 3.2% and 3.3%) were more reliable than

Mean power and Relative mean power (*CV* 6.2% and 6.4%). Flight time:Contraction time (*CV* 8.2%) was the least reliable CMJ1 variable overall.

Analysis of CMJ5 overall reliability shows a number of variables to have acceptable levels of reliability. Relative mean force (*CV* 1.6%) and Flight time (*CV* 1.9%) were the most reliable. Peak power and Relative peak power also displayed good overall reliability (*CV* 5.3% and 4.5% respectively). Mean force (*CV* 2.4%) was more reliable than Peak force (*CV* 3.8%) and Relative Peak Force (*CV* 3.1%). End eccentric force (*CV* 14.1%) became unreliable on the inter-day comparison and remained this way in the overall analysis. No CMJ5 variables appear capable of detecting the *SWC*.

3.4 Discussion

The results of both studies demonstrate that a number of variables obtained during CMJ1 and CMJ5 performance exhibit high reliability (*CV* < 10%). Despite this, only CMJ1 Mean force appears capable of detecting the *SWC* with a $TE < SWC$. A comparison of results from the intra and inter-day analysis in both the CMJ1 and CMJ5 revealed only minor differences. This suggests that time of day has little influence on either single or short duration repeated CMJ performance. Interestingly, a number of variables not commonly used in CMJ1 analysis such as Flight time:Contraction time proved to have acceptable overall reliability.

3.4.1 Intra-day Reliability

The extensive number of CMJ1 and CMJ5 variables with high reliability suggests that performance of these movements remains stable across a single day. Somewhat surprisingly, CMJ1 Height was not the most reliable of the variables measured despite the emphasis on jumping as high as possible in the instructions given to subjects. This may be due to the fact that Height reflects a relatively gross performance measure and that even though subjects employed maximum effort; the ultimate outcome is limited by contributing factors that are measured directly by the forceplate. Evidence of this may be found in the high repeatability of both CMJ1 and CMJ5 Flight time which are measured directly by the forceplate. Reliability of Height is

therefore likely to be affected by the fact that displacement has not been measured directly, but rather inferred by mathematical assumption.¹⁵³ Previous work utilising a position transducer has demonstrated single CMJ Height to have a *CV* of < 3%.¹⁰² Values of 6.3% and 2.8% have been reported when Height is measured using a timing mat.^{105,106} These results are similar to those of the current study despite the different measurement apparatus used.

In contrast to the high repeatability of CMJ1Height; CMJ5Height was extremely unreliable. In a similar fashion, Theodorou and Cooke¹⁰³ concluded that mean peak height was significantly different from test to re-test. Interestingly this group found mean Height measured in 7.5s periods over a 30s continuous CMJ on force-plate to have a Pearson correlation coefficient of $r = 0.97$ which suggests high reliability, however *CV%* or *TE* data was not presented. A major difference between the current study and this previous work is the overall length of the repeated CMJ performance (~ 5s v 30s). A longer performance may result in subjects adopting some type of pacing strategy whereas the CMJ5 may elicit repeated maximal efforts. It is possible that adopting a pacing strategy increases reliability in repeated CMJ tasks. It is also possible that analysing the 30s jump task as used by Theodorou and Cooke¹⁰³ to incorporate the full length of the trial, rather than in 7.5s blocks, could alter the reliability. The lack of *TE* and *CV%* data makes comparisons with previous work difficult, but Height reliability in our study appears similar to others who have measured this indirectly. In the current study, any error in the CMJ5 compared to the CMJ1 is likely to be compounded by the repetitive nature of the CMJ5 condition and this may account for the poor *CV%*. It may also be important to consider that previous work has been conducted on an inter-day comparison basis. It is possible that if these experiments were repeated on an intra-day manner that the results could be different. The excellent reliability of CMJ5Flight, probably due to its direct measurement, suggests that this may be a more appropriate variable than Height for athletic assessment.

The direct measurement of force is likely to be a major component in the high reliability of CMJ1 and CMJ5Mean force and Relative mean force. In both jump conditions, Peak force and Relative peak force also proved to be highly reliable but it appears that mean force values are more reliable. This may be explained by the fact that minor fluctuations in Peak force become inconsequential in the Mean force score, whilst

constituting the full value assigned to Peak force. It has been proposed that measurement of repeated rather than single efforts may increase the reliability of variables because the importance of “one-off” high or low scores is diminished as more repetitions are completed.⁹⁹ As Mean force and Relative mean force scores constitute a number of scores averaged across time, rather than a single score, this concept may apply. The slightly higher reliability of the Mean force and Relative mean force scores and the fact that CMJ1Mean force has a $TE < SWC$, suggests these measures may be more sensitive than Peak force measures to small performance changes in athletic populations.

There are some important differences in the reliability of power variables when comparing the CMJ1 and CMJ5. Whilst CMJ1Peak power, Mean power and their relative values are highly reliable; CMJ5Mean power and CMJ5Relative mean power proved less reliable. This appears in contrast to the findings of others who report average power in repetitive jumping tasks (15s blocks during a 60s test) to have a test-retest correlation of $r = 0.95$.¹⁰ Peak power and Mean power has also been measured during 30 repetitions of CMJ's with the addition of 30% of body weight and found to produce CV's of 3.2% and 4.4% respectively.¹⁰⁴ These values are considerably lower than those from the CMJ5. A major factor in the results of Alemany & Pandorf et al.¹⁰⁴ could be that testing was conducted in a Smith machine rather than free standing. This is likely to decrease positional errors on landing and lead to more consistent performance. The direct measurement of displacement is also likely to have been critical and it also possible that the less homogenous nature of subjects used in other studies may have produced higher r values.

Although CMJ5Mean power and Relative mean power intra-day values are unreliable at a CV cut off of 10%, they follow a similar pattern to the CMJ1. In the CMJ1, Mean power and Relative mean power are also less reliable than their peak counterparts. It is likely that Mean power is largely affected by changes in contact time brought about by variations in countermovement range and speed. The requirement to repeatedly land, stabilise and perform the next jump in the CMJ5 condition may be a reason why Mean power and Relative mean power variables display lower reliability compared to CMJ1 values.

The reliability of a number of CMJ1 and CMJ5 variables that have received little previous attention are worthy of discussion. CMJ5End eccentric force displayed much higher reliability than CMJ1End eccentric force. The repeated measure of End eccentric force reported as an average in the CMJ5 may limit the influence of a “one-off” high or low value.⁹⁹ End eccentric force is likely to depend considerably on countermovement depth. A decreased range in the countermovement would result in a more rapid stretch of the leg extensor musculature and result in higher End eccentric force. Subjects may vary their countermovement strategy to allow Height to be maintained. It could also be that the short duration of the CMJ5 elicits some type of “pacing strategy” resulting in a far more consistent performance than a one-off maximum effort. Alternatively, subjects may exert more conscious control over their countermovement strategy to allow execution of consecutive ballistic movements.

The ratio of jump height to contact time has previously been proposed as a variable of interest in assessing drop jump performance.¹⁴⁷ As Height in the current study has been calculated using the impulse-momentum relationship and appears unreliable, Flight time:Contact time may be considered a more appropriate measurement reflecting the same qualities. In the CMJ5, intra-day analysis revealed this to be an unreliable measure. There is potential for this result to have been influenced by the instructions provided to subjects as has been shown in previous research.¹⁴⁷ In an attempt to maximise jump height it is likely that subjects have manipulated contact time. This is evidenced by the unreliable nature of CMJ5Eccentric time and CMJ5Contraction time (*CV* 21.8% and 19.6% respectively). Although, given the strict pre-test control, it is unclear why a change in strategy would be required. An instruction to jump as quickly as possible may have elicited a different response and therefore potentially improved reliability of the CMJ5Flight time:Contact time variable.

It may be argued that the analogous measure to CMJ5Flight time:Contact time is CMJ1Flight time:Contraction time, as this measure provides a ratio of the flight time to the sum of eccentric and concentric contraction time. Interestingly, this measure proved reliable in the intra-day comparison. Whilst subjects may have manipulated contraction time to achieve maximum height, the combination with flight time may contribute to the reliability in this ratio measure. It seems that in this case, one effort has resulted in less variation than the repeated efforts of the CMJ5Flight time:Contact time. This is in

contrast to the potential reasons why some CMJ5 variables have shown acceptable reliability (ie. average scores negating the influence of variations in peak scores). There may be a complex interaction of factors that result in some variables showing high reliability and other seemingly related variables proving to be unreliable. Repeated performance as occurs in the CMJ5 may increase reliability in some variables and reduce it in others.

Whilst a number of variables proved to be extremely reliable on an intra-day basis, a group of CMJ1 and CMJ5 variables produced results just outside the CV 10% cut-off (CMJ1Eccentric time, Flight time:Eccentric time and CMJ5Flight time:Eccentric). Both CMJ1Flight time:Eccentric time and CMJ5Flight time:Eccentric time represent flight time relative to the time spent in the countermovement phase of the jump and in both jump conditions, Flight time is extremely reliable and Eccentric time less so; possibly due to variations in countermovement depth in an effort to achieve maximum jump Height. In combination, these variables produce a variable of marginal reliability which may prove worthy of further study, as measures displaying the highest reliability are not always the best for monitoring performance changes.⁹⁹

3.4.2 Inter-day Reliability

CMJ1 and CMJ5 inter-day reliability was almost identical to that of the intra-day analysis. Despite many similarities, CMJ1Flight time:Contraction time (CV 10.4%), and CMJ5EEF (CV 18.7%) displayed lower repeatability than in the intra-day comparison. From this data it seems that these variables may be less able to detect subtle changes in performance from day to day than within a single day. This could be important for coaches and sports scientists when deciding which variables to use in assessing the acute and longer term impact of training and competition.

3.4.3 Overall Reliability

As the overall reliability calculations are the average of intra and inter-day results, it is not surprising that analysis revealed identical results to other comparisons. The same mechanisms are likely to be responsible in each case. It is potentially important that CMJ1 Mean force has a $TE < SWC$. In theory, this variable may have the greatest chance of detecting performance changes. However, the response in elite athletes is unknown.

It is interesting that CMJ1 intra-day and overall reliability analyses show the same variables to be reliable, whilst CMJ5 inter-day and overall reliability are identical. On strict assessment, it appears that some CMJ1 variables may be more useful on an intra-day basis and some CMJ5 variables more able to detect small changes in an inter-day comparison. In the case of the CMJ1, low intra-day Flight time:Contraction time $CV\%$ contribute positively to overall reliability. Conversely, poor inter-day reliability of CMJ5 End eccentric force negatively influences the overall reliability of these variables. Therefore, the ability of some variables to assess change may depend on the nature of the pre and post comparison.

3.5 Practical Applications

Before a measure is used to assess the impact of training or performance, its reliability should first be established. This study is the most comprehensive assessment of performance variables in CMJ performance completed in elite athletes to date. We have demonstrated that numerous CMJ1 and CMJ5 variables possess high reliability from both an intra-day and inter-day perspective, although some variables are more reliable in one comparison than another. Coaches and sport scientists can confidently examine these variables to assess the effect of various interventions in the knowledge that changes are likely to be biological in nature rather than due to noise in the test. It could be valuable to assess responses in single and repeated CMJ's to various strength and power training regimens or the impact of elite competition on numerous variables to assess their ability to detect aspects such as fatigue.

3.6 Conclusions

A large number of CMJ1 and CMJ5 variables appear to be stable both within and between days. In addition to commonly measured variables such as Flight time and Peak power, variables such as CMJ1Flight time:Contraction time may be valuable in athletic assessment. Interestingly, CMJ5Height was found to be extremely unreliable. This is likely to be due to the fact that jump height was not measured directly. It is possible that the reliability data obtained in both the CMJ1 and CMJ5 conditions may have differed with the direct measurement of displacement or with different instructions to subjects (eg. jump as quickly as you can). It is also conceivable that controlling countermovement knee angle could have modified the results. Various other jump types such as single leg CMJ and drop jumps may be worthy of similar investigations in elite athlete populations and further research should also look to quantify the kinematic variations and neuromuscular changes associated with modifications in CMJ performance.

A short duration repeated CMJ such as the CMJ5 may be useful in investigating the impact of training and performance in elite athletes. A number of variables measured in this condition may respond differently than their CMJ1 counterparts and provide insight into mechanisms affecting responses in high level sport.

CHAPTER 4

4.0 EXPERIMENTAL STUDY 3

NEUROMUSCULAR AND ENDOCRINE RESPONSES OF ELITE PLAYERS TO AN AUSTRALIAN RULES FOOTBALL MATCH

4.1 Abstract

Purpose: To examine the acute and short term responses of variables obtained during a single countermovement jump (CMJ1), repeated countermovement jump involving 5 consecutive efforts without a pause (CMJ5) and Cortisol (C), Testosterone (T) and Testosterone to Cortisol ratio (T:C); to an elite Australian Rules Football (ARF) match with a view to determining which variables may be most useful for ongoing monitoring.

Methods: Twenty-two elite ARF players participating in a pre season cup match performed a CMJ1, CMJ5 and provided saliva samples 48h prior to the match (48pre), pre match (pre), post match, 24h post (24post), 72h post (72post), 96h post (96post) and 120h post (120post). The magnitude of change in variables at each time point compared to pre and 48pre was analysed using the effect size (ES) statistic. **Results:** A substantial decrement in the pre to post match comparison occurred in CMJ1Flight time:Contraction time (ES -0.65 ± 0.28). Cortisol (ES 2.34 ± 1.06) and T:C (ES -0.52 ± 0.42) displayed large pre to post match changes. The response of CMJ variables at 24post and beyond compared to pre match and 48pre was varied, with only CMJ1Flight time:Contraction time displaying a substantial decrease (ES -0.32 ± 0.26) post match compared to 48pre. Cortisol displayed a clear pattern of response with substantial elevations up to 24post compared to pre and 48pre. **Conclusion:** CMJ1Flight time:Contraction time appears to be the most useful variable for monitoring neuromuscular status in elite ARF players due to its substantial change compared to 48pre and pre match. Monitoring C, due to its predictable pattern of response, may provide a useful measure of hormonal status.

4.2 Introduction

Muscle fatigue has been defined as a reduction in maximal force generating capacity⁴³ and is believed to involve many factors at various sites including both central and peripheral origins.³⁶ It has been suggested that a practical test capable of assessing low frequency fatigue in athletes is warranted.⁵⁸ The effective planning of post competition recovery and preparation for subsequent competition necessitates accurate assessment of the impact of game play on the neuromuscular system.

Stretch shortening cycle (SSC) activities may be useful in the study of neuromuscular fatigue because metabolic, mechanical and neural elements are taxed in conjunction with disturbances of stretch-reflex activation.⁴⁶ Recovery from SSC exercise occurs in two phases characterised by an initial large drop in performance, followed by a transient recovery and then a further drop that generally peaks 48 to 72hrs post exercise.⁴⁶

Various forms of vertical jump (VJ) have been used in the assessment of athletic performance^{11,22,68,69} and assessing repetitive VJ power may also be important.¹¹ However, the use of VJ protocols to study the fatiguing effect of team game performance is limited. Hoffman et al.⁶⁸ found CMJ Peak power and force was maintained pre to post soccer match whilst Peak force was lower at 24post compared to pre. Hoffman et al.,²² found various changes in Peak force and power in American football players whilst Ronglan et. al.;⁷² demonstrated a significant decrement in countermovement jump (CMJ) height over 3 days of elite handball competition. There appears to have been no investigation examining the impact of an elite ARF match on CMJ variables to assess their potential usefulness as a measure of neuromuscular status.

In addition to changes in muscular performance due to fatigue, numerous researchers have examined the influence of team game performance on endocrine response.^{21,24,123,133} Cortisol (C) is considered an important stress hormone and its presence is said to indicate the neuroendocrine system's response to exercise.²⁵ Testosterone (T) is anabolic in nature and important in muscle hypertrophy and increasing muscle glycogen synthesis.¹¹⁷ Testosterone has also been implicated in

aggressive behaviour.¹¹⁷ As C and T vary in opposite directions in response to exercise, this may represent an imbalance between anabolic and catabolic hormones resulting in a decreased T:C when loads are increased.¹³³ It is possible that various hormonal measures may assist in assessing the response to training,²⁵ however their potential usefulness in ARF is unknown.

Previous work¹³³ has found T and C rest day values comparable to competition day values in rugby players with T decreased and C and T:C increased post game. Hoffman et al.²¹ found elevated C levels during a season of American Football but within normal ranges and T:C was lower at the end of the season whilst T remained at baseline. Filaire et al.²⁴ revealed C was not influenced by 9 months of professional soccer training, although an intensive training block resulted in decreased T. The nature of ARF provides a unique vehicle for the study of hormonal response to performance as it combines the contact nature of Rugby and the running volumes of soccer.

Uncertainty remains regarding the pattern of neuromuscular fatigue and hormonal responses to elite level contact sport and the influence of an elite ARF match is unknown. It is currently unclear whether such measures, including a functional athletic task capable of detecting low frequency neuromuscular fatigue, are useful monitoring tools. Quantification of the impact of game play on the neuromuscular and endocrine systems is essential to planning effective training over the subsequent week. Therefore, the purpose of this study was to examine the acute and short term impact of an elite level ARF match on neuromuscular status and hormonal response in an attempt to determine which measures may be most useful for ongoing monitoring of elite ARF players.

4.3 Methods

4.3.1 Subjects

This study involved 22 elite ARF players (Age 23.3 ± 2.7 years, Height 1.9 ± 0.1 m and Mass 89.6 ± 7.3 kg) representing an Australian Football League (AFL) team in a pre season cup match. Subjects had played an average of 64.3 ± 51.7 AFL regular season matches. The research was approved by the University Human Research Ethics Committee and all subjects signed an informed consent document.

4.3.2 Design

The testing and training schedule is displayed in Figure 2. Single countermovement jump (CMJ1), 5 repeated countermovement jump (CMJ5) data and saliva samples were collected at 48pre, pre match, post match, 24post, 72post, 96post and 120post match. Subjects were familiar with the CMJ1, CMJ5 and saliva sample techniques after participating in multiple practice sessions and completing pre and post match testing in two intra-club matches prior to the pre season cup match. All data, except for post, were collected between 1500 and 1530hrs. Post data was collected between 1830-1850hrs and was within 20min of match completion. For various reasons, some subjects were unable to provide data at all time points. Data was analysed for between 16 and 21 subjects for the CMJ and 17 to 22 subjects for hormonal variables at each time point. Subjects participated in the team's regular weekly training schedule (Figure 2) throughout the data collection period.

Time/Day	1	2	3	4	5	6	7	8
AM	Off	Off	Off	Pool based recovery	Off	Flexibility	Individual Skill Training	Off
	<i>48pre</i>	Off	<i>Pre</i>	<i>24post</i>	Off	<i>72post</i>	<i>96post</i>	<i>120post</i>
PM	Skill Training		Match <i>Post</i>	Strength Training		Skill Training	Strength Training	Skill Training

Figure 2. Test and Training Schedule 48pre to 120post (test times in *italics*).

4.3.3 Methodology

Prior to each CMJ1 trial, subjects performed a 2 minute dynamic warm up consisting of various running patterns including jogging, high knees and skipping. Subjects then performed 3 practice CMJ's prior to the measurement trial. The CMJ1 trial was followed by collection of a 60s unstimulated saliva sample for analysis of T, C and T:C. Saliva samples were collected by passively drooling directly into a plastic tube. There is a strong relationship between salivary and serum unbound C both at rest ($r = 0.93$) and during exercise ($r = 0.90$)¹³⁷ and salivary measures of C and T concentrations are independent of saliva flow rate.¹³⁸ All subjects were requested to maintain their normal training diet throughout the study period and refrain from ingesting anything other than water in the 60min prior to provision of each saliva sample. Subjects were also required to provide samples in a rested state with a minimum of 5 hours inactivity and participate in only the prescribed weekly training sessions. Saliva samples were placed in a refrigerator and then frozen at a temperature of -80°C and stored for subsequent analysis. Cortisol ($\mu\text{g/dL}$) and T (pg/mL) were determined in duplicate by enzyme linked immunosorbent assay (Salimetrics, PA, USA) using a microplate reader (SpectraMax 190, Molecular Devices, CA, USA). Typical Error and coefficient of variation as a % of the T and C assays was 9.1/8.1% and 0.07/3.9% respectively. Following provision of a saliva sample, subjects performed the CMJ5 trial.

CMJ trials were performed on a commercially available forceplate (400 Series Performance Plate - Fitness Technology, Adelaide, Australia) connected to computer software (Ballistic Measurement System - Fitness Technology, Adelaide, Australia) capable of recording vertical ground reaction forces. In both the CMJ1 and CMJ5 conditions, subjects were required to perform a CMJ with hands held in place on the hips. In the CMJ1, subjects were instructed to jump as high as possible, whilst in the CMJ5, subjects were required to jump as high as possible for 5 consecutive efforts without a pause between jumps. Countermovement depth was self selected by the subject. Each trial was then analysed using custom designed software (Mathworks, Natick, Massachusetts, USA) capable of automatically detecting values for the variables of interest.

As a result of previous work¹⁵⁴ that has determined the CMJ1 and CMJ5 variables with the highest reliability (*CV* 0.8% to 8.0%), the following variables were collected for analysis. In the CMJ1; Height in cm, Flight Time in s, Peak power in watts, Relative peak power in watts/kg, Mean power in watts, Relative mean power in watts/kg, Peak force in N, Relative peak force in N/kg, Mean force in N, Relative mean force in N/kg and Flight time:Contraction time (representing the time from the initiation of the countermovement until the subject leaves the force plate) in s were recorded. In the CMJ5; Flight time, Peak power, Relative peak power, Peak force, Relative peak force, Mean force and Relative mean force were collected with the score representing the average of the values for each of the 5 jump repetitions.

4.3.4 Statistical Analysis

Variables were log transformed to reduce bias due to non-uniformity of error and analysed using the effect size statistic (ES) with 90% confidence intervals (CI) and % change to determine the magnitude of change at each time point compared to 48pre and pre match values. Calculations were performed using an Excel spreadsheet.¹⁵⁵ The ES was calculated using the following formula: $ES = (M_1 - M_2)/s$ where; M_1 = mean of one group, M_2 = mean of second group, s =standard deviation. The magnitude of change was classified as a substantial increase, substantial decrease, trivial or unclear. The description of a substantial increase or decrease was applied when there was a 75% or greater likelihood of the effect being equal to or greater than the $ES \pm 0.2$ (small) reference value. Less certain effects were classified as trivial and where the $\pm 90\%$ CI of the ES crossed the boundaries of $ES -0.2$ and 0.2 the magnitude of change was reported as unclear. This methodology has been described in detail elsewhere.¹⁵⁶ It has been suggested that an important step in increasing the applicability of research to practice is to calculate and report statistics that show the magnitude of a treatment effect,¹⁵⁶ and a similar approach has been used previously.¹⁵⁷

In this study, CMJ variables displaying an ES decrease of ≥ 0.40 from pre to post were considered for analysis beyond the pre versus post match comparison in order to highlight CMJ variables that are depressed by ARF match play. An ES of this magnitude lies halfway between ES that have been classified as small (0.2) and

moderate (0.6).⁹⁸ The ES 0.4 threshold was chosen as a change of this magnitude allowed an initial reduction of CMJ variables for analysis, by highlighting those variables impacted by more than a small magnitude in the pre match to post match comparison, without unnecessarily removing variables by using a stricter ES 0.6 threshold.

4.4 Results

Subjects played an average of 80.0 ± 12.0 min ($74.3 \pm 11.1\%$ of total match time).

4.4.1 Excluded CMJ Variables

The following variables have been excluded from further analysis on the basis of ES decrements of < 0.40 in the pre versus post match comparison.

CMJ1Height showed a small (ES -0.32 ± 0.46) decrease from pre to post match. The response of CMJ1Peak power was trivial (ES 0.11 ± 0.27) whilst CMJ1Relative peak power increased (ES 0.49 ± 0.48) from pre to post match. CMJ1Peak force displayed a trivial change (ES -0.16 ± 0.26) from pre to post match whilst the magnitude of change in CMJ1Relative peak force was unclear (ES 0.00 ± 0.39). CMJ1Mean force decreased by a small (ES -0.35 ± 0.11) magnitude from pre to post match.

The response of CMJ5Peak power from pre to post match was trivial (ES 0.02 ± 0.10) whilst CMJ5Relative peak power increased by a large magnitude (ES 1.21 ± 0.64). CMJ5Peak force and Relative peak force were lower post match by a small margin (ES -0.33 ± 0.24 and -0.22 ± 0.34 respectively). Post match CMJ5Mean force displayed a small decrease (ES -0.25 ± 0.07) whilst the response of CMJ5Relative mean force was trivial (-0.02 ± 0.15).

4.4.2 CMJ and Hormonal Variables 48pre to 120post

Table 5 displays CMJ ES \pm 90% CI change and % change compared to pre match for those variables meeting the previous criteria of an ES decrease of ≥ 0.40 in the pre versus post match comparison. Changes in CMJ variables compared to 48pre are shown in Table 7.

CMJ1Mean power, CMJ1Relative mean power and CMJ1Relative mean force displayed substantial decreases from pre to post match with decrements ranging from -1.5% to -9.4%. CMJ1Flight time:Contraction time decreased by the largest amount (-16.7%). CMJ1Flight time was substantially lower at 48pre than pre match. The pattern of response in CMJ1 parameters varied from 24post to 120post. CMJ5Flight time was substantially lower at all time points compared to pre except for 96post where the response was trivial.

Hormonal variable responses compared to pre match are shown in Table 6. Testosterone response compared to pre match was unclear or trivial at all comparison points. Cortisol increased substantially post match (+34.2%) and 24post (+41.8%) with an unclear response at 72post followed by substantial decreases at 96post and 120post. Cortisol was substantially lower (-16.5%) at 48pre than pre match. Testosterone: Cortisol decreased substantially post match and 24post compared to pre match with unclear or trivial responses at other time points.

In comparison to 48pre, C displayed a substantial increase post match (ES 4.05 \pm 1.09, 60.8%), 24post (ES 4.59 \pm 1.28, 71.4%), 72 post (ES 1.72 \pm 1.34, 22.3%) and 120post (ES 0.70 \pm 0.48, 8.6%) with and unclear response at 96post (ES 0.18 \pm 0.87, 2.14%). The magnitude of change in T post match compared to 48pre was trivial (ES -0.74 \pm 0.80, -27.5%) with substantial decreases ranging from ES - 0.41 \pm 0.41 (-16.3%) at 72post to ES - 0.96 \pm 0.53 (- 34.0%) at 96post. Testosterone:Cortisol was substantially lower at all time points compared to 48pre with the greatest decrements occurring post match (ES - 1.93 \pm 0.98, -58.8%) and 24post (ES -1.69 \pm 0.79, -54.0%) with the smallest change seen at 72post (ES -0.78 \pm 0.61, -30.2%).

Table 5. CMJ ES $\pm 90\%$ CI change, qualitative descriptor and % change compared to pre match. A substantial increase or decrease was classified as $\geq 75\%$ likelihood of the effect being \geq the ES ± 0.2 (small) reference value. Less certain effects were classified as trivial and where the $\pm 90\%$ CI of the ES crossed the boundaries of ES -0.2 and $+0.2$ the magnitude of change is described as unclear.

VARIABLE/TIME	48PRE	POST	24POST	72POST	96POST	120POST
CMJ1	-0.53 \pm 0.41	-0.89 \pm 0.56	-0.84 \pm 0.56	-0.10 \pm 0.36	-0.02 \pm 0.51	-0.07 \pm 0.47
Flight Time(s)	substantially \downarrow	substantially \downarrow	substantially \downarrow	unclear	unclear	unclear
	-2.2%	-3.6%	-3.5%	-0.4%	-0.1	-0.3
CMJ1	-0.17 \pm 0.31	-0.57 \pm 0.39	-0.81 \pm 0.39	-0.37 \pm 0.32	-0.08 \pm 0.40	-0.27 \pm 0.29
Mean power(w)	trivial	substantially \downarrow	substantially \downarrow	substantially \downarrow	unclear	trivial
	-2.9%	-9.4%	-13.0%	-6.1%	-1.5%	-4.5%
CMJ1	-0.19 \pm 0.36	-0.53 \pm 0.44	-0.87 \pm 0.43	-0.40 \pm 0.36	-0.06 \pm 0.45	-0.28 \pm 0.33
Relative mean power(w/kg)	trivial	substantially \downarrow	substantially \downarrow	substantially \downarrow	unclear	trivial
	-2.8%	-7.7%	-12.4%	-5.9%	-0.9%	-4.2%
CMJ1	-0.22 \pm 0.22	-0.42 \pm 0.32	-0.69 \pm 0.33	-0.24 \pm 0.21	-0.11 \pm 0.3	-0.17 \pm 0.27
Relative mean force(N/kg)	trivial	substantially \downarrow	substantially \downarrow	trivial	trivial	trivial
	-0.8%	-1.5%	-2.5%	-0.9%	-0.4%	-0.6%
CMJ1	-0.28 \pm 0.26	-0.65 \pm 0.28	-0.67 \pm 0.28	-0.14 \pm 0.22	-0.13 \pm 0.35	-0.20 \pm 0.22
Flight time:Contraction time(s)	trivial	substantially \downarrow	substantially \downarrow	trivial	unclear	trivial
	-7.6%	-16.7%	-17.1%	-3.7%	-3.5%	-5.4%
CMJ5	-0.80 \pm 0.29	-0.50 \pm 0.22	-0.76 \pm 0.31	-0.45 \pm 0.26	-0.20 \pm 0.23	-0.31 \pm 0.20
Flight time(s)	substantially \downarrow	substantially \downarrow	substantially \downarrow	substantially \downarrow	trivial	substantially \downarrow
	-3.8%	-2.4%	-3.6%	-2.1%	-1.0%	-1.5%

Table 6. Cortisol (C), Testosterone (T) and Testosterone:Cortisol (T:C) ES \pm 90% CI change, qualitative descriptor and % change compared to pre match. A substantial increase or decrease was classified as a \geq 75% likelihood of the effect being \geq than the ES \pm 0.2 (small) reference value. Less certain effects were classified as trivial and where the \pm 90%CI of the ES crossed the boundaries of ES -0.2 and +0.2 the magnitude of change is described as unclear.

VARIABLE/TIME	48PRE	POST	24POST	72POST	96POST	120POST
C(μg/dL)	-1.43 \pm 0.42	2.34 \pm 1.06	2.78 \pm 1.16	0.34 \pm 1.30	-1.44 \pm 0.91	-0.78 \pm 0.43
	substantially \downarrow	substantially \uparrow	substantially \uparrow	unclear	substantially \downarrow	substantially \downarrow
	-16.5%	34.2%	41.8%	4.4%	-16.6%	-9.3%
T(pg/mL)	-0.09 \pm 0.69	-0.29 \pm 0.40	-0.37 \pm 0.53	-0.08 \pm 0.36	-0.27 \pm 0.44	-0.22 \pm 0.48
	unclear	unclear	unclear	unclear	trivial	unclear
	-3.9%	-21.8%	-26.5%	-6.5%	-20.1%	-16.9%
T:C	0.25 \pm 0.36	-0.52 \pm 0.42	-0.67 \pm 0.52	-0.06 \pm 0.40	-0.02 \pm 0.50	-0.10 \pm 0.46
	trivial	substantially \downarrow	substantially \downarrow	unclear	unclear	unclear
	24.0%	-36.0%	-43.7%	-5.0%	-1.9%	-8.3%

Table 7. CMJ ES $\pm 90\%$ CI change, qualitative descriptor and % change compared to 48pre. A substantial increase or decrease was classified as a $\geq 75\%$ likelihood of the effect being \geq the ES ± 0.2 (small) reference value. Less certain effects were classified as trivial and where the $\pm 90\%$ CI of the ES crossed the boundaries of ES -0.2 and +0.2 the magnitude of change is described as unclear.

VARIABLE/TIME	POST	24POST	72POST	96POST	120POST
CMJ1	-0.31 \pm 0.57	-0.17 \pm 0.57	0.33 \pm 0.43	0.43 \pm 0.31	0.47 \pm 0.29
Flight time(s)	unclear	unclear	trivial	trivial	trivial
	-1.5%	-0.8%	-1.6%	2.0%	2.2%
CMJ1	-0.31 \pm 0.73	-0.47 \pm 0.41	-0.19 \pm 0.34	0.12 \pm 0.36	0.02 \pm 0.23
Mean power(w)	unclear	substantially \downarrow	trivial	unclear	unclear
	-4.8%	-7.1%	-3.0%	1.8%	0.3%
CMJ1	-0.26 \pm 0.99	-0.57 \pm 0.56	-0.26 \pm 0.46	0.19 \pm 0.50	0.03 \pm 0.33
Relative Mean power(w/kg)	unclear	substantially \downarrow	unclear	unclear	unclear
	-3.1%	-6.6%	-3.0%	2.2%	0.4%
CMJ1	-0.17 \pm 0.45	-0.44 \pm 0.15	-0.03 \pm 0.18	0.15 \pm 0.26	0.18 \pm 0.22
Relative Mean force(N/kg)	unclear	substantially \downarrow	trivial	trivial	trivial
	-1.5%	-1.3%	-0.1%	0.4%	0.5%
CMJ1	-0.32 \pm 0.26	-0.33 \pm 0.17	0.20 \pm 0.30	0.06 \pm 0.25	0.21 \pm 0.34
Flight time: Contraction time(s)	substantially \downarrow	substantially \downarrow	trivial	trivial	trivial
	-7.5%	-7.8%	5.0%	1.6%	5.2%
CMJ5	0.19 \pm 0.36	-0.10 \pm 0.28	0.26 \pm 0.34	0.45 \pm 0.27	0.50 \pm 0.26
Flight time(s)	trivial	trivial	trivial	substantially \uparrow	substantially \uparrow
	1.1%	-0.5%	1.4%	2.5%	2.8%

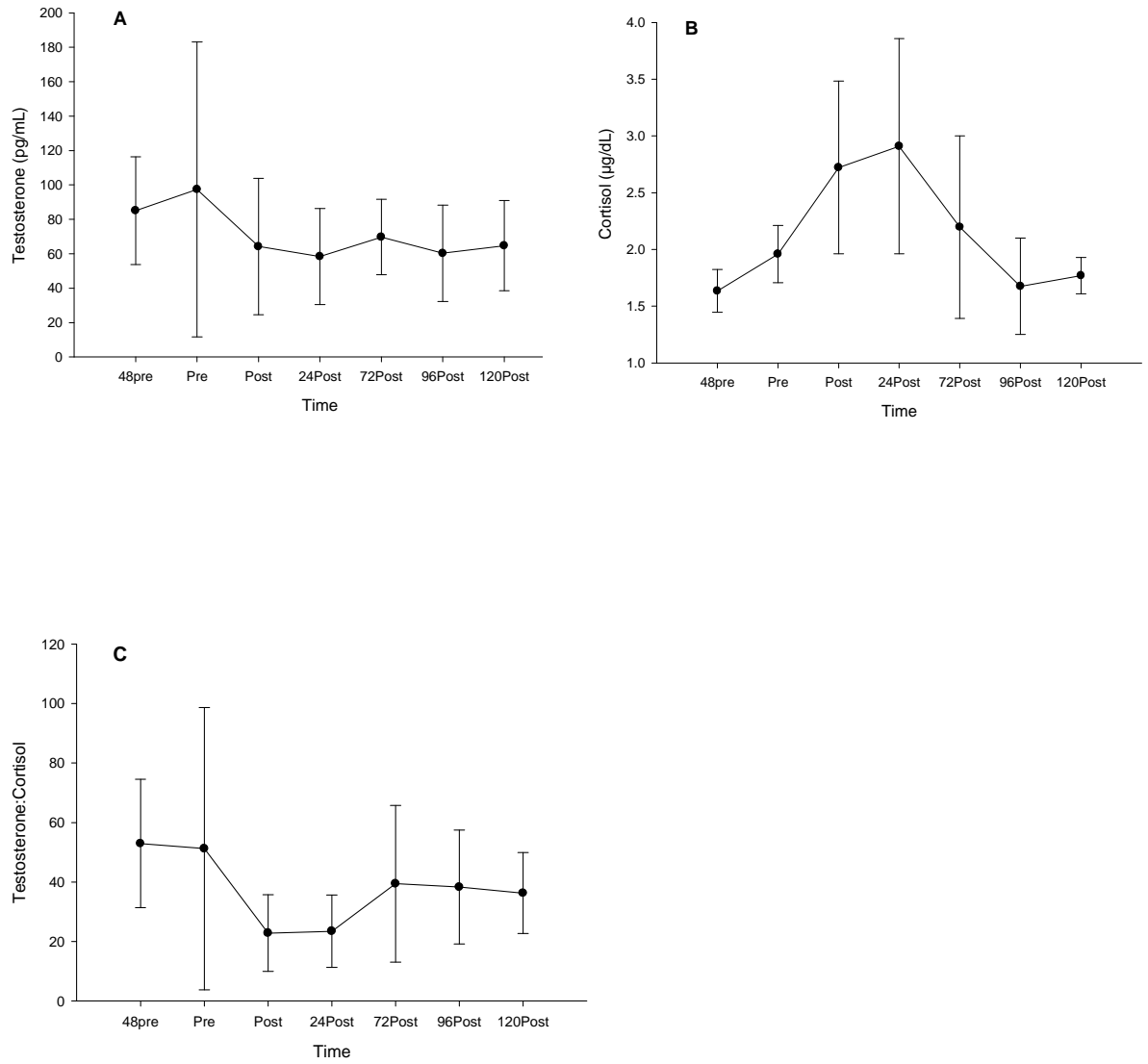


Figure 3. Endocrine responses 48pre match to 120post match. (A) Testosterone, (B) Cortisol and (C) Testosterone:Cortisol. Values are represented as mean \pm SD.

4.5 Discussion

4.5.1 Responses Compared to Pre

The initial finding of this research is the lack of change in numerous CMJ variables in response to an ARF match. Surprisingly, given the instruction to jump as high as possible, CMJ1Height was in this category. This may be in part due to the inherent limitations associated with estimating height based on the impulse momentum relationship. The substantial decrease in CMJ1Flight time, which is measured directly, provides support for this notion. Previous research has demonstrated a decrease in CMJ1Height using the same methods as the current study in International handball players over the course of 3 matches, although pre and post match scores were not reported.⁷² It could be that CMJ1Height lacks the sensitivity to detect changes from a single ARF match. Flight time is an attractive measure however, due to the ease and relatively cheap technology required for assessment of this variable.

The response of CMJ1 and CMJ5Relative peak power suggests the potential for an increase in Relative peak power from pre to post match. Running and CMJ skill rehearsal, as occurs in ARF, has been shown to potentiate jumping performance via increased readiness of the neuromuscular system.¹⁴⁶ However it is unclear why potentiation would affect Relative peak power variables and not others. Previous work examining Peak power in American Football²² and women soccer players⁶⁸ has shown no difference between pre and post match Peak power levels. This suggests team sport athletes may be able to maintain Relative peak power following a match, particularly as the rate of decrease has been shown to be no different between starters and non-starters.²²

The reduction in CMJ1Mean power and Relative mean power suggests that these variables are depressed by an ARF match until at least 72post. This timeline may reflect the influence of low frequency fatigue;⁵⁵ manifested in an altered technique whereby knee flexion angle during the countermovement is modified in an attempt to achieve maximum height⁶¹ resulting in decreased Mean power scores. The continued

depression of these measures until 72post and lack of clarity in values at 96post is a limitation to the usefulness of these variables for monitoring purposes.

Reductions in CMJ Peak force following maximal run performance have been demonstrated previously,⁶⁰ however in the current study only CMJ1Relative mean force displayed this post match decrement. This result is similar to that of previous research in American Football²² and collegiate soccer⁶⁸ showing post match CMJ1Peak force to be unchanged from pre match. Decreased Mean force production may be due to a combination of reduced central drive and failure of the excitation-contraction coupling mechanism.³⁶ It is likely that similar technique alterations⁶¹ affecting Mean power scores have impacted Mean force results. It appears that CMJ1Relative Mean force decrements are largely recovered by 3 days post match. As a result, this variable may be useful for monitoring neuromuscular fatigue because substantial decrements in Relative mean force beyond 72post may be indicative of delayed recovery.

Whilst CMJ1 and CMJ5Flight time are substantially depressed until 24post, different patterns of response from 72post onwards may be evidence of greater sensitivity in the CMJ5 variable. The substantial decrease demonstrated by CMJ5Flight time at 72post compared to pre match may reflect low frequency fatigue⁵⁵ generated by the ARF match. A similar decrease at 120post may reflect the secondary drop in performance approximately 48h following intense eccentric exercise (72post training session) as suggested by others.⁴⁶ Alternatively, the decrease could be a more acute response to the strength training session conducted at 96post. The lack of clarity in the response of CMJ1Flight time variable is a limitation to its usefulness in monitoring neuromuscular fatigue in elite ARF players. In contrast, CMJ5Flight time may reflect fatigue associated with the match until 96post where a substantial decrement may be a reflection of compromised neuromuscular status. However, 96post may be too close to the next performance in week to week competitions to allow for adequate modifications of the training stimulus.

In a similar manner to Flight time, CMJ1Flight time:Contraction time displayed a substantial decrease post match and 24post. This variable provides an indication of the

relationship between the countermovement phase and resulting flight time. Research using hopping has shown changes in hip and knee angles after a fatigue intervention.⁶¹ Other research has shown a decrease in muscle-tendon stiffness from prior SSC exercise resulting in increased ground contact time in drop jump performance.⁶⁹ Similar mechanisms may be responsible for the changes in Flight time:Contraction time. This variable is depressed by an ARF match for at least 24h post game and although the response is trivial at 72post, it is likely to be a small decrease at most. Therefore a substantial decrease in CMJ1Flight time:Contraction time 72h after an ARF match may reflect delayed recovery. The timeline of response in this variable appears to allow an opportunity for interventions aimed at recovering neuromuscular status to be implemented in time for the next weekly competition. Based on comparisons with pre match values, this variable may be the most useful CMJ variable for assessing neuromuscular fatigue.

Cortisol and T:C showed the greatest change among endocrine variables in the pre to post match comparison. The increase in C is similar to that of Haneishi et al.¹²³ who found post soccer match C to be significantly increased above pre game values. Other research has shown C to be unchanged from pre to post game in American Football players, although differences post game existed between starters and non-starters.²² In a similar fashion to the current study, C values have been shown to rise post competition in elite swimmers.¹⁵ Post competition T:C in rugby players has been shown to be 2.5 times lower than rest day values¹³³ and the substantial reduction in this ratio seen in the current study may reflect a catabolic state in response to an ARF match that extends for at least 24h.¹¹⁹ The unclear nature of the T:C response at 72post and beyond makes inferences regarding the expected pattern of response in this variable difficult. In comparison, C is substantially decreased at 96post and 120post; possibly due to the training session conducted after 72post and the strength training session conducted after 96post.

The generally unclear response seen in T from post match to 120post makes determinations about anabolic processes due to an ARF match difficult. The expected pattern of response is unknown given previous research has found T to be unchanged

from pre to post match in American football players²² but higher in the days following an elite level rugby match than on a rest day,¹³³ although this comparison does not consider change from pre match values. The unclear change at the majority of time points suggests that T responds in a varied manner to an ARF match therefore limiting its usefulness for regular monitoring of elite ARF players.

4.5.2 Responses Compared to 48pre

The response of CMJ variables post match compared to 48pre may provide an insight into the sensitivity of individual variables. In a similar fashion to the sensitivity shown by CMJ1Flight time:Contraction time in comparisons to the pre match value, this variable was the only CMJ measure capable of detecting a substantial change from 48pre to post match. The decrement shown in this comparison was maintained in the 24post versus 48pre comparison. CMJ1Mean power, Relative mean power and Relative mean force were also substantially lower at 24post than 48pre, however their ability to detect a change between 48pre and post match is unclear. The response at 24post versus 48pre in these variables may be attributable to similar mechanisms that are responsible for change in comparisons with pre; such as reduced central drive and failure of the excitation-contraction coupling mechanism,³⁶ in conjunction with potentially altered technique.⁶¹ The unclear nature of the response post match compared to 48pre suggests these variables lack the sensitivity to detect match induced changes in neuromuscular status from a rested baseline. CMJ1Flight time:Contraction time responds trivially at 72post versus 48pre and thereafter, following substantial reductions post match and 24post, adding weight to the concept that this measure reflects the return of neuromuscular status to 48pre baseline levels following the match and further highlighting its usefulness.

Cortisol was the only hormonal variable to display a substantial change from 48pre to pre match, suggesting an anticipatory rise similar to that demonstrated previously.^{15,136} The unclear nature of the change in T from 48pre to pre is further evidence of the limitations for the use of this hormone for the regular monitoring of elite ARF players. A correlation ($r = 0.40$, $p < 0.04$) between T and number of attacks in

Judo players has been shown previously;¹¹⁷ suggesting a link with aggressive behavior. Interestingly the subjects in the current study were on the losing team. It is possible that subjects were not sufficiently aroused pre match, as higher arousal may have resulted in a greater difference between 48pre and pre match T. The trivial change in T:C is likely to be a function of the diversity in T and C response and is similar to results of research utilizing elite rugby players that demonstrated T:C to be similar on rest and competition days.¹³³

Elevated C until 72post compared to 48pre provides further support for the large impact of ARF match play on this variable and is a similar result to previous work.¹³³ The secondary increase at 120post may be due to training conducted after 72post, as the impact of the match is likely to have diminished.¹¹⁵ The substantial decrease in T:C in all comparisons with 48pre may be evidence that in elite contact team sports where a match is followed by multiple training sessions, these measures are continually depressed, representing a catabolic environment with implications for the design of training programs. These results are in contrast to a study using elite Rugby players in which T:C remained elevated above baseline values until 5 days post match.¹³³ The use of T:C to monitor the anabolic to catabolic balance in elite ARF players may be worthy of further investigation, however the performance of two salivary assays may be problematic.

4.6 Practical Applications

An easy to administer functional test of neuromuscular status may be of great benefit to scientists and coaches working with high level team sport athletes.⁵⁸ In elite ARF football players, CMJ1Flight time:Contraction time appears to be the most useful variable for assessing the neuromuscular response to a match. CMJ5Flight time may be the most appropriate monitoring variable for programs that only have access to devices such as a timing mat.

Cortisol and T:C display the most predictable pattern of response of the hormonal variables studied. Whilst T:C may be useful, the performance of two

independent assays could be a limitation. Therefore, regular monitoring of C is likely to provide the most practically useful hormonal measure, as levels may be expected to be substantially lower than pre match by 96post. Whilst the increase in C observed from pre to post match suggests the impact of the match has overridden the normal diurnal decrease in C, it is possible that the increase in C post match was blunted by this diurnal effect. Therefore, it may also be useful in further research to assess the diurnal pattern of C in elite ARF players without the influence of a match or intense training to further clarify the impact of competition or training. Obtaining fatigue free baseline values is likely to be important for measures of neuromuscular and endocrine status.

4.7 Conclusions

Although numerous CMJ variables were substantially lower at post match than pre match, CMJ1Flight time:Contraction time was the only CMJ variable to also show a substantial decline (-7.4%) from 48pre to post match. This magnitude of change, in conjunction with trivial responses pre match to 72post (-3.7%) and 48pre to 72post (+5%) suggests CMJ1Flight time:Contraction time is the most sensitive and useful variable for the assessment of neuromuscular status in elite ARF players. A decrement in this variable of a substantial magnitude compared to pre or 48pre at 72post may indicate incomplete recovery of the neuromuscular system.

Cortisol showed a clear pattern of response in the pre to post match comparison with a substantial 34.2% increase. Testosterone:Cortisol ratio was substantially lower (-36.0%) post match compared to pre match. Given a similar training schedule to the one undertaken by athletes in this study, it is reasonable to expect C at 96post to be substantially lower than pre match.

CHAPTER 5

5.0 EXPERIMENTAL STUDY 4

NEUROMUSCULAR AND ENDOCRINE RESPONSES OF ELITE PLAYERS DURING AN AUSTRALIAN RULES FOOTBALL SEASON

5.1 Abstract

Purpose: To examine variations in neuromuscular and hormonal status and their relationship to performance throughout a season of elite Australian Rules Football (ARF). **Methods:** Fifteen elite ARF players performed a single (CMJ1), 5 repeated countermovement jump (CMJ5) and provided saliva samples for the analysis of Cortisol (C) and Testosterone (T) prior to the season commencing (Pre) and during the 22 match season. Magnitude of effects were reported with the effect size (ES) statistic. Correlations were performed to analyse relationships between assessment variables and match time, training load and performance. **Results:** CMJ1Flight time:Contraction time was substantially reduced on 60% of measurement occasions. Magnitudes of change compared to Pre ranged from $1.0 \pm 7.4\%$ (ES 0.04 ± 0.29) to $-17.1 \pm 21.8\%$ (ES -0.77 ± 0.81). Cortisol was substantially lower (up to $-40 \pm 14.1\%$, ES of -2.17 ± 0.56) than Pre in all but one comparison. Testosterone response was varied, whilst T:C increased substantially on 70% of occasions with increases to $92.7 \pm 27.8\%$ (ES 2.03 ± 0.76). CMJ1Flight time:Contraction time ($r = 0.24 \pm 0.13$) and C displayed small correlations ($r = -0.16 \pm 0.1$) with performance. **Conclusion:** The response of CMJ1Flight time:Contraction time suggests periods of neuromuscular fatigue. Change in T:C indicates subjects were unlikely to have been in a catabolic state during the season. Increase in C compared to Pre had a small negative correlation with performance. Both

CMJ1Flight time:Contraction time and C may be useful variables for monitoring responses to training and competition in elite ARF athletes.

5.2 Introduction

Whilst previous work^{21,22,24,28,34,68,75,76,124,133,158} has detailed various neuromuscular and endocrine responses to athletic competition and training, a limited amount has investigated season long responses in elite team sport athletes. There is uncertainty regarding the expected pattern of response in these variables and their usefulness in determining the appropriateness of training loads; the impact of training and competition volumes on change in these measures and the relationships between change in measurement variables and performance.

There is a suggestion that low frequency neuromuscular fatigue is an important capacity to quantify in elite athletes and functional stretch shortening cycle (SSC) activities may be capable of this.⁵⁸ Recently, the ratio of Flight time to Contraction time (measured from the commencement of the countermovement phase until the subject leaves the ground) from a single CMJ proved the most useful variable for assessing low frequency fatigue in ARF, due to the capacity to detect delayed neuromuscular recovery.¹⁵⁸ Another potentially useful variable identified in this study was the average Flight time from 5 consecutive CMJ's.¹⁵⁸ Examination of short term responses using a squat jump and CMJ have also been conducted in collegiate soccer⁶⁸ and American Football.²² Whilst measures of force and power have been shown to decrease following collegiate soccer play,⁶⁸ both measures demonstrated a return to baseline after the American Football match.²² Despite providing insight into short term neuromuscular responses, these results may not transfer to long competition phases. Furthermore, neuromuscular responses may be sport specific and the ability of SSC tasks to detect neuromuscular fatigue may depend on the sport and assessment variable.

Although limited, some work has examined responses in team sport athletes over longer periods.^{33,71,72} A reduction in CMJ height was found after 3 days of international handball competition⁷² and various neuromuscular changes up to 120h after an elite ARF match have also been reported.¹⁵⁸ Research in rugby league players has produced

varied results^{33,71} and it may be that measures such as jump height lack the resolution to detect neuromuscular fatigue in high level team sport athletes.^{33,158} Monitoring neuromuscular fatigue in longer term studies may be enhanced by assessing the response of alternative variables, and scope exists for examinations over entire competitive seasons.

There is relatively more research investigating long term hormonal response to elite team sport competition than exists in the study of neuromuscular fatigue. Rugby league,^{33,71} and soccer^{20,24,28,76,124} have been studied repeatedly, in addition to American Football.³⁴ Cortisol has a role as a stress hormone and its presence is suggested as an indicator of the endocrine systems response to exercise.²⁵ Testosterone is important in muscle hypertrophy and muscle glycogen synthesis¹¹⁷ and it is possible that T, C or their ratio value T:C¹³³ could be useful in assessing the impact of training and competition as a reflection of the balance between anabolic and catabolic processes.²⁵ However, results of longer term studies^{28,34,76,124} have been equivocal and included a rise in C during a soccer season and return to baseline 2 months post season with no change evident in T or T:C,²⁸ whilst a reduction in T was the only change noted during 15 weeks of American Football training.³⁴ The expected hormonal response and therefore usefulness of these measures for early detection of overreaching or overtraining in team sport athletes over extended periods is unclear. Responses may be sport specific and cyclic across longer periods, necessitating profiling of individual sports.

Despite previous examinations of neuromuscular and endocrine responses in team sports, weekly variations in elite level contact team sport are poorly understood. There is likely to be some modification to endocrine and neuromuscular status during a season of elite ARF. These responses may include various magnitudes of suppression or elevation that occur independently or in parallel. It is possible that change in these variables is related to workload or performance and in the case of hormonal measures, may reflect modifications to total body anabolic:catabolic balance. Therefore, the purpose of this research was to examine weekly variations of low frequency neuromuscular fatigue and hormonal status in elite ARF players over a competitive

season with a view to determining the response to training and playing loads, and examine the relationship between these variables and performance.

5.3 Methods

5.3.1 Subjects

This study involved 15 elite ARF players (Age 24.9 ± 2.4 years, Height 1.87 ± 0.07 m and Mass 88.0 ± 7.9 kg) representing an Australian Football League (AFL) team during a 22 match regular season. Subjects had played an average of 124 ± 53 AFL regular season matches prior to the study commencing. The research was approved by the University Human Research Ethics Committee and all subjects signed an informed consent document.

5.3.2 Design

The typical weekly training and match schedule is displayed in Figure 4. Countermovement jump data and saliva samples were collected on the morning of Day 3 (approximately 72-144h post match). Subjects were familiar with the CMJ1, CMJ5 and saliva sample techniques after participating in multiple practice sessions prior to the commencement of the season. Baseline data was collected in a rested state approximately 36h prior to the first match of the season (Pre) and on 20 occasions throughout the 22 match season (Mid 1-2 to Mid 21-22). A bye occurred following the Round 12 match and no data was collected Mid bye-12 or Mid 13-14. Subjects unable to produce maximum effort during the CMJ1 and CMJ5 did not perform these tests, resulting in a varied number of data sets across the study period and a mean of 10.1 ± 1.6 subjects per data collection point.

Time/Day	1	2	3	4	5	6	7
AM	Training or Recovery if match on Day 7	Off	Data collection & Flexibility	Individual skill training	Training	Recovery if no match PM	Recovery
PM	Weights	Off	Training	<i>Match</i> or Weights	<i>Match</i> or Off	<i>Match</i> or Off	<i>Match</i>

Figure 4. Typical weekly training and match schedule. *Italics* indicate when matches were played. Data collection occurred in the morning on Day 3. The day following each match included a water based recovery session. Training consisted of various skill and tactical drills.

5.3.3 Methodology

Subjects performed a 2 minute dynamic warm up consisting of various running patterns including high knees, heel flicks and lateral movements followed by 3 practice CMJ's prior to the CMJ1 measurement trial. The CMJ1 trial was followed by collection of a 60s unstimulated saliva sample for analysis of T, C and T:C. Saliva samples were collected by passively drooling directly into a plastic tube. A strong relationship exists between salivary and serum unbound C at rest ($r = 0.93$) and during exercise ($r = 0.90$)¹³⁷ with concentrations independent of saliva flow rate.¹³⁸

Subjects were requested to maintain their normal training diet throughout the study period and ingest only water in the 60min prior to data collection. Samples were provided in a rested state following approximately 36h inactivity and subjects participated in only the prescribed weekly training sessions. Saliva samples were placed in a refrigerator and then frozen at -80° C for subsequent analysis. Cortisol ($\mu\text{g/dL}$) and T (pg/mL) were determined in duplicate by enzyme linked immunosorbent assay (Salimetrics, PA, USA) using a microplate reader (SpectraMax 190, Molecular Devices, CA, USA). Typical Error and coefficient of variation as a % of the T and C assays was 9.1/8.1% and 0.07/3.9% respectively. The CMJ5 trial was performed after provision of the saliva sample.

Countermovement jumps were performed on a commercially available force plate (400 Series Performance Plate - Fitness Technology, Adelaide, Australia) connected to a computer running software (Ballistic Measurement System - Fitness Technology, Adelaide, Australia) that recorded vertical ground reaction forces. Subjects performed the CMJ1 and CMJ5 with hands held in place on the hips. In the CMJ1, subjects were instructed to jump as high as possible, whilst in the CMJ5, subjects were required to jump as high as possible for 5 consecutive efforts without a pause between jumps. Countermovement depth was self selected by the subject. Trials were analysed using custom designed software (Matlab - Mathworks, Natick, Massachusetts, USA) capable of automatically calculating values for key performance variables.

Previously, the most useful CMJ variables for monitoring neuromuscular fatigue in an elite ARF population have been identified.¹⁵⁸ As a result, CMJ1Flight time:Contraction time (representing the time from the initiation of the countermovement until the subject leaves the force plate) in s and CMJ5Flight time in s (representing the average flight time of the 5 repetitions) were collected at each sample point.

In addition to CMJ and hormonal data as both absolute scores and % difference to Pre (%Pre); training volume (min) representing total time active in all training drills performed in a week, excluding rest periods between drills; match time (min); and % match time for each round, cumulative totals after each round, and season totals were collected. Votes based on playing performance awarded by 5 coaching staff on a 0-5 (maximum of 25 per match per subject) basis for all subjects in each match, that determined Club Champion Awards, were also recorded. Votes represented an assessment by the coaching staff on the effectiveness of the subjects' performance compared to the role assigned to them for the match.

5.3.4 Statistical Analysis

Variables were log transformed to reduce bias due to non-uniformity of error and analysed using the ES statistic with 90% confidence intervals (CI) and % change to determine the magnitude of effects. Magnitudes of change were classified as a

substantial increase or decrease when there was a $\geq 75\%$ likelihood of the effect being equal to or greater than the smallest worthwhile change estimated as $0.2 \times$ between subject standard deviation (small ES). Effects with less certainty were classified as trivial and where the $\pm 90\%$ CI of the ES crossed the boundaries of ES -0.2 and 0.2, the effect was reported as unclear.^{156,158}

Pearson correlations (r) were calculated using SPSS for Windows (Version 13.0), to assess relationships of absolute and %Pre values between CMJ and hormonal measures, match time, training volume and Votes. Correlations were calculated for variables measured at the same time point (e.g. Pre) and also to assess delayed relationships (e.g. Pre v Mid 1 – 2). The magnitude of $r \pm 90\%$ CI was classified as 0.1 – 0.3 small, 0.3 - 0.5 moderate, 0.5 – 0.7 large, 0.7 – 0.9 very large and 0.9 – 0.99 nearly perfect⁹⁸ and classified as practically important where there was a $\geq 75\%$ likelihood of the correlation exceeding the smallest practically important (0.1) value, using an Excel spreadsheet.¹⁵⁹ Correlations ≥ 0.1 with less certain practical importance have not been reported.

5.4 Results

5.4.1 Training and Performance Data

Values are reported as mean \pm SD. Weekly training volume and match time was 58 ± 19 min per week and 102 ± 15 min per subject respectively. Total season match time was 2071 ± 230 min ($78.5 \pm 8.7\%$ of possible match time). Combined weekly match time and training volume was 144 ± 43 min per subject. Season total Votes were 346 ± 63 per athlete (13 ± 6 per round). The team won 17 of 22 matches during the study period.

5.4.2 CMJ Measures

CMJ|Flight time:Contraction time (Tables 8 and 9) was substantially lower than Pre at 60% of sample points. Magnitudes of change compared to Pre ranged from

unclear ($1.0 \pm 7.4\%$, ES 0.04 ± 0.29) Mid 5-6 to a substantial decrease ($-17.1 \pm 21.8\%$, ES -0.77 ± 0.81) Mid 8-9. The response was trivial on 4 occasions and unclear 20% of the time.

In contrast, CMJ5Flight time (Figure 5A) responded unclearly at 70% of data points and displayed a substantial decrement only 3 times throughout the season. Magnitudes of change ranged from $-4.3 \pm 3.6\%$ (ES -0.83 ± 0.67) to $2.0 \pm 2.5\%$ (ES 0.39 ± 0.48).

5.4.3 Hormonal Measures

Cortisol (Tables 8 and 9) was substantially lower than Pre (mean \pm SD 2.34 ± 0.62 $\mu\text{g/dL}$) in all comparisons except for Mid 1-2 where the response was trivial ($-6.1 \pm 9.7\%$, ES -0.27 ± 0.39). The largest decrease occurred Mid 6-7 ($-40 \pm 14.1\%$, ES -2.17 ± 0.56) and the smallest substantial decrease (Mid 14-15) was $-10.2 \pm 9.6\%$ (ES -0.46 ± 0.39).

Testosterone (Figure 5B) response was the most varied of the hormonal measures; with substantial increases, decreases and unclear responses in 45%, 10%, and 45% of comparisons respectively versus the Pre value (mean \pm SD 90.90 ± 18.78 pg/mL). The largest reduction occurred Mid 17-18 ($-38.7 \pm 35.7\%$, ES -2.29 ± 1.43) and the largest increase occurred Mid 1-2 ($50.7 \pm 14.4\%$, ES 1.92 ± 0.63). Testosterone responded unclearly on more occasions (9) than any other variable.

Table 8. ES \pm 90% CI change, qualitative descriptor and % change Mid 1-2 to Mid 11-12 compared to Pre for CMJ1Flight time:Contraction time (s) and Cortisol ($\mu\text{g/dL}$). A substantial increase or decrease was classified as $\geq 75\%$ likelihood of the effect being \geq the ES 0.2 (small) reference value. Effects were classified as unclear where the \pm 90%CI of the ES crossed the boundaries of ES -0.2 and +0.2.

Sample (Hrs from previous match)	Flight time:Contraction time (s)	Cortisol ($\mu\text{g/dL}$)
Mid 1-2(+144)	-0.39 \pm 0.33 substantial \downarrow -9.2%	-0.27 \pm 0.39 trivial -6.1%
Mid 2-3(+72)	-0.20 \pm 0.22 trivial -4.9%	-1.23 \pm 0.67 substantial \downarrow -25.9%
Mid3-4(+96)	-0.39 \pm 0.31 substantial \downarrow -9.1%	-1.10 \pm 0.6 substantial \downarrow -22.8%
Mid4-5(+72)	-0.57 \pm 0.58 substantial \downarrow -13.1%	-1.06 \pm 0.62 substantial \downarrow -22.1%
Mid 5-6(+96)	0.04 \pm 0.29 unclear 1.0%	-1.35 \pm 0.73 substantial \downarrow -27.2%
Mid6-7(+96)	0.21 \pm 0.18 trivial 5.4%	-2.17 \pm 0.56 substantial \downarrow -40.0%
Mid 7-8(+96)	-0.35 \pm 0.32 substantial \downarrow -8.1%	-0.88 \pm 0.47 substantial \downarrow -18.8%
Mid8-9(+72)	-0.77 \pm 0.81 substantial \downarrow -17.1%	-1.29 \pm 0.42 substantial \downarrow -26.2%
Mid9-10(+72)	-0.31 \pm 0.51 unclear -7.4%	-1.15 \pm 0.51 substantial \downarrow -23.7%
Mid10-11(+96)	-0.57 \pm 0.59 substantial \downarrow -13.0%	-1.15 \pm 0.54 substantial \downarrow -23.7%
Mid11-12(+72)	-0.59 \pm 0.58 substantial \downarrow -13.4%	-0.75 \pm 0.53 substantial \downarrow -16.1%

Table 9. ES \pm 90% CI change, qualitative descriptor and % change Mid Bye - 13 to Mid 21-22 compared to Pre for CMJ1Flight time:Contraction time (s) and Cortisol ($\mu\text{g/dL}$). A substantial increase or decrease was classified as $\geq 75\%$ likelihood of the effect being \geq the ES 0.2 (small) reference value. Effects were classified as unclear where the $\pm 90\%$ CI of the ES crossed the boundaries of ES -0.2 and +0.2.

Sample (Hrs from previous match)	Flight time:Contraction time (s)	Cortisol ($\mu\text{g/dL}$)
Mid Bye-13(+360)	-0.48 \pm 0.41 substantial \downarrow -11.2%	-0.58 \pm 0.57 substantial \downarrow -12.7%
Mid 14-15(+96)	-0.49 \pm 0.53 substantial \downarrow -11.4%	-0.46 \pm 0.39 substantial \downarrow -10.2%
Mid 15-16(+96)	-0.71 \pm 0.49 substantial \downarrow -15.9%	-0.74 \pm 0.72 substantial \downarrow -15.9%
Mid 16-17(+96)	-0.47 \pm 0.99 unclear -10.9%	-0.85 \pm 0.55 substantial \downarrow -18.1%
Mid 17-18(+96)	-0.06 \pm 0.47 unclear -1.4%	-0.67 \pm 0.45 substantial \downarrow -14.6%
Mid 18-19(+120)	-0.34 \pm 0.47 trivial -8.0%	-0.62 \pm 0.52 substantial \downarrow -13.6%
Mid 19-20(+96)	-0.41 \pm 0.28 substantial \downarrow -9.6%	-0.50 \pm 0.50 substantial \downarrow -11.2%
Mid 20-21(+72)	-0.56 \pm 0.42 substantial \downarrow -12.7%	-0.63 \pm 0.66 substantial \downarrow -13.9%
Mid 21-22(+72)	-0.15 \pm 0.27 trivial -3.5%	-0.52 \pm 0.47 substantial \downarrow -11.5%

Testosterone:Cortisol (Figure 5C) increased substantially on 14 (70%) occasions and responded unclearly in all other comparisons to Pre (mean \pm SD 40.88 ± 11.02). Increases ranged from $28.1 \pm 25.8\%$ (ES 0.77 ± 0.71) at Mid 15-16 to $92.7 \pm 27.8\%$ (ES 2.03 ± 0.76) at Mid 6-7.

5.4.4 Correlations

CMJ1Flight time:Contraction time %Pre displayed a small correlation with T:C %Pre ($r = 0.20 \pm 0.13$). A similar magnitude relationship was evident between CMJ1Flight time:Contraction time %Pre from one data point and T:C %Pre from the following data point ($r = 0.25 \pm 0.13$). CMJ1Flight time: Contraction time had a small correlation ($r = -0.16 \pm 0.13$) with Votes received 1 match later than the match immediately following the CMJ sample. CMJ1Flight time:Contraction time %Pre also correlated with Votes obtained 2 matches after the match immediately following the CMJ sample ($r = 0.24 \pm 0.13$). CMJ5Flight time correlated with Votes ($r = -0.16 \pm 0.14$) awarded 2 matches later than the one immediately post CMJ sample. CMJ5Flight time was also correlated with C ($r = -0.17 \pm 0.14$) 1 data point after the CMJ sample. Cortisol %Pre displayed a small correlation with Votes ($r = -0.16 \pm 0.1$) in the match immediately following the C sample. Cortisol had a similar magnitude relationship ($r = 0.16 \pm 0.1$) with Votes awarded 1 match later than the match immediately following provision of the C sample.

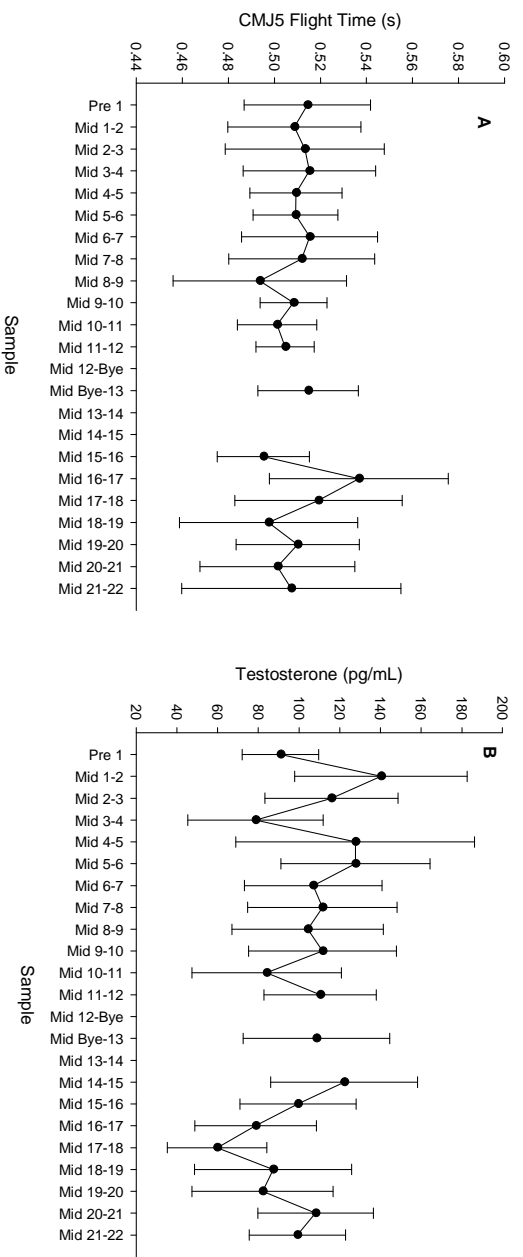


Figure 5. (A) CMJ5Flight time (s), (B) Testosterone (pg/mL) and (C) Testosterone:Cortisol Pre to Mid 21-22. Values are displayed as mean \pm SD.

Match time displayed a small ($r = 0.2 \pm 0.13$) correlation with with CMJ1Flight time:Contraction time %Pre measured after the match. Total cumulative match time had small correlations with T ($r = -0.19 \pm 0.1$), T %Pre ($r = -0.15 \pm 0.1$), C ($r = 0.18 \pm 0.1$) and T:C ($r = -0.15 \pm 0.1$). Total cumulative match time as a % of possible match time displayed small correlations with CMJ1Flight time:Contraction time ($r = -0.3 \pm 0.11$), T ($r = 0.16 \pm 0.1$), T %Pre ($r = 0.17 \pm 0.1$) and T:C %Pre ($r = 0.2 \pm 0.1$). No practically important correlation was revealed between any hormonal or neuromuscular measure and number of hours from the previous match.

5.5 Discussion

5.5.1 CMJ Measures

In the current study, CMJ1Flight time:Contraction time showed a substantial reduction in numerous comparisons whilst CMJ5Flight time responded less clearly. Most previous studies have addressed neuromuscular responses over relatively short training periods, rather than extended competition seasons. A study of collegiate soccer players discovered reduced sprint speed and CMJ performance late into an 11 week season.⁷⁶ A study of semi-professional rugby league players³³ found no change in CMJ after 6 weeks of overload training, whilst a similar group of athletes⁷¹ displayed a clinically important reduction in the same measure after a period of overload training. The relatively short term nature of previous research limits the capacity to compare results with those of the current study as acute responses may be unrepresentative of longer term changes. However, as CMJ1Flight time:Contraction time has demonstrated a clear pattern of depression and recovery following an ARF match,¹⁵⁸ it is reasonable to assume that substantial decrements seen in this study are indicative of acute low frequency neuromuscular fatigue.⁵⁸ Periods of non-functional overreaching or overtraining would likely have resulted in extended periods of substantial reductions and less frequent return to baseline due to the longer time required for recovery.³⁴ Critically, previous research suggests that the strength training stimulus applied on Day 1 (PM) is of little consequence to the pattern of neuromuscular fatigue and recovery measured on Day 3 (AM).¹⁵⁸ Whether the neuromuscular fatigue evident is of central or

peripheral origin,³⁶ cannot be determined from our results, although changes in hip and knee angles⁶¹ and a decrease in muscle-tendon stiffness resulting from prior SSC exercise⁶⁹ may be responsible for the decrements observed.

Interestingly, the longest period of neuromuscular fatigue was 5 consecutive measurements (Mid 10-11 to Mid 15-16), although this is possibly an exaggeration of the extent of neuromuscular fatigue, as no measurements were taken Mid 12 – bye or Mid 13-14. If the trend for a substantial reduction was maintained in the weeks without data; it may indicate that athletes involved in high level weekly team sport competitions have a threshold capacity to cope with repeated loading, after which time they enter a period of neuromuscular overreaching³⁴ but rebound, given effective periodisation.⁷¹ Inappropriate periodisation may result in an extended period of non-functional overreaching and potentially overtraining.³⁴ This may have implications for the design of training programs for elite level contact team sport athletes who compete on a weekly basis over long seasons.

The response of the CMJ5Flight time variable in comparison to CMJ1Flight time:Contraction time suggests it is less able to discriminate between degrees of neuromuscular status. Of the 3 occasions where CMJ5Flight time displayed a substantial reduction compared to Pre, CMJ1Flight time:Contraction time was also depressed on 2 of these occasions. On the other occasion (Mid 18-19), CMJ1Flight time:Contraction responded trivially but with a larger decrement (-8.0%) than CMJ5Flight time (-3.9%). Other research⁷⁵ has demonstrated an 8% reduction in 5 bound hop for distance following 4 weeks of overload training in triathletes. It appears that CMJ5Flight time or a similar measure, may show decrements only in the presence of non-functional overreaching or overtraining,³⁴ such as that brought about by deliberate overloading or periods of extreme training and competition stress.^{34,75} As the Pre time point in the current study is analogous to 48h pre match in previous research,¹⁵⁸ CMJ5Flight time is less likely than CMJ1Flight time:Contraction time to have displayed substantial decrements. Despite this, it could represent a variable capable of detecting non-functional neuromuscular overreaching as opposed to acute cyclical low frequency fatigue. The usefulness of this variable throughout a season may be enhanced by

obtaining a pre match sample as a baseline to compare with weekly values, as it has been shown to be more sensitive in this comparison.¹⁵⁸

5.5.2 Hormonal Measures

The substantial reduction in C evident at 95% of comparison points is in contrast to previous work in soccer where C increased at the end of a 7 week high intensity training phase²⁴ and throughout a season.^{28,124} Research using American Football skill position players³⁴ during a 15 week off season training program and 6 weeks of overload training in Rugby League resulted in no change to C levels.³³

There may be a number of explanations for the results seen in the current study. First, the Pre sample may represent an elevated level in response to approximately 20 weeks of training prior to commencement of the competitive season. Previous work⁷⁶ that discovered C to be elevated in male collegiate soccer players at the end of a pre season phase supports this contention. Second, the training and playing load undertaken by the players throughout the competitive season may have allowed C to decrease in relation to (potentially elevated) Pre values, whereas excessive loading may have resulted in maintenance or increases compared to Pre.⁷⁶ The underlying mechanism responsible for the endocrine variation in this research is unclear. It may be related to modifications in the action of the hypothalamo-pituitary axis (HPA) on testicles or adrenals in response to the balance between exercise and recovery.^{24,28} Inappropriate physiological loading would likely have resulted in increased C due to an over secretion of adrenocorticotrophic hormone as a response to the increased sensitivity of the HPA to stress.¹²⁷ From a hormonal perspective, the potential for inappropriate periodisation resulting in overreaching appears to have been avoided⁷¹ via a stabilization of the action of the HPA.²⁶ This likelihood is supported by previous work where C was substantially elevated 72hrs post an elite ARF match compared to baseline,¹⁵⁸ therefore emphasising the practical importance of the reductions seen in the current study.

The response of T, and particularly T:C, may indicate the presence of a predominantly anabolic environment throughout the season; suggesting subjects were

able to recover from the stresses of training and competition.^{34,76} Any regular reductions in T would probably have been the result of inhibited testicular secretion.²⁶ It has been proposed that T:C may be a particularly useful tool in monitoring the adaptive response to physical loading^{71,133} as decreases in this ratio of > 30% may indicate overtraining.¹²⁸ However, other researchers have proposed caution in the use of this ratio as a decrease does not necessarily translate to decreased performance or a state of overtraining.²⁴

Research examining change in T and T:C has produced varied results. Testosterone has displayed an elevation during soccer training and competition,^{76,124} in conjunction with unchanged T:C.⁷⁶ In contrast, T and T:C have shown decreases in soccer and rugby league players^{24,35} whilst T remained unchanged at the end of a professional soccer season.²⁸ Confounding the comparison with previous research is the relatively few data points analysed in other season long studies. Regular analysis allows interpretation of week to week responses and trends over the longer term, whilst less frequent samples may provide only a snapshot of endocrine variation that is unrepresentative of the overriding response. In the current study, T responded with substantial increases and unclearly at the same rate (45% of data points each), whereas T:C was more predictable with predominantly large increases. In conjunction with other research,¹⁵⁸ increases in this ratio in the current study suggest an anabolic environment,³⁴ with athletes tolerating the training and competition loads.³³ Repeated high training loads during periods of hormonal imbalance may have resulted in further endocrine system disruption and ultimately compromised recovery.²⁶ However, the precise physiological impact of this anabolic environment is uncertain as even large reductions in T:C may be unrepresentative of performance decrements or confirmation of overreaching or overtraining.^{33,75}

5.5.3 Correlations

Whilst a number of correlations with practical importance are evident, the effects are generally small and variable. The use of a $\geq 75\%$ likelihoods threshold and $r \geq 0.1$ to signify practical importance suggests further work is needed to clarify the strength and practical importance of these relationships.

Despite this, it is interesting that some comparisons suggest a lag effect between change in the measurement variable and performance. For example, CMJ1Flight time:Contraction time %Pre had a small positive correlation ($r = 0.24 \pm 0.13$) with Votes obtained 2 data points later than the CMJ variable. It is possible that changes in neuromuscular status may have a delayed influence on performance. This has potentially important practical applications, as opportunity may exist to influence performance with interventions aimed at recovering neuromuscular status. Although speculative, the delayed relationship between neuromuscular fatigue and performance may be the result of an alteration in the time course of low frequency neuromuscular fatigue and recovery,¹⁵⁸ brought about by repeated loading such as that undertaken by subjects in the current study.

The relationship between C and performance in the current study is varied. The small negative correlation between C %Pre and Votes ($r = -0.16 \pm 0.1$) indicates the potential for higher levels of performance with low levels of catabolic hormone, although this relationship has a high degree of uncertainty and is in contrast to the relationship between absolute C and Votes one round later. Further analysis is required to define the link between change in endocrine parameters and performance in elite ARF.

Uncertainty exists regarding the practical importance of the correlations between competition load and the majority of measurement variables in this study. However, total cumulative match time as a % of possible match time appears linked to the response of CMJ1Flight time:Contraction time. The relationship between competition load and hormonal measures is varied, although C shows a small increase in relation to match time which may be important for the potential use as of this variable as a marker of training and competition load.

Evidence of a relationship between neuromuscular and hormonal measures in the current study is displayed in correlations between CMJ1Flight time:Contraction time %Pre and T:C %Pre; and T:C %Pre 1 data point after the CMJ sample. Although small and variable, these relationships may indicate change in neuromuscular status is

immediately and prospectively related to endocrine response. Previous work has identified significant negative correlations between C and CMJ performance in a group of soccer players considered non-starters and significant positive correlations between T:C and CMJ performance in starters at the end of the season.⁷⁶ A study in rugby league players found no significant correlation between endocrine measures and performance, although the authors suggested a catabolic state prior to an endurance test influenced the reduced performance.⁷¹ The concept of a decrease in neuromuscular status preceding an increase in C is a variation on the notion of a catabolic state leading to reduced force production.⁷⁶ Whilst the correlation between CMJ1Flight time:Contraction time %Pre and T:C %Pre in the current study supports the traditional concept, the relationship between the CMJ variable and T:C %Pre 1 sample point later, may have been revealed because of the frequency of monitoring. Monitoring with high regularity could reveal more subtle variations in measurement variables than less frequent data collection and consequently, important relationships may be discovered. It may be that this relationship existed in other team sport research, however limited sampling data may have masked underlying changes.

5.6 Practical Applications

A reduction in CMJ1Flight time:Contraction time and/or increase in C compared to baseline suggests incomplete recovery of neuromuscular and hormonal status respectively. Regular monitoring of these variables throughout the season may allow instigation of appropriate interventions such as reduced training loads or periods of rest aimed at recovering neuromuscular and hormonal status. Responses should be examined in comparison to individual baseline measures on a weekly basis to specifically target manipulations of the training and competition stimulus in an effort to maximize performance.

Further research should look to confirm these results and investigate methods of moderating neuromuscular and endocrine response. The impact of changes in neuromuscular and hormonal measures should also be investigated in relation to more precise workload and performance measures such as distance run or average speed.

Exploring relationships between hormonal response and anabolic:catabolic balance via imaging technology or monitoring of protein signaling pathways is an attractive area of research.

5.7 Conclusions

A competitive season of elite ARF competition elicits fluctuations in neuromuscular and endocrine responses. The response of CMJIFlight time:Contraction time indicates subjects were in a compromised neuromuscular state at 60% of data points and this reduction had a delayed relationship with Votes. The pattern of response seen in C and T:C suggests subjects were unlikely to have been in a catabolic state as a result of the training and competition load. Cortisol had a small relationship to performance and in addition to CMJIFlight time:Contraction time may be a useful variable for monitoring the response to elite ARF competition and training.

CHAPTER 6

6.0 CONCLUSIONS

One of the most important factors in evaluating the worth of a variable for the assessment of elite athletes is its level of reliability. The initial conclusion of this research is that numerous variables obtained from both single and repeated CMJ performance in elite ARF athletes display acceptable levels of reliability, in this case a *CV* of $\leq 10\%$. The overall reliability of CMJ1 variables revealed CMJ1Mean Force (*CV* 1.1%) to have the highest level of repeatability and only this measure was capable of detecting the *SWC*. In addition, CMJ1Peak force and Relative peak force displayed excellent reliability (*CV* 1.2 – 2.8%). Peak power measures were more reliable than their mean counterparts whilst Height was less reliable (*CV* 5.1%), which may be related to the indirect measurement technique used for this variable in this study. The identification of CMJ1Flight time:Contraction time (*CV* 8.2%) time as a reliable measure was interesting, although this variable is incapable of detecting the *SWC*. To our knowledge, neither the reliability nor usefulness of this variable has been previously assessed. This variable may be particularly attractive for regular practical use due to ease of measurement by forceplate systems.

Despite no CMJ5 variables analysed appearing capable of detecting the *SWC*, numerous measures display high levels of reliability. Relative Mean force was the most repeatable (*CV* 1.6%) whilst Flight time, in addition to various peak and mean force and power measures, also displayed good reliability. It seems particularly important that CMJ5Height was shown to be extremely unreliable (*CV* 28%) and this may also be related to the indirect measurement of this variable coupled with the requirement for repeated performance.

The response of reliable CMJ variables to a single match of elite ARF suggests varying levels of sensitivity in these measures to both acute and longer lasting low frequency fatigue. Although numerous variables including CMJ1Flight time, CMJ1Mean power, CMJ1Relative Mean force and CMJ5Flight time displayed substantial pre to post match reductions, CMJ1Flight time:Contraction time was the only variable to decrease in both this comparison (-16.7%) and the post match versus 48pre match analysis (-7.5%). Coupled with the pattern of response evident in this variable from 24 to 120post match, it appears that CMJ1Flight time:Contraction time is the most useful CMJ variable of those analysed for the purpose of assessing neuromuscular fatigue in elite ARF athletes. Critically, reductions of a substantial magnitude in CMJ1Flight time:Contraction time at 72post compared to 48pre may be considered indicative of the presence of low frequency neuromuscular fatigue extending beyond the expected time course of recovery. Although less sensitive, CMJ5Flight time may also be useful, particularly for testing environments without access to forceplate technology because this variable can be easily measured using contact mat timing systems.

In a similar manner to CMJ1Flight time:Contraction time, C responded markedly to a single elite ARF match with a substantial post match increase (34.2%). In contrast, T:C was substantially depressed after competition (-36.0%). The results of this experiment suggest that C may be expected to return to levels substantially lower than pre match values by 96post match. Maintenance of pre match C levels beyond this time may be indicative of endocrine imbalance. Such disruption to the endocrine system may also be considered evident if C is substantially elevated compared to 48pre match at 72post match or beyond. The most varied hormonal response occurred in T, which displayed unclear responses in the majority of comparisons, and this uncertainty makes it difficult to infer expected patterns. This is likely to be a limitation to the isolated use of this variable for monitoring purposes in elite ARF athletes, however monitoring of C and/or T:C may be valuable.

Across the competitive season, a clear pattern of fatigue and recovery was identified by the response of CMJ1Flight time:Contraction time. The magnitude of

change in this variable across the season suggests low frequency neuromuscular fatigue was evident at 60% of measurement points. The cyclical nature of this response suggests acute fatigue and recovery from competition and training loads rather than non-functional overreaching or overtraining. The decrease in C on 95% of occasions compared to baseline, combined with an increase in T:C at 70% of measurement points, suggests that athletes were not in a catabolic state for large portions of the season. This is encouraging in terms of the periodisation, training and recovery programs implemented for the athletes in this study.

The relationship demonstrated between CMJ1Flight time:Contraction time and performance ($r = 0.24 \pm 0.13$) provides evidence of the potential value of this measure of neuromuscular fatigue. CMJ5Flight time may be classified as a less sensitive measure of neuromuscular fatigue in elite ARF athletes; however it may possess the capacity to detect periods of overreaching resulting from extreme training and competition stress because it appears to demonstrate a decrement in elite ARF players in this state. In addition to the correlations demonstrated between neuromuscular status and performance, a small correlation also existed between C %Pre and performance ($r = -0.16 \pm 0.1$). Furthermore, C had a small correlation with match time, suggesting this measure may be sensitive to workload. Whilst the results of these correlations indicate the potential for relationships between neuromuscular and hormonal variables and workload or performance, more work is needed to confirm the strength and importance of these interactions.

6.1 Practical Applications

From a practical perspective, a number of key issues are evident as a result of this series of studies.

1. Initial assessment of the ability of variables to assess change in elite athletes should commence with determining the reliability of these measures. This should be conducted on a population specific basis. Variables should be assessed for their $TE/CV\%$ and their capacity to detect the SWC.

2. Variables displaying the highest levels of reliability are not necessarily the most useful for a particular task. Once a threshold level of acceptable reliability has been established, these variables should be tested on the population in question to determine their suitability for the intended assessment task.
3. In the case of elite ARF athletes, CMJIFlight time:Contraction time is a valuable measure of neuromuscular fatigue, although this level of sensitivity may not exist in other team sport environments.
4. Scientists and coaches considering using CMJIFlight time:Contraction time as a measure of neuromuscular fatigue should establish appropriate fatigue free baseline measures. Magnitudes of change should then be assessed on an individual basis at regular intervals in comparison to the *TE/CV%* and *SWC*.
5. Decrements in this measure compared to baseline beyond 72h post match may be indicative of neuromuscular fatigue persisting beyond the expected recovery time in elite ARF players.
6. Neuromuscular fatigue in elite ARF athletes appears to have a small but practically important relationship with performance. Therefore, a manipulation of the training stimulus may be warranted in an attempt to restore neuromuscular homeostasis.
7. Cortisol is a useful marker of endocrine response to elite ARF training and competition that also displays a small practically important relationship with performance (although this relationship has some variability). As a result, it may be valuable to consider implementing a modified training program for athletes displaying elevated C in order to minimise the increase between acute values and baseline scores.
8. The response of C should be evaluated on an individual basis against the *TE/CV%* of the assay. Individuals performing the C assay should establish their own levels of reliability.
9. Assays must be performed in a timely fashion to allow results to be used in training load manipulations in week to week competitions.
10. Scientists and coaches should determine for their particular sport, whether measures of neuromuscular and/or hormonal responses are useful markers of acute fatigue, overreaching or overtraining.

6.2 Recommendations for future research

Although providing an insight into the response and value of functional measures of neuromuscular fatigue and endocrine variation in elite ARF athletes, there are various avenues available to build on the data obtained in the current research.

1. Future work should look to examine the response of CMJ1Flight time:Contraction time and other SSC tasks in addition to endocrine status in a variety of elite contact team sport athletes. It is possible that the responses may be markedly different than those evident in the current series of studies.
2. Further analysis of the mechanisms underlying hormonal responses and their impact would be valuable. For example, the use of DEXA scans to monitor changes in muscle mass could be used to assess relationships with variations in anabolic:catabolic balance.
3. Investigation into the relationship between neuromuscular and hormonal changes and more precise elite ARF workload or performance measures appears worthwhile. These workload measures may be in the form of data obtained from Global Positioning System devices or camera monitoring systems. Additional performance measures may include data from the various statistical companies currently serving the elite ARF competition. An assessment of relationships to measures such as rate of perceived exertion, or other load indices may be enlightening.
4. The usefulness of alternative markers such as IgA may also be worthy of study, although the inability to analyse a variety of markers including hormones in saliva could be a limitation.
5. An important area of future work related to the current research could involve examination of single subject case studies and the development of mathematical models to assist in the prediction of performance, injury and fatigue.

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APPENDICES

Appendix 1



INFORMATION LETTER TO PARTICIPANTS

The Reliability of Single and Repeated Countermovement Jump Tests

Purpose of the Study

The research described below forms part of my PhD being conducted at Edith Cowan University and has been approved by the ECU Human Research Ethics Committee. The purpose of this research is to determine the reliability of various measures such as height and power that are obtained during the performance of a single and repeated (5 continuous) countermovement jumps.

Test Procedure and Measurements

If you agree to participate in this study you will be asked to perform either a single or 5 repeated countermovement jump on 7 different occasions. The first 3 occasions will be practise trials to ensure you are comfortable with the required technique. You will then be asked perform a maximum effort of the test in the morning and afternoon of the same day. This process will then be repeated 7 days later.

The jumps will be performed on a force plate connected to a computer which enables the calculation of height, flight time, and power. The results of these measures will be analysed to determine whether the test is accurate from morning to afternoon and week to week. You will be required to maintain the same training, diet, and rest regimes in the two days leading up to each day of maximal testing.

Benefits

Determining the reliability of this test will allow further investigation to assess whether it is capable of detecting fatigue associated with playing and training. This will allow more precise individual manipulation of training loads and aid you in achieving optimal levels of performance.

Risk and Ethical Considerations

Due to the maximal nature of the test procedure there is a minimal risk that you may incur a soft tissue injury such as a muscle strain. To minimise the risk of this occurring

you will have the opportunity to fully familiarise yourself with the technique and completely warm up prior to testing. In the unlikely event of an injury occurring, you will be immediately referred to the club physiotherapist for treatment.

Further Information

All results obtained during the testing will be kept confidential. No data analysis or presentation will include your name or other personal details. It is important that you are aware that your participation is voluntary and that you are free to withdraw from this study at any stage for any reason without penalty.

If you have any questions you can contact me on the details below.

Stuart Cormack (PhD candidate)

School of Biomedical and Sports Science

Edith Cowan University

100 Joondalup Dve

Joondalup WA 6027

Ph: [REDACTED]

Mobile: [REDACTED]

[REDACTED]

If you have any concerns or complaints about the research project and wish to talk to an independent person, you may contact:

Research Ethics Officer

Edith Cowan University

100 Joondalup Drive

JOONDALUP WA 6027

Phone: (08) 6304 2170

Email: research.ethics@ecu.edu.au

Thank-you for your interest in this research project.

Yours sincerely,

Stuart Cormack

Appendix 2



INFORMED CONSENT

**Project Title: The Reliability of Single and Repeated Countermovement
Jump Tests**

Declaration

I _____ have read the above information regarding this study and am clear about the requirements and risks of participation in this research. I have also had any questions relating to this study answered to my satisfaction.

I agree to participate in this study with the knowledge that I am free to withdraw at any time for any reason.

I also agree that the research data obtained during this study may be published, provided I am not identifiable in any way.

Participant: _____ Date: _____

Investigator: _____ Date: _____

Appendix 3



INFORMATION LETTER TO PARTICIPANTS

Neuromuscular and Hormonal Responses to Australian Rules Football Match Play

Purpose of the Study

The research described below forms part of my PhD being conducted at Edith Cowan University and has been approved by the ECU Human Research Ethics Committee. The purpose of this study is to assess the impact of participation in an AFL pre season match on various measures of fatigue, and to examine how these measures respond in the week after the match.

Test Procedures and Measurements

If you agree to participate in this study you will undergo a number of measurements. These measurements will be taken approximately 24-48 hours pre game, pre and post game, and every 24 hours for the 7 days following the match.

The first tests are a single and repeated countermovement jump (requiring you to jump for maximum height 5 times in a row). The second test involves providing a saliva sample into a collection tube. This saliva sample will be analysed for levels of the hormones Testosterone and Cortisol.

These measurements will provide a picture of your overall fatigue and recovery response to participation in an AFL match.

Benefits

The data obtained in this study will allow a more in depth understanding of the physiological response to AFL match play. From this information it may be possible to more effectively plan training programs. There may be particular benefits in areas such as manipulating training loads in response to fatigue in a more individual and objective manner.

Risk and Ethical Considerations

Due to the maximal nature of the test repeated jump procedure, there is a minimal risk that you may incur a soft tissue injury such as a muscle strain. To minimise the risk of this occurring you will have the opportunity to fully familiarise yourself with the technique and completely warm up prior to testing. In the unlikely event of an injury occurring, you will be immediately referred to the club physiotherapist for treatment.

Further Information

All results obtained during the testing will be kept confidential. No data analysis or presentation will include your name or other personal details. It is important that you are aware that your participation is voluntary and that you are free to withdraw from this study at any stage for any reason without penalty.

If you have any questions you can contact me on the details below.

Stuart Cormack (PhD candidate)
School of Biomedical and Sports Science
Edith Cowan University
100 Joondalup Dve
Joondalup WA 6027



If you have any concerns or complaints about the research project and wish to talk to an independent person, you may contact:

Research Ethics Officer
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JOONDALUP WA 6027
Phone: (08) 6304 2170
Email: research.ethics@ecu.edu.au

Thank-you for your interest in this research project.

Yours sincerely,

Stuart Cormack

Appendix 5



INFORMATION LETTER TO PARTICIPANTS

Hormonal Profiles and Neuromuscular Fatigue During an Australian Rules Football Season

Purpose of the Study

The research described below forms part of my PhD being conducted at Edith Cowan University and has been approved by the ECU Human Research Ethics Committee. The purpose of this study is to assess the impact of participation in a season of AFL football on various measures of fatigue, and to examine how these measures compare to changes in strength and power performance.

Test Procedures and Measurements

If you agree to participate in this study you will undergo a number of measurements on a regular basis throughout the season. Hormonal and neuromuscular measurements will be collected on a weekly basis following a rest day.

The first tests are a single and repeated countermovement jump (requiring) you to jump for maximum height 5 times in a row. The second test involves providing a saliva sample into a collection tube. This saliva sample will be analysed for levels of the hormones Testosterone and Cortisol. It has been suggested that these hormones may be reflective of how your system is responding to playing and training loads.

Benefits

The data obtained in this study will allow a more in depth understanding of the physiological response to a season of AFL match play. From this information it may be possible to more effectively plan training and recovery programs. There may be particular benefits in areas such as manipulating training loads in response to fatigue in a more individual and objective manner. An important benefit of this study will be the possibility of determining whether any of the measures utilised during the study are more valuable than others in monitoring responses to a season of high level team sport play. This will allow those involved in prescribing training loads to utilise the most effective monitoring methods.

Risk and Ethical Considerations

Due to the maximal nature of the repeated jump test, 3 repetition maximum strength and power test procedures, there is a minimal risk that you may incur a soft tissue injury such as a muscle strain. To minimise the risk of this occurring, you will have the opportunity to fully familiarise yourself with the technique and completely warm up prior to testing. In the unlikely event of an injury occurring, you will be immediately referred to the club physiotherapist for treatment. There is a very small risk of infection from the finger prick but this is performed under sterile conditions. A new lancet drawn from an individually wrapped sterile packet is used for each finger prick.

Further Information

All results obtained during the testing will be kept confidential. No data analysis or presentation will include your name or other personal details. It is important that you are aware that your participation is voluntary and that you are free to withdraw from this study at any stage for any reason without penalty.

If you have any questions you can contact me on the details below.

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If you have any concerns or complaints about the research project and wish to talk to an independent person, you may contact:

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Phone: (08) 6304 2170
Email: research.ethics@ecu.edu.au

Thank-you for your interest in this research project.

Yours sincerely,

Stuart Cormack

Appendix 6



INFORMED CONSENT

Project Title: Hormonal Profile and Neuromuscular Fatigue During an Australian Rules Football Season

Declaration

I _____ have read the above information regarding this study and am clear about the requirements and risks of participation in this research. I have also had any questions relating to this study answered to my satisfaction.

I agree to participate in this study with the knowledge that I am free to withdraw at any time for any reason.

I also agree that the research data obtained during this study may be published, provided I am not identifiable in any way.

Participant: _____ Date: _____

Investigator: _____ Date: _____