Factors influencing recovery of neuromuscular function post Australian Rules football matches.

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School of Health and Exercise Science

“Let’s work the problem, people. Let’s not make things worse by guessing”

Gene Kranz

Statement of Authentication

The work presented in this thesis is, to the best of my knowledge and belief, original except as acknowledged in the text. I hereby declare that I have not submitted this material, either in full or in part, for a degree at this or any other institution.

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Abbreviations

ARF	Australian Rules Football
NF	Neuromuscular function
RFD	Rate of force development
IMTP	Isometric mid-thigh pull
CMJ	Counter movement-jump
EIMD	Exercise induced muscle damage
LFF	Low frequency of fatigue
GPS	Global positioning software
RPE	Ratings of perceived exertion
HSR	High speed running
VHSR	Very high-speed running
AccDecLoad	Acceleration deceleration load
MAS	Maximal aerobic speed
PQ	Physical qualities
BL	Baseline
LBS	Lower body strength
LBP	Lower body power
Vift	Velocity at find stage of 30.15 test
CK	Creatine kinase
MVC	Maximal voluntary contraction
LMM	Linear mixed models
SD	Standard deviation
CV	Coefficient variation
RM	Repetition max

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Factors influencing recovery of Neuromuscular function post Australian Rules football matches.

Norris, D

1.1. Thesis Purpose:

To examine the influence and interaction of individual physical fitness qualities upon neuromuscular function (NF) in both isometric and dynamic conditions following elite Australian Rules Football (ARF) matches.

1.2. Thesis Rationale:

Australian Rules Football (ARF) is a contact invasion sport played by two teams of 22 players in which players can cover distances of 10-18km with frequent high-intensity efforts [3,4]. A potential of 26 games over 28 weeks can be played in a season with a range of six to eight days between games.

High speed running and acceleration efforts have been suggested to be important variables for success in ARF and other team-based sports such as Football and Rugby League [5-8]. Due to the subsequent fatigue response associated with these variables and the potential of a fatigued state to negatively influence performance, monitoring of an athlete's recovery post competition is considered of importance [9].

Research monitoring the acute time course recovery of neuromuscular, metabolic, endocrine and perceptual measures of fatigue following elite competition have shown disturbances developing within hours post-game, and lasting multiple days before returning to baseline levels [10]. In particular, neuromuscular function (NF) has been shown to be an important component of recovery, as reductions have been related to an increased injury risk and reduction in both physical and skill related performance across a variety of football codes [4,6,11,12].

Neuromuscular fatigue has been defined in literature as the impairment of a muscle's ability to produce force [9,13]. It is thought that reductions in force production can be due to both central and peripheral causes, with central mechanisms stemming from the brain or spinal level, and peripheral mechanisms located at the motor unit level [14,15]. Due to the invasive and time-consuming nature of measuring central fatigue mechanisms, assessment of NF in elite sport settings has largely been studied in reference to peripherally-mediated reductions (voluntary force production) [9,10,12]. A commonly used assessment of peripheral NF in elite sports is the unloaded vertical jump, where variables of peak power, jump height and flight time/contact time have shown acute reductions post ARL, Rugby and soccer matches and can remain supressed for up to 72 hours [8,10,16]. Whilst this test is considered reliable and easy to implement, there is still conjecture over ability of the vertical jump to assess the fatigue state with inconsistent associations to training load metrics reported and limited agreement between laboratory measures of NF [17-21]. A potential reason for this may be due to dynamic nature of the vertical jump where the loading period or stretch short cycling component may attenuate some of the performance loss seen in a fatigued state[22]. This need to monitor both loading and contraction periods may make identification of a fatigued state difficult as decreases in parameters such as eccentric loading time may be offset by improvements in other measures such as jump height [23].

In contrast, laboratory assessments of NF have often utilised isometric contraction modalities so as to minimize potential influences or noise [13]. This isolation of contraction may also allow for stronger inference of mechanisms influencing force-time development in fatigue states. For example, the rate of force development (RFD) within initial/early time frames (<75ms) of contraction onset have been shown to be largely influenced by neural components (rate coding, motor unit discharge rate), with later time frame RFD (100-200ms) being influence by contractile components of the muscle [12,24]. While insightful, traditional testing of isometric force production has often involved expensive dynamometers within laboratory settings, which may not always offer a feasible or time effective solution for weekly monitoring in team-based sports settings. One isometric test that has been adopted in elite team settings for athletic profiling is the Isometric Mid-Thigh Pull (IMTP), where force-time and peak force variables collected from the IMTP having reported moderate to strong relationships with 10m and 20m sprint time, vertical jump performance, and dynamic strength [25]. Interestingly, while RFD variables produced from the IMTP have been previously assessed across a variety of sports (Weightlifting, College Football and Cycling) [26-29] this research has largely focused on peak RFD, with limited research examining time interval RFD variables in elite sport settings which may give additional insight into NF.

A final and important consideration in the assessment of NF is an understanding of factors that may influence observed NF responses. In particular, it has recently been suggested that recovery of NF may be positively influenced by higher baseline physical qualities such as muscular strength and cardiovascular endurance [16]. Factors such as increased metabolite clearance and enhanced contractile resilience subsequently reducing acute and transient fatigue following competitive match play [30-32]. Indeed, research of sub-elite Rugby League players showed a faster return to NF baseline, as measured by vertical jump, in players with higher aerobic capacity. Secondly, stronger players as measured by squat strength showed a similar NF recovery time-course to weaker players despite performing greater collisions, running loads and reporting higher internal loads as measured by Ratings of perceived exertion (RPE) post-match [16]. Whilst informative, the above research was only assessed following two competitive matches. Due to the high degree of week-to-week variability in the recovery of NF observed in other studies [18,33,34], longer term studies are needed to better identify the magnitude of impact that physical qualities play on recovery of NF. Secondly, other physical variables such as lower body power may also influence recovery of NF through similar mechanisms stated above, yet the impact of these athletic qualities has yet to be assessed.

1.3. Significance of Research

The following body of work has aimed to enhance a vast body of literature on the topic of neuromuscular fatigue in elite sports. Key aspects of this research have attempted to account for the interaction of multiple influencing factors on NF in a longitudinal design that has predominately been studied in separation in the current literature. Furthermore, to this author's knowledge, this is the first to research where two NF testing modalities have been analysed in a longitudinal design whilst accounting for physical qualities and external loading measures in an elite cohort. An understanding of how the interaction between loading and physical qualities impacts NF recovery measures may allow for more individualised micro-cycle preparation for elite athletes.

1.4. Key Aims:

Aim 1: Examine the recovery of force–time characteristics collected from the IMTP following Australian Rules Football Matches. *Chapter 4*.

Aim 2: Examine the influence of physical qualities upon seasonal trends in dynamic and isometric measures of neuromuscular fatigue. *Chapter 5a.*

Aim 3: Examine association/interchangeability between dynamic and isometric measures of neuromuscular fatigue. *Chapter 5a.*

Aim 4: Identify whether physical qualities exert a moderating influence on neuromuscular responses to external load in isometric and dynamic conditions over an ARF season. *Chapter 5b.*

1.5. Thesis Structure:

Chapter 2:
Literature review: Thesis background

Chapter 3:
Extended methods:
Outline of key methods utilised within experimental chapter

Chapter 4:
Experimental chapter 1:
First of experimental chapters: chapter explores **aim 1** of thesis

Norris D, Joyce D, Siegler J, Clock J, Lovell R. Recovery of Force-Time Characteristics Following Australian Rules Football Matches: Examining the Utility of the Isometric Mid-Thigh Pull. Int J Sports Physiol Perform. 2019: vol. 14(6), pp 765-770.

Chapter 5a:
Experimental chapter 2:
Second of experimental chapters: chapter explores **aim 2&3** of thesis

Norris D, Siegler J, Joyce D & Lovell R (2019) Influence of physical qualities on seasonal trends in dynamic and isometric measures of neuromuscular function. World Congress of Science and Football (WCSF). Melbourne, Australia.

Chapter 5b:
Experimental chapter 3:
Third of experimental chapters: chapter explores **aim 4** of thesis

Norris D, Siegler J, Joyce D & Lovell R (2019) Do physical qualities have a moderating influence on the load fatigue response. World Congress of Science and Football (WCSF). Melbourne, Australia.

Chapter 6:
Thesis Summary:

Light grey fill represents chapters resulting in a peer reviewed publication while chapters with light blue fill represents chapters with academic conference presentations.

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2. Literature Review

2.1 Synopsis

This literature review will begin with a review of the framework underpinning the monitoring of fatigue in elite sports, introducing key terms and concepts behind sources of fatigue and testing methods of fatigue. This review will then aim to evaluate the current literature regarding peripheral-related fatigue monitoring in elite sports. The final section will discuss possible influences that may impact upon recovery of neuromuscular fatigue.

2.2 Background

It is widely accepted that post a physical stimulus or competition that there is a subsequent period of fatigue that follows [9,35]. The length of time in this fatigued state is dependent on the stimulus in relation to the current homeostatic position [36]. In order to have positive biological response to a physiological stimulus it is suggested that the following stimulus bout should not begin until adequate recovery from the previous stimulus [36,37].

However if the length between recovery and the next training stimulus is too long the positive physiological adaptions realised may return to pre-stimulus levels [37]. Secondly, acute mis-management of the stimulus/ regeneration period has been related to a reduced force producing capacity, increased risk of injury, illness and a diminished psychological state [3,38,39]. If this imbalance is continued for prolonged periods an athlete may develop a state known as Non-Functional over reaching (NFOR), where the above stated negative effects can persist for weeks or months [9].

This creates a unique challenge within elite sport and notably team-based sports where the need to maintain fitness levels are balanced against allowing for adequate recovery time between weekly competitions. To help ensure that the stimulus /recovery state is managed appropriately, monitoring an athlete's fatigued state following a stimulus is considered an important practice in elite sport. Defining a fatigued state though is difficult as multiple systems such as neuromuscular, endocrine, immunological and psychological systems likely influence this state [9]. Indeed, research monitoring responses post competition in elite sports has shown an acute disruption of these systems that usually remains up to 72 hours, however can last up to a week before normalizing [10,40,41]. Due to the multiple associations between muscular force/power characteristics versus sporting performance, fatigue has largely been studied in reference to the inability to maintain muscular force/power output against normalized values and is usually referred to as neuromuscular function (NF) [23,42-44]. In particular, the fatigued muscle is characterized by a slower rise in force during Maximum voluntary contractions [45].

2.3 Neuromuscular Function

Whilst the exact cause of reduction in NF is still debated and multiple sites for fatigue likely exist, the Excitation-contraction coupling (EC coupling) model describes the complex sequence of events necessary for converting an action potential to cross bridge formation in the muscle cells [23]. It has been suggested that ionic changes in the muscle cell caused by exercise metabolism and structural damage to the muscular apparatus, most notably through high-intensity eccentric actions, are likely contributors to reductions along the EC coupling pathway [14,23]. Whilst the mechanisms mentioned above are peripheral in origin, centrally-mediated reductions in force output have also been noted, referring to inadequate output from either brain and/or spinal regions to activate the contractile machinery [14,45,46].

2.3.1 Central Fatigue

Central fatigue can be demonstrated by a difference between voluntary and evoked force properties from either transcranial magnetic stimulation (TMS) for supraspinal stimulation or electromagnetic stimulation (EMS) for spinal stimulation during maximal contractions [21,47]. It is suggested that reductions in central output may serve as a protection mechanism against excessive exercise induced muscle damage (EIMD) and that this reduction in motor output is mediated through multiple sensory peripheral feedback mechanisms and a suppressed motivation to perform the task [48,49]. Whilst monitoring of central fatigue may offer useful information on identifying the potential source of fatigue, measurement of this central contribution is time consuming, requires highly skilled practitioners, and often has low movement specificity to muscular demands seen in sport. Importantly, current available literature suggests that contribution of centrally mediated fatigue to be largely acute in nature with normalization to baseline levels usually observed 3-24 hours post competitive match play [48,50,51]. For example Thomas et al[50] observed normalization of centrally mediated reductions of NF as measured by cortical output by 48 hours following simulated soccer match-play in 15 semi-elite soccer players. These findings were consistent with earlier work by Rampinini et al[51] who also observed acute centrally mediated reductions in NF with return to baseline levels observed by 24 hours. Indeed, it is clear that more research is needed in this area, however the limited available longitudinal and repeated measures research designs available in the research literature is indicative of the practical measurement difficulties

2.3.2 Peripheral Fatigue

In contrast to the fast restoration observed for centrally mediated neuromuscular fatigue, peripheral mediated reductions in NF have been observed for periods ranging from immediately post to multiple days in both laboratory and field settings [48,52,53]. Similarly to central measures, laboratory-based assessment of peripheral fatigue have utilised nerve and magnetic stimulation techniques coupled with a maximal voluntary contraction to identify the degree of peripheral contribution to reductions in NF [54]. Specifically, peripheral related fatigue is identified as a difference between force produced from a stimulated force contraction and maximal voluntary force contraction, where the strength of stimulation has been categorized into high (50-100hz) and low frequency (10-20hz) [21]. Reductions in force producing capability at either of these frequencies are accordingly labelled lower frequency fatigue (LFF) and high frequency fatigue (HFF). In particular, it has been suggested that LFF may be of interest within the elite settings as longer lasting reductions in this measure have been noticed post stretch-shortening fatiguing protocols, resistance training bouts, competitive soccer matches, and prolonged endurance tasks [19-21,55] [50] with relatively stable responses observed under high frequency stimulations . Importantly, the time-course of LFF in these studies ranged from 20 hours, with some reports observing sustained reductions at 96 hours [50]. LFF has also been linked to greater sense of effort during submaximal tasks and subsequently linked to a perception known as “heavy legs” [56,57]. However, similarly to central measures of fatigue, LFF determination requires the use of skilled practitioners, is time consuming and can be considered invasive which is an important consideration within team-based sport settings. Therefore, like central related measures of NF, a lack of longitudinal research designs adopting stimulation-based peripheral fatigue assessment exist in team-based settings, which may be reflective of its practical utility as a weekly monitoring tool.

2.4.1 Peripheral Fatigue Assessment – Dynamic

To address the need for less invasive and time-consuming methods of fatigue assessment, a wide variety of non-invasive measures of peripheral fatigue have been suggested. These testing protocols have utilized a range of isometric and dynamic contractions [12,51,58,59]. Whilst these tests are not able to identify the source of fatigue, they assume a relationship between performance of force-time variables and neuromuscular fatigue [4,23,53]. Of these assessments, dynamic actions such as the counter movement jump (CMJ) have been widely studied in elite sports settings as they are considered to have greater ecological validity versus other contraction types [60]. Measures of peak power, flight time/contraction time (FT/CT) and jump height (JH) collected from the CMJ have shown time course reductions post a number of elite sports [6,39,53,60]. These reductions typically peak immediately post activity and generally return to baseline values within 72 hours [8,10,53].

Due to the recovery time-course of CMJ parameters being similar to that observed with LF stimulation, it is suggested that CMJ indices may be indicative of peripheral fatigue or LFF [52]. Interestingly, research comparing both field and laboratory measures of fatigue are limited and report inconsistent relationships. For example Raastad and Hallen[61] showed similar time-course changes in vertical jump height and LFF following a resistance training program. While not statistically reported Thomas et al[50] observed concordant time-course recoveries with both the CMJ Jump height and peripheral fatigue measured following a simulated soccer match. In contrast, no relationship between vertical jump measures and LFF were seen following a marathon race, a resistance training over reaching protocol, and following an eccentric damaging protocol of 100 maximal drop jumps [19,22]. Taylor et al[62] in a longitudinal training design only observed small relationships between LFF and a range CMJ measures, suggesting that the mechanisms influencing CMJ reductions may not be entirely influenced by LFF.

A range of methodological considerations may explain the limited agreement between these measures such as; training age, contraction duration/modality of CMJ, fatiguing protocols, and force-time variables explored. However, of these considerations the influence of the loading phase of the vertical jump has been suggested to potentially act as a pre-stimulation technique which may mask LFF symptoms [23]. Specifically, it is proposed longer loading times may allow for increase saturation of calcium ions within the sarcoplasmic reticulum[23] . Byrne and Eston [22] investigated the potential effect of the loading phase in the CMJ by comparing it to a squat jump (SJ) which has no loading phase, following an exercise induced muscle damaging protocol (10 sets of 10 squat repetitions at 70% of 1RM). They reported larger reductions from baseline in the SJ height when compared to CMJ height, suggesting that the pre-loading phase or stretch shortening cycle (SSC) utilised in the CMJ may attenuate some of the NF loss observed. Indeed, many studies have since suggested that monitoring of the eccentric phase within the CMJ via either force plates or linear position transducers may give insight into NF previously unavailable via JH assessment alone [2,10,63-65]. For example Cormie et al[63] observed significant improvements in a range of force-time variables in both eccentric and concentric phases of the CMJ following a 12 week power training program. Additionally, Cormack et al [17] found monitoring of the ratio of flight time to contraction time (inclusive of eccentric time) to be both a reliable and sensitive measure of fatigue following elite level AFL matches.

Mixed results however have been observed with this variable in elite soccer players with Rowell et al[66] reporting FT/CT to be sensitive to differences in load performed during competitive match play, while Lovell et al[67] observed no deviations from baseline for FT/CT at match day +1,2,3,4 and 5 following multiple competitive soccer games. Finally in contrast to the previously mentioned findings by Byrne and Eston[22] more recent work by Gathercole et al[53] reported greater and longer lasting reductions in CMJ based indices than the SJ based measures following a fatiguing protocol (three sets of YO-YO IR2 test). Interestingly, despite differences in fatiguing protocols, comparison of JH alone suggests consistency between studies, with longer reductions evident in the SJ when compared to the CMJ. Discrepancies in findings were only observed between other force-time measures collected throughout the eccentric and concentric phase of the CMJ.

Current available literate is therefore suggestive of monitoring both eccentric and concentric force-time variables when identifying NF from the CMJ. Indeed, the CMJ does offer a viable solution to NF assessment in team-based settings, however, the above reported literature highlights difficulties in discerning factors such as central or peripheral contribution to NF.

2.4.2 Isometric Assessment

In contrast to dynamic field-based measures of fatigue, isometric measures were considered to have low ecological validity in sport settings and difficult to practically implement. Isometric contractions however are considered favourable in laboratory settings due to the ability to control joint position and therefor minimize potential sources of noise when assessing recovery of NF [12]. Besides this ‘nonspecific’ contraction mode, similar time-course recovery of force-time metrics have been noted across a variety of fatiguing protocols and competitive sport settings similar to those observed with dynamic measures [12,50,52].

Traditionally, measures of maximum voluntary force or torque production performed during an isometric contraction have been explored in both field and lab-based settings to identify a fatigued state [50,56,67,68]. Yet, a recent review by Maffiuletti[12] has suggested assessment of rate of force development (RFD) may give more insight to NF than maximal force measures. This is because RFD seems to be: (1) better related to common performance tasks in sport; (2) more sensitive to detect changes in NF; and (3) give insight into different physiological mechanisms affecting performance [11,12,14,69,70].

Indeed, early phase RFD (0-50ms) has been suggested to be largely influenced by neural determinates (agonist activity, motor unit discharge frequency) while later phase RFD (>75ms) are likely influenced by contractile components of the muscle [71-73]. It has therefore been suggested that monitoring RFD time windows may give indirect insight to the source of fatigue e.g. being mediated through neural reduction or reduction through contractile damage [12,74]. For example, Peñailillo et al[69] observed later phase RFD (100-200ms) to be a better indicator of muscle damage versus peak force measures following a repeated eccentric cycling protocol. Similar findings were also observed by Oliveira et al[75] who reported greater reductions in RFD (0-100ms) than MVC torque after a 35-minute-high intensity running (95% of OBLA) protocol.

Whilst monitoring of RFD may offer potential insight to a fatigued state, reliable and accurate measurement of this window is difficult. Factors such as degrees of freedom in testing (Multiple joint position), machine compliance, filtering techniques, feedback, pre-tension and identifying contraction onset are all factors which may influence the ability to accurately assess early phase RFD [12]. Secondly, a large degree of available RFD research has utilized knee flexion or extension protocols for which required dynamometers can be expensive and time consuming to test, which may question its continued long-term use within elite team-sport settings. Recently, however, the increased availability and affordability of force plates, has lead to isometric tests being explored within applied settings. For example, McCall et al[68] proposed the use of a prone isometric knee flexion test, which reported high reliability and acute sensitivity to fatigue following soccer match play. Unfortunately, RFD based measures were not assessed within their design, so it is unclear whether the reported reliability and sensitivity extends to these measures. Other isometric assessments such as the isometric mid-thigh pull (IMTP) may also offer a viable solution to monitoring of peak force and RFD intervals. Indeed, use of the IMTP as a profiling tool for muscle strength and power have been widely studied and suggested as a criterion measure [5,25,27,76-78]. While current research examining the IMTP has focused on its relationship to performance measures and or association with other dynamic measures [26,76,79-81], relatively little research examining the acute and longitudinal recovery trends of both peak force and time interval RFD in team based settings exist. Hence given its proposed practical utility and relationships to performance measures, further research is warranted to identify whether force-time measures (RFD) can be reliable and accurately utilised as a measure of NF following competitive match play.

2.5. Factors Influencing NF

With the increases accessibility of data sources in professional sport such as training load measures, psychological wellbeing questionnaires, skill related performance markers, and physical screening/profiling assessments, it is often of interest to understand how these factors may interact to influence or moderate a specific outcome measure [6,35,82]. While many approaches to both identifying and interpreting these complex interactions are continuously being explored [82], inclusion of covariates and or interaction terms within a multi-level mixed models are more commonly utilised to map these relationships within elite sport settings [35,83,84] . Indeed, the ability to directly specify observations being clustered within individuals and its robustness to missing data entries[35,85,86], which can be common place in sport settings, gives support to its utilization.

While it is likely that a range of complex interactions and latent variables not yet measured in sport exert an influence recovery of NF, of current interest is the potential moderating influence of physical qualities (PQ's) such as lower body strength (LBS), power (LBP), aerobic fitness and external training load measures. These measures are of interest as they are potentially modifiable factors and may allow for an earlier estimated fatigue response following competitive match play.

2.5.1 Physical qualities

Current available literature has highlighted the potential moderating impact of advanced levels of physical qualities such as aerobic endurance and muscular strength on favourably influencing recovery of neuromuscular function following competitive match-play [16,30]. It is proposed enhanced aerobic endurance capacity may elicit this influence by reducing the metabolic disturbances observed during a game, and therefore elicit a lesser degree of fatigue [30]. Higher levels of LBS may positively benefit recovery through multiple mechanisms. Firstly, enhanced eccentric strength following resistance-training programs has been linked to decreased perceived soreness by limiting the amount of micro-trauma to the muscle [87,88]. Secondly, increases in muscular strength have also been linked to improvements in rate of force development, running economy and associated with enhanced shortening cycle capacity [32,71,89]. Together these factors may limit the amount of strain placed on both the energetics and contractile components of the muscle, which in turn lessens transient and residual fatigue responses.

In support of this framework, research in elite AFL players showed enhanced aerobic endurance, as measured by 6-min run performance, was associated with smaller disturbances in creatine kinase (CK), a measure of muscle damage that commonly peaks 24-36 hour post to competition[30]. These findings were supported by Johnston et al[16] where a faster recovery of both CMJ performance (Peak Power/body mass (kg)) and smaller disturbances of CK were observed post sub-elite rugby league games in players with enhanced aerobic fitness (as measured via the Yo-Yo IR2). This study also reported a positive influence of baseline lower body strength (as measured by 3 RM squat) on recovery of NF, where despite performing significantly more external work during match play, stronger players had a similar NF recovery profile to athletes who performed less work. One weakness of this study's' design however, was the use of categorization (median split) of physical qualities into subgroups (i.e. high vs. low). While increasing interpretability and equalizing sample size between groups, this method likely over- or under-estimates observed effects as individuals closer to the cut-off value (median) are treated differently, rather than as similar. Owen et al[90] avoided this categorization concern by examining the relationship between CK and muscular strength within a regression framework, where both muscle strength and damage were analysed as continuous measures. Indeed, they too observed favourable effects of muscle strength, with moderate to large negative correlations between the amount of muscle damage and lower body strength following elite level soccer match-play. Finally, while no direct measure of NF or recovery capacity was measured, Malone et al[91]reported a better tolerance to workload changes as measured by injury risk in players with advanced levels of LBS and repeat sprint ability. While speculative, given the observed decays in NF seen after injury [11], it is plausible that this decreased injury risk may be mediated through faster recovery of NF despite changes in workload.

Collectively, the studies highlighted above give credible support to the moderating influence that PQ's may exert on recovery of NF However, the lack of longitudinal designs, the categorization techniques used, and limited application of NF force-time may limit the ability to identify the true strength of moderation, and moreover the potential mechanisms involved. Indeed, longer term studies monitoring NF performance have identified individual variability in NF responses and that this may be mediated through differences in response to training load [18]. This is coupled with the high week-to-week variation in both weekly and competition loads in professional sport, suggest the need for continued research in this area, particularly with longitudinal designs. [33,34]

2.5.2 Measures of load

As mentioned, an understanding of how measures of load may influence recovery of NF is warranted. Indeed, a variety of load monitoring strategies have been explored and utilized within the literature and applied settings [92,93], where approaches are typically categorized as either internal or external load estimates. Internal load measures such as ratings of perceived exertion and heart rate (HR) aggregates or weighted scores (TRIMP) are commonly reported in team-based settings and are typically sensitivity to fluctuations in external measures of load [92,93]. External load monitoring techniques have included use of global position software (GPS), accelerometry, and time motion analysis with the majority of studies reporting on GPS derived measures of load within team settings.

While context to both internal and external measures of load are likely favourable in applied settings, current literature has mostly explored the influence of external load measures collated from GPS and time motion analysis on NF [66,94,95]. It is proposed that eccentric muscle actions observed in movement qualities such as sprinting, accelerating and decelerating efforts may cause damage to the muscular architecture which in turn may influence subsequent NF recovery [8,16,96]. Indeed, in support of this Russell et al[94] observed an association between the amount high intensity running volume/efforts and number of acceleration and deceleration efforts versus both CK and reductions in NF (CMJ; Peak Power), 24 hours post competitive soccer match-play. Similarly, Nedelec et al[95] utilising time motion analysis observed a significant relationship between magnitude of decay in NF (CMJ; JH) at 24 hours post-match play versus the number of hard changes in direction performed in a match. Furthermore, Rowell et al[66] observed a relation between volume of PlayerLoad; a measure instantaneous rate of change measured by the tri-axial accelerometers, and the time-course recovery of NF (JH and FT/CT) following elite competitive soccer matches.

Though the above research gives support to the influence of external load on NF responses, findings have been limited to acute time frames, and have treated expected responses to load as equal across participants. As both positional and individual variation in fitness levels and match loads have been observed between across a variety of sports [34,35,97,98], it is likely that differing NF responses to standardized loads exist. Interestingly, current available longitudinal research between load measures and NF gives less confidence to the association between load and NF recovery, with small to trivial relationships reported. For example Thorpe et al[99] observed trivial to small associations between rolling aggregations (2,3 and 4days) of high-speed running distance and NF response (CMJ; JH) during an in-season period in elite soccer. A similar strength correlation ($r = - 0.31$; 90% CI ± 0.1) between total cumulative match time and FT/CT responses was also observed over an Australian rules football season [17]. Further research may therefore be warranted to identify potential causes for these contrasting observations between acute and longitudinal study designs. Additionally, a broader understanding of the potential influence of load variants on both isometric and dynamic measures of NF may be of interest to practitioners.

2.6. Summary

Season long competitions in team-based sports create unique challenges for the high-performance staff in allowing for both adequate recovery time from competition but also to maintain or develop physical capacities. Therefore, assessments that aid in quantification of recovery following competitive match play are of interest to practitioners. In particular, an understanding of an athlete's NF is deemed important given its relation to both performance and injury markers. Laboratory assessment of NF may allow for a more detailed insight into mechanisms or sites responsible for observed reductions in NF, however may not offer a strictly feasible or time effective solution in elite team-sport settings. Field-based tests such as the CMJ may offer a practical solution to identifying NF status, however its dynamic nature may increase the potential for noise when assessing a fatigued state. In contrast isometric measures of fatigue assessment aim to limit degrees of freedom and allow for a more detailed understanding of mechanisms influencing an observed NF response. In particular, time intervals of RFD may give insight into both neural and contractile components of fatigue, where reductions in early phase RFD (> 75ms) may be linked to reduced agonist activity and motor unit discharge frequency while later phase RFD windows (100-200ms) may be more associated muscle damage and cross-bridge kinetics.

As traditional isometric assessment has largely utilised dynamometers often only seen in laboratory, limited longitudinal research examining RFD measures within team-sport settings exist. However, with the increased availability of high-quality force plates, alternative isometric tests have been recently been suggested, in particular the IMTP may offer a potential solution to assessment of RFD intervals in team sports. Finally, an understanding of variables which may influence recovery of NF may also be important to practitioners. Currently indices such as muscular strength, aerobic endurance and external loads have been observed to influence recovery of NF. However, research has largely been studied in isolation or over short time periods, making identification of the magnitude of impact of these variables difficult. Indeed, longer term studies accounting for both physical qualities and load on isometric and dynamic test of load may allow for a more detailed understanding of NF responses following competitive match play.

Chapter 3: Extended methodology

The following section will provide an outline and the rationale underpinning the common methodologies administered in the following experimental chapters. The main emphasis of this chapter is in regard to the methodological considerations of the isometric mid-thigh pull (IMTP) and counter movement jump (CMJ) to measure NF. Tests adopted to determine participants' physical qualities and the technology used to ascertain physical loads is also outlined. Finally, a brief review of the statistical techniques and interpretation utilized within the thesis is presented. Unique study design or procedural differences are presented within the methods of the proceeding experimental chapters. All study procedures presented both here and in subsequent chapters were approved by the university ethics committee (HREC number 11987; see *appendix i*) and were in accordance with the Declaration of Helsinki.

As outlined in chapter 1, there are three key questions that are examined over the following experimental chapters. These questions include:

1) Identifying the utility of, and rate characteristics collected from IMTP as a measure of neuromuscular fatigue in an elite team-based environment
2) Assessing the moderating influence of physical qualities on seasonal NF trends collected in both the IMTP and CMJ.
3) Examine the association/interchangeability between isometric and dynamic measures of NF
4) Identifying whether physical qualities moderate the influence of neuromuscular responses to load.

3.1. Participants:

The participants that volunteered for the following three experimental chapters were professional full-time athletes from an elite Australian rules football team (ARF) with all playing positions represented. Due to nature of the squad make-up, players within this sample represented a mixture of First Team and Reserve Team competitions. Differing sized samples from this cohort are used for chapter 4 when compared to chapters 5a and b, with differences outlined within the relevant chapters. An example micro-cycle in which testing protocols for the following experimental chapters were conducted in can be seen below in table 3.1

Table 3.1 Example micro-cycle structure for 7-day turn around during the in-season. Text in bold represents the average duration spent within each training modality.

	Match Day	G+1 (24hrs)	G+2 (48hrs)	G+3 (72hrs)	G+4 (96hrs)	G+5 (120hrs)	G+6 (146hrs)
AM		Recovery modalities. Off site	Light run/flush run. **10-20mins** Upper body weights **45mins**	Screening and monitoring. On-field training **45 -55mins**.	Screening and monitoring Main Training on field **60-90mins**		Captains run.
PM				Lower Body power/movement qualities **(45mins)**	**-**Whole body strength -Pilates -Skill development (**50mins**, per group)		

3.2. Equipment:

Both CMJ and IMTP neuromuscular testing was performed on a dual force platform (ForceDecks ©, FD4000) sampling at 1000hz with unfiltered left and right force traces summated at each sampling instance to identify total force. While, the use of filtering and smoothing techniques (eg; Butterworth, wavelet) have been previously explored, and may help reduce noise of the signal, it may additionally influence the ability to accurately infer contraction onset [12,100,101]. It therefore has been suggested where possible to use unfiltered/raw data throughout measurement and ensure that the same method of smoothing/filtering has been used when comparing across research designs [12, 101].

Force platforms are considered the gold standard of measuring ground reaction forces and kinetic (e.g, force, torque, work) data. Furthermore, estimation of CMJ kinematic data (displacement, velocity) via the impulse momentum relationship from force plates has been shown to be valid and reliable [76,102,103], with sampling frequencies of 350-700hz (CMJ) and 500-2500hz (IMTP) suggested to adequately capture rate characteristics of force development [76] . This recommendation is based upon the Nyquist-Shannon sampling theorem[104], which states that the critical sampling frequency must be a minimum of two times the highest frequency in the signal of interest, to minimise potential information loss. While the sampling frequency of 1000hz utilised in the following experimental chapters may be under the proposed upper limit for rate of force development isometric contractions (2500hz), high reliability and agreement of RFD measures have been observed from sampling frequencies as low as 500hz when compared to 2000hz for IMTP [105]. Similar findings have also been observed for CMJ based measures with sampling frequencies as low as 200hz observed to give reliable estimates of peak force and velocity measures when compared to 500hz [106]. The above suggest that while an effort should be made to maximize information gain from appropriate sampling, reliable inference may still be assessed from the rates sampled in this thesis.

3.3. Collection time:

Meaningful changes in CMJ and IMTP performance have been observed between morning and afternoon assessments, with higher values being observed in the later [107-109]. However research by Taylor et al[107] highlighted that while higher observations are observed in the afternoon, morning testing showed greater between session reliability, suggesting it may be more appropriate when longitudinal monitoring is of focus. Accounting for all of this, and to avoid diurnal variation, NF assessment collection time was held constant for all designs in the following three chapters (8:00-9:30 AM).

3.4. Warm-up:

Standardized warm-ups were completed prior to NF assessment (CMJ and IMTP), including 10 lying hip bridges, 10 standing leg swings and two sub maximal attempts (50% and 70% perceived maximal effort). While, this warm-up procedure is similar to other studies in elite team-based sport [4,10,63,66,96]**,** without direct measurement of body temperature we are not able to fully assess whether core or muscle temperature was standard across all testing sessions. This concern was outlined by Taylor et al[108] who showed that body temperature likely explains the diurnal variations observed between morning and afternoon testing. They also showed that extended warm-ups were able to diminish the diurnal variations observed between afternoon and morning testing. Similar findings were also previously observed by Racinais et al[110] in power measures observed during cycling tasks. While, extended warm-ups may offer better control over testing outcomes, they are not always feasible within elite team-based sport settings where often little time is given to test large amounts of athletes. Nonetheless, the warm-up protocol outlined for the following three chapters is equivalent to previous research in similar level athletes and therefore facilitates between-study comparison [6,10,40,63,66].

3.5. IMTP procedures:

Prior to each player performing the assessment the force plate was zeroed (no mass applied). Once zeroed, the body mass of the participant was measured by standing still on the platform for 1-2 seconds. To aid in identifying the correct position required for IMTP assessment, participants were instructed to assume a quarter squat position or a position similar to a 'hang clean'. Key cues used to aid in this identification were "shoulders just behind the line of the bar", "knees over the toes" and "torso upright". These phrases were adopted as they were frequently utilised within training programs and understood by the participants, and were also similar to recommendations in previous literature [77,111].

Participants hands were then strapped to an immovable bar placed at mid-thigh (adjustable in 2.5cm increments) using standard lifting straps, and from here small self-selected adjustments to hip and knee angles were allowed for the player to get into a position where they felt more "powerful". Conjecture over the ideal hip and knee angles for IMTP exist within the literature, with values ranging from 120-145° for knee angles and 124-175° for hip angles reported [112]. In particular, acceptable between session and within reliability estimates have been observed for time specific force characteristics and RFD with a hip angle of 145° where it has been suggested that this may allow for lower levels of pretension before contraction [112-114]. More recently, in contrast to previous research[77,112-114] , Guppy et al[115] reported low between session reliability in all RFD estimated regardless of body position. It was suggested that differing familiarisation periods between studies may explain some of the differences observed in reliability estimates. This is further supported by Comfort et al[77] who showed that self-selection of hip and knee angles had both high within- and between-session reliability and similar magnitude estimates of rate and peak characteristics when compared to prescribed angles, including 145° hip and knee. It was noted that self-selection is likely to reduce the learning effect, decrease familiarization time, and overall testing time which are important considerations within team-based sport settings.

Once in position, participants were encouraged to apply a small level of “pre-tension” to the bar or reference a 10% effort, to reduce slack and minimize the potential influence of tissue structures upon outcome measures [12]. The degree of pre-tension was controlled by allowing the subject to observe their real-time force trace on a screen, as even minor changes in the degree of pre-tension have been shown to influence early phase RFD[116]. The participants were then encouraged to pull “as fast and hard” as possible after a “3-2-1 go” count for 3 seconds, performing a minimum of 2 repetitions. This terminology was chosen as it has been suggested to maximize both RFD and peak measures collected through isometric assessment. For example, research which compared the terminology of contract “hard and fast” vs “fast” as possible reported a 20-46% improvement in peak RFD with the contract “fast” terminology in both elbow flexion and leg press exercise [117]. However, as strong relationships exist between peak MVC and RFD, Maffiuletti et al[12] suggested that by switching terms from “hard and fast” to “fast and hard”, both outcome measures can be maximized.

Throughout the contraction, visual analysis of the technique was used to identify any changes in hip or knee angle. Post contraction, immediate inspection of the force trace identified whether any counter-movement was evident. In the case where initial visual inspection cast doubt on either joint angles or counter movement the trial was discarded, and another trial was performed following a 2-minute passive rest period. The repetition which achieved peak force was used for subsequent analysis.

3.5.1 Contraction onset

Raw data was exported to a custom excel spreadsheet for analysis of all variables. This spreadsheet was utilised to identify a contraction onset point from which all subsequent rate variables and peak characteristics were calculated. Identification of contraction onset was achieved using both automated and visual inspection approaches. Indeed, in the literature a range of automated techniques have been suggested for identifying contraction onset, including % of body mass, % of MVC, standard deviation increases from baseline mass, and absolute measurement units [12,111]. For example Dos'Santos et al[111] who compared 5 different approaches for contraction onset (2.5, 5, 10% BW [body mass, 75 N [Newtons] and 5 SD [Standard deviation] of BW), showed acceptable reliability and limits of agreement between 2.5 and 5% when compared to their criterion measure of 5SD BW. As the highest reliability in RFD values was observed with a 2.5% BW onset [111], this technique formed the automatic procedure and was utilised in conjunction with visual inspection. Within our study, visual inspection was used to identify any anomalies where inconsistencies between the automated method and visual inspection existed. In cases where the automated method showed low agreement with visual inspection, the visual inspection point was selected. Whilst visual inspection does have inherit subjectivity involved, it has been shown to be reliable when used in conjunction with systematic definitions such as "the last trough before force deflects above the range of the baseline force" [118,119]. Importantly, it was noted by Maffiuletti et al[12] that if early phase RFD components are of inferential interest, then either a low threshold automatic method or systematic visual inspection approach may better approximate contraction onset.

3.5.2 Variables:

Once contraction onset was identified; time specific rate measures were calculated using the derivative of $\frac{\Delta Force}{\Delta Time}$. This approach was applied to both 0 centred RFD (e.g. 0-50ms, 0-100ms, 0-200ms) and sequential RFD zones (e.g. 100-200ms). Peak force was calculated in absolute and relative (peak force/BW [kg]) terms as the highest instantaneous force achieved through the contraction. Indeed, a variety of other variables have been recorded in the literature including force at specific times, impulse variants, average RFD, peak instantaneous RFD and time to peak force. Of these however, only force at specific time points, time specific RFD, and impulse have reported acceptable reliability [77,114,120] . As force at specific time points is numerically equivalent to RFD, and agreement between impulse and RFD has been reported, only RFD intervals are reported in the following chapters [12] (see figure 3.1).

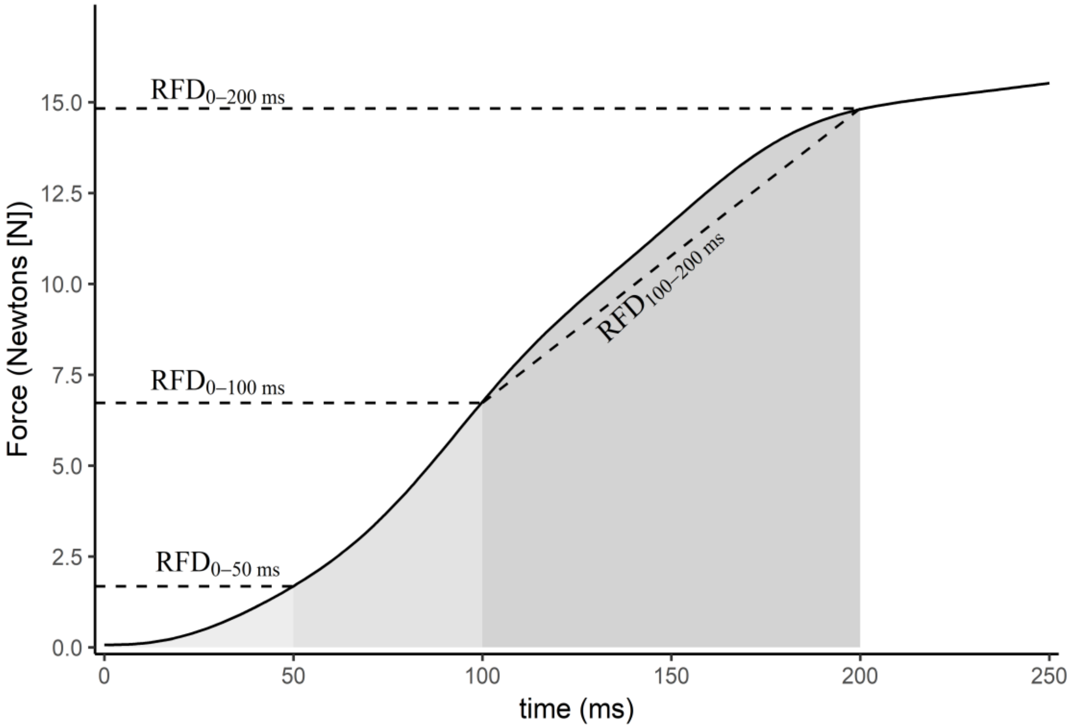

Figure 3.1. Example force time trace from an isometric contraction. The RFD intervals outlined represent the force-time variables that will be explored within the following chapters. Graphical representation was adapted from Rodrigues et al[1].

3.6. CMJ – procedures.

Initial zeroing and body mass procedures as outlined for the IMTP were followed prior to CMJ assessment. Once weighed, participants placed their hands on their hips and instructed to keep them akimbo (hands remain on hips) throughout the duration of assessment. They were then encouraged "jump as high as they can" whilst maintaining stiff, straight legs throughout flight prior to landing. These instructions are consistent with what has been previously reported in the literature [4,53,66,96,121,122]. Participants were able to self-select the depth throughout the eccentric phase of the movement. Participants performed two sets of two CMJ attempts with a 5 second rest between repetitions, the highest max repetition based of relative peak power was used in the subsequent analysis [17,66,96,123].

3.6.1 Phase initiation and separation:

The onset of movement was initiated when the vertical ground reaction force (vGRF) deviated 20N from baseline body mass and was considered the "unweighing phase" (see Fig 3.3) until the VGRF returned to baseline body mass. The subsequent "Eccentric" phase commenced at peak negative COM (centre of mass) velocity and continued until COM velocity was zero [124]. Finally, the "concentric" or "propulsive" phase was initialized once COM velocity was greater than zero and continued until "take off"; initiated the instant VGRF was equal to baseline body mass.

3.6.2 Variables:

Once eccentric and concentric phases were identified, all necessary variables were calculated utilising the impulse-momentum relationship, and derivatives from velocity, displacement and vGRF. Indeed, a variety of force-time, displacement-time and power-time derivatives have been assessed in the literature including peak and mean characteristics (i.e. peak force, power and velocity) and rate characteristic's (i.e. rate of force development, time to peak force and power) [10,40,63,64,66,121,122,125]. Of these measures, indices assessing the demands throughout the eccentric phase have been suggested to be more sensitive to both acute and longer term fatigue versus concentric only measures as they may identify movement strategies deployed in a fatigued state (see chapter 2) [10,40,63,64,66,121,122,125]. Whilst it is possible to examine a plethora of derivatives from the CMJ, it is likely that most are highly related.

For example Gathercole et al[121] reported that 24 hours after fatiguing exercise, 19 of 22 CMJ variables assessed showed small to moderate reductions, and 12 still showed meaningful reductions from baseline at 72 hours. Additionally, similar reliability estimates were also observed between constraints with 21 out of 22 jump derivatives having reported CV% of less than 10%. Taylor [126] also observed consistent changes in a range CMJ indices following a resistance training over reaching phase in elite surf boat rowers while, Cormack et al[10] reported that inference of NF may be possible from monitoring one variable from the CMJ in flight time: contraction time (FT/CT) .Therefore, the CMJ derivatives analysed in the following experimental chapters were chosen based on their ability to allow for appropriate inference against the available research (see table 3.2).

Table 3.2. Counter movement jump variables utilised within chapters 5a and 5b

Variable	Units	Description
Jump height (I-M)	cm	Greatest estimated height achieved via impulse momentum relationship
Peak power/kg	W·kg^{-1}	Greatest power achieved through the jump normalized to body weight
Eccentric duration	ms	Length in (ms) of the eccentric phase of the jump (start of unweighing phase to start of concentric phase)
Eccentric mean power	W·kg^{-1}	mean power produced through the eccentric phase of the jump expressed relative to body mass
Eccentric RFD/kg	W·s^{-1}	Rate of force development measured from the start of eccentric phase to start of concentric phase.
Flight time: Contraction time (FT/CT)	ratio	the ratio of the flight time to contraction time
Concentric RPD	N.s^{-1}	Rate of power development throughout the concentric phase
Force at zero velocity (F@0v)	N	The force exerted at the end of the countermovement where the jump transitions from eccentric to concentric contraction

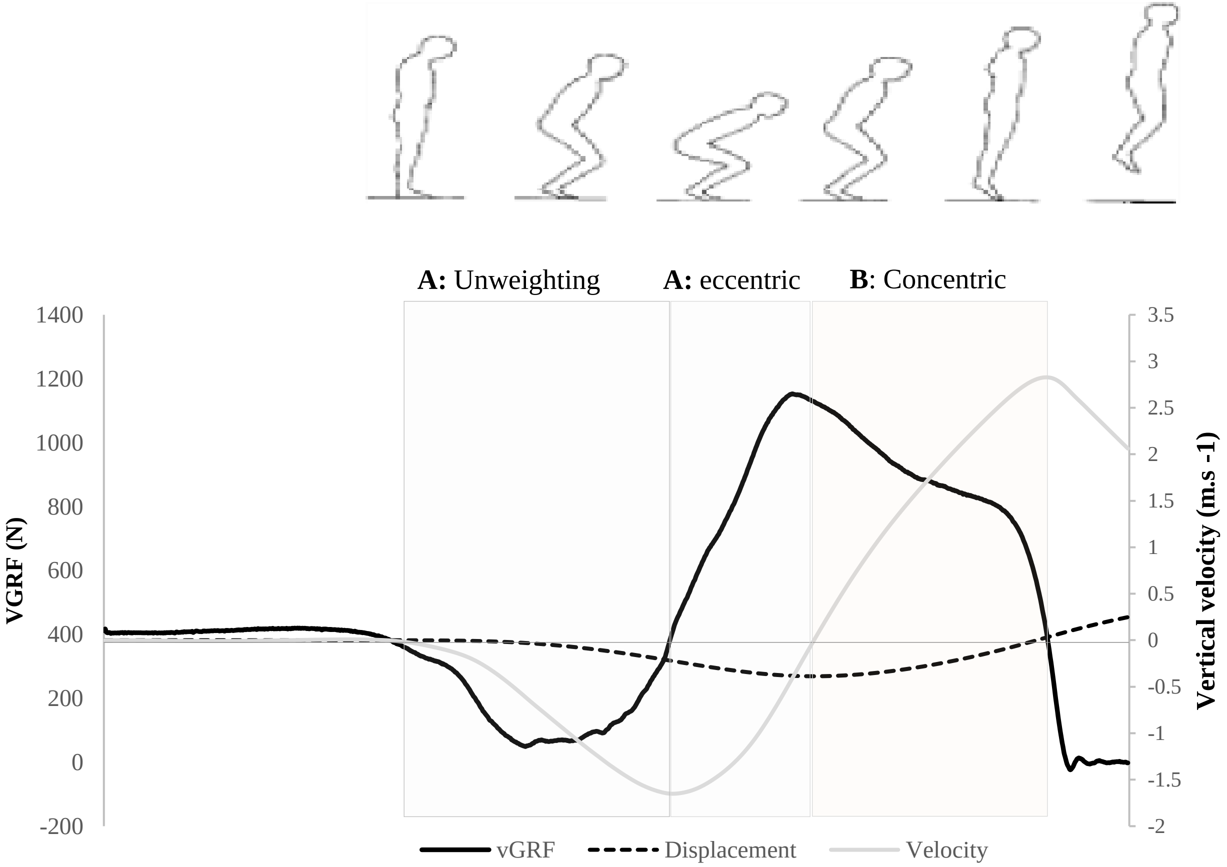

Figure 3.2: Force, displacement velocity curves during a typical CMJ trial. For explanation of key movement stages see "phase separation and initiation" within CMJ – procedures. Figure examples of jump phases were taken from Thorlund et al[2] and give an approximate example of the movement position during key phases of the CMJ.

3.7. Physical qualities:

The impact of lower body strength, power and aerobic fitness on both seasonal trends and neuromuscular responses to load will be assessed in chapters 5a and 5b. The rationale for selecting these variables was discussed in chapter 2. This section will outline the rationale and procedures for the measures used to infer these qualities.

3.7.1 Scaling:

Throughout the rest of this thesis, many variables and some key interaction terms (LBS and LBP) discussed below are represented in relative to body mass ($W{\cdot}kg^{-1}$, $N{\cdot}kg^{-1}$), technically termed ratio scaling. This method of scaling has been previously reported in the literature to help control for the variability in both height and mass seen in team based sport settings. Whilst existing literature may support the use of this method with stronger relationships to performance outcomes [127-129] and its discriminant ability to identify starts and non-starters in elite team based sports [128,130], it does assume a linear relationship between body mass and performance outcomes.

To combat this assumption other measures such as allometric scaling attempts to use geometric assumptions about body mass and power which can be accounted for by raising body mass by a specific power (e.g. body weight $[kg]^{\wedge 0.67}$) to infer performance [131,132]. Interestingly, research examining ratio and variety of allometrically scaled techniques and IMTP performance found that while allometric measures may give less biased estimates of performance for heavier and lighter individuals, normality assumptions required for these methods may not always be met [132]. Additionally , Comfort and Pearson [129] also reported similar correlations between sprint performance and lower body strength regardless of the scaling method applied. While, practitioners should be mindful of the of the assumptions made when using ratio scaling, due to its reported similarity to other scaling measures and previous research supporting its’ use in a elite athletes, this method was used to normalize performance markers.

3.7.2 Lower body strength (LBS):

Relative peak force (PF/kg) collected from the IMTP was used as the key measure of lower body strength for studies 5a and 5b. Indeed, a variety of exercises have been previously reported as LBS indicators in team-based sport settings including the Barbell Squat, Box Squats, Deadlift variations and Olympic lifting variations [16,29,76,91]. While differences in muscular contribution and recruitment patterns exist between the above exercises, all have demonstrated high agreement with IMTP PF/kg performance. For example, Haff et al[133] observed strong correlations between IMTP peak force (PF) and weight lifting derivatives of the clean and jerk (r = 0.64) and snatch (r = .93), while correlations with the barbell Squat (r = 0.97) and Deadlift (r = 0.88) have also been reported [29,79].

IMTP PF/kg has been related to performance outcomes across a variety of sports including, weightlifting, wrestling, American football and cycling [26,28,29,133]. Associations between fluctuations in IMTP PF and both volume load and salivary makers of anabolic/catabolic state have also been observed in female weightlifters [81], suggesting it to be a sensitive measure to training stimulus. Importantly, PF collected from the IMTP has reported high reliability (0.80-0.99 intra class correlation; ICC) [134], and due to its static nature reducing technical error, reliable estimates of LBS are able to be obtained much quicker and with minimal-induced fatigue [77,80,120,133,135] in team based settings where a range of training ages likely exist.

3.7.3 Lower body power (LBP):

Relative peak power (PP) collected from the CMJ was adopted as the key measure of lower body power in studies 5a and 5b. Similar to peak force from the IMTP, a range of exercises have been suggested for LBP assessment in the literature including Squat Jumps (non-counter movement), drop jumps from different heights, broad jump and loaded squat jumps with a variety of different loading schemes [76,102,136-139]. While each of these tests aim to quantify LBP under slightly different assumptions, moderate-to-strong relationships between CMJ performance and these variables have been previously observed. For example, Cronin and Hansen[127] reported a strong (r = .73) correlation between a loaded squat jump (30 kg) and CMJ height in sub-elite rugby league players. Similar results were also seen in elite level sprinters with strong correlations observed between CMJ performance versus the broad jump (r = .86), loaded squat jump (40% kg; r = .81) and non-countermovement squat jump (r = .88) [140]. CMJ Peak power has also reported moderate to strong relationships with sprinting times over 10m (r = -0.43), 20-40m (r = -0.65) and flying 30m [130,141] and shown to discriminate between starters and nonstarters (Cohens d: 1.26, p = 0.03) in elite level ARF over a season [7]. While conjecture over the most appropriate methodology for identifying LBP does still exist [142,143], given its moderate-to-strong relationship with neighbouring approaches and its ability to discriminate performance within a similar ARF population examined in this thesis, relative peak power collected from CMJ was employed to identify LBP within chapters 5a and 5b.

3.7.4 Aerobic fitness – Final Velocity of the 30-15 Intermittent Fitness Test (V_{IFT}):

The velocity attained in the final stage of the 30-15 intermittent fitness test was used to identify the aerobic capacity of participants in chapters 5a and 5b. The design of this test aims to incorporate relevant physiological capacities associated within team sports performance, including aerobic capacity, acceleration, deceleration, change of direction (COD) and peak high intensity running while allowing for a 15 second inter-effort recovery period [144,145]. Indeed, the 30-15 shares similarities with other commonly used incremental field-based assessments of aerobic fitness such as the multistage shuttle run (MSFT) and the Yo-Yo intermittent recovery tests (Yo-Yo IR1 and 2), however, practical limitations to the MSFT and Yo-Yo tests have been identified. For example, the MSFT does not include inter-effort recovery periods which may question its construct validity for team sports, and although reliable, its validity as a surrogate measure of maximal oxygen uptake has been questioned[146,147 148]. Contrary to the MSFT, the Yo-Yo (IRT 1 and 2) does include inter-effort rest and indeed has shown similar sensitivity to training stimulus and ability to discriminate performance as the 30-15 [149], however, results obtained from the Yo-Yo test cannot be used to prescribe training intensity [147,150,151]. Comparatively, the final velocity collected from the 30-15 [V_{IFT}] has shown to provide an appropriate reference value for prescribing physiological responses to training stimuli. For example Buchheit [144] observed smaller inter-player variability in HR responses during a intermittent high intensity running protocol informed by the V_{IFT} versus a maximal aerobic speed determination obtained from a continuous incremental test (Leger – Montreal Track test; 3 vs. 9%). Indeed, while research has observed relationships between V_{IFT} and other physical qualities such as maximum speed and lower body power (CMJ), multiple regression analysis has revealed that this only accounts for a small proportion of explained variance when compared to aerobic qualities [147], suggesting that it is predominately a measure of aerobic capacity or power.

3.8. Physical quality procedures (chapters 5a and 5b)

LBS and LBP

Both IMTP and CMJ procedures were incorporated into the participants' strength program. Three sets of 2 repetitions were performed over three consecutive weeks on the same day of a micro-cycle during the pre-season. This equated on average to 18 repetitions per participant over the baseline period, where the best set (averaged repetitions) was adopted as the baseline. This period was also utilised to establish bar positioning and baseline force for the IMTP assessment. The typical error (CV%) assessed between trials over the familiarization period was 4.8% for IMTP PF/kg, which is similar to other research where high repeatability was also observed for peak force [76-78,112,152,153]. The typical error for relative peak power collected from CMJ was 3.6%, consistent with other findings in elite athletes [60,107,154].

V_{IFT} (30-15)

The 30-15 was conducted twice during the pre-season with one-week separation between tests. The initial test was used for familiarization purposes with the results of the 2nd test used to identify the individuals' aerobic power for use in chapters 5a and b. The 30-15 is an intermittent ramp test that required participants to run a 40-metre for 30-seconds, interspersed 15 second passive recovery periods. After each 45-second cycle, the running velocity was increased by 0.5 $km \cdot h^{-1}$, with the initial running velocity set at 10 $km \cdot h^{-1}$. Running pace throughout the assessment was governed by a pre-recorded audio signal that provided participants with 3-meter zone warning signals. The test was terminated when the player was unable to reach a 3-meter zone signal on three consecutive occasions. In the instance where a player was unable to complete a stage, the velocity from the prior stage was used to identify V_{IFT}. The typical error for the 30-15 test has been reported to be 0.3 $km \cdot h^{-1}$ or 1 level [150].

3.9. Load assessment (chapter 5b)

Chapter 5b explores the influence that physical qualities may play on neuromuscular responses to external load. For this chapter measures of external load were collected via GPS (Global Positioning Software; Optimeye S5, Catapult Sports, Victoria, Australia) sampling at 10hz. Each participant was assigned an individual unit worn in a small pouch within their jersey between the scapulae in line with industry requirement. After each game and/or training session, data were downloaded from the devices using proprietary software (Openfield 1.17.1, Catapult Sports, Melbourne, Australia) with subsequent filtering and processing performed with the manufacturer's bespoke algorithm that analyses Doppler velocity and inertial sensor readings in synchrony to detect spurious locomotor data [155]. Signal quality of the GPS units was assessed via number of connected satellites (12.00 ± 0.94) and horizontal dilution of precision (HDOP; 0.8 ± 0.1).

The use of GPS units is commonplace within elite team sport settings and is utilised by high performance staff for load monitoring, locomotor and activity profiling, and subsequent training planning [156,157]. A number of derived measures are assessed from GPS units and have been commonly reported, including but not limited to; distance-based measures both in absolute units and expressed relative to exposure ($m.min^{-1}$), distances, times or efforts within velocity thresholds (e.g. 12-15 $km.h^{-1}$, >15 $km.h^{-1}$), with a similar approach applied for quantifying acceleration and deceleration loads [157]. A recent meta-analysis comparing relationships of GPS derived measures of load to sessional RPE (sRPE) and heart rate measures (TRIMP), revealed unclear to possibly very large relationships [158]. For example GPS derived measures of total distance ($r = 0.79$), high speed running ($r = 0.47$) and accelerometer load ($r = 0.63$) reported possibly likely moderate to very large relationships to sRPE. Only accelerometer load however showed possibly large ($r = 0.54$) agreement with TRIMP loads, with unclear responses observed within total distance, high speed running distance and very high-speed running distance. While limited longitudinal designs exist, GPS derived measures have also reported associations with acute neuromuscular function decay in both dynamic and isometric measures (0.5hr – 48 hrs) post competitive soccer match play [66,94,95]. Additionally, relationships between high speed running (HSR; >15 km.h^{-1}]) distance and match performance (ball disposal, player ranking points; Champion data) have also been reported in elite level ARF players, with higher distances covered being favourable. Opposing, research in English football's Premier League revealed less total and HSR distance in higher ranked teams versus lower, where it was suggested that this may be explained by inherent lower technical standards that in turn require lower ranked teams to exert higher physical output [159]. Nonetheless these findings support the utility of GPS as a measure of load and activity profiling.

The loading measures collated for chapter 5b are outlined in table 3. Reviews by Sweeting et al[157] & Malone et al[156] have outlined the discrepancies of terminology and cut off values for speed and accelerations thresholds; between manufactures filtering and processing techniques; and between-unit variability [156]. While, this thesis does not further examine these issues, the proposed loading variables outlined below are similar to those previously reported in comparable cohort of athletes [4,6,160,161] and represent measures that are used for practical inference on training design and identifying loading accumulation.

Table 3.2 GPS derived measures (m.s = metres per second)

Measure name	Thresholds	Description
Total Distance		Total distance covered
High Speed Running (HSR)	> 17 km.hr^{-1} (>4.7 m.s^{-1})	Distance covered greater than threshold
Very High Speed Running (VHSR)	>23 km.hr^{-1} (>6.4 m.s^{-1})	Distance covered greater than threshold
Acceleration load + Deceleration load *(AccDeccLoad)*	Acceleration > 2.5 m.s^{-2} Deceleration <-2.5 m.s^{-2}	Sum of accelerations and decelerations efforts greater than the specified threshold unit.

3.9.1 Data transformation **(chapters 5b):**

It is common for practitioners to both monitor and report different transformations of raw data collected from external load devices such as GPS units. Indeed, the aim of such transformation techniques is to give a standardized context to a given value of load for an individual, and may include comparing a value to a range of pre-set thresholds, values from within or between participant distributions (z score; distribution represented as a mean and standard deviation) and or a ratio of the current workload to chronic workloads (acute-to-chronic workload; A:C) [3,38,84,91,161,162]. It should be noted however, while transformation may give context of load within a new domain, it often requires back transformation to the original unit scale to have practical utility (e.g. periodization and planning of loads) [163]. Furthermore, for transformation procedures such as the A:C ratio it may not be clear what the appropriate acute and chronic windows are, whether these windows should be coupled or uncoupled, or whether inclusion of decay terms are appropriate [164,165]. Additionally, multivariate analysis methods have shown that the magnitude of acute and chronic load likely moderate the interpretation of the ratio derived from these parameters, which further increase complexity of appropriate interpretation [3,166]

For chapter 5b, transformation of GPS measures outlined above was undertaken via individualized z -scores method, calculated as:

$$Z\ score = \frac{Current\ value_i - \mu Mean\ value_I}{\sigma Standard\ deviation_i}$$

Where *i* denotes “individual”.

This method allowed inference of 1 SD increases of load to be interpreted as a relative increase for each individual.

3.10. Statistical Analysis:

For the following three chapters the use of linear mixed effects models (LMM) are used to assess the influence of the covariates of interest (Game day recovery means [chapter 4], influence of PQ on seasonal trends [chapter 5a] and influence of PQ on external load measures [chapter 5b]). The use of mixed models has become increasingly popular in a variety of research fields including sport [35,86]. A key strength of the LMM framework is the ability to explicatively model non-independence in a data set, such as repeated observations within individuals over time [86]. This mapping of non-independence is outlined via a random effects term, where non-independent variation can be modelled via individual level intercept or slope effects. Another key advantage of LMM’s within elite sport settings is the ability to handle missing data, without the need for list wise deletion which would occur within a repeated measures ANOVA framework and therefore reduce power[86].

3.10.1 Model assessment:

The use of information criteria techniques and likelihood ratio test [86,167] will be used throughout chapters 5a and 5b to identify the influence of physical qualities on moderating both seasonal trends and neuromuscular responses to load. This approach attempts to optimize the trade-off between the fit of a model and its complexity, where for example a more complicated interaction model is compared to a univariate model [86]. More explicitly, a chi squared statistic (X^2) can be calculated from the differences in deviance values from a reduced model to a full model. This X^2 statistic can be then compared to the X^2 distribution via a likelihood ratio test to obtain a p-value with relevant degrees of freedom/penalization being the difference between numbers of parameters in the full vs reduced model. In situations where either a univariate effect was observed or an interaction model (full) had statistically ($p<0.05$) more support from the data than a less complex model, fixed effects (coefficients) from these models effects were standardized by the baseline standard deviation of that measure to give a Cohen's d effect size [168]. For clarity it should be noted that there remains conjecture regarding the most appropriate standard deviation method (pooled, pre-test, SD of change scores) to be used when assessing effect size in unbalanced within-subject designs [169] [170]. Hence, as one of the primary aims of this thesis was assessing seasonal responses, it was postulated the pre-test SD would give us the best representation of population variance as it cannot be influenced by seasonal variability [170], which due to our unbalanced design (testing individuals at different time points) may potentially over or underestimate a post-test standard deviation. A more detailed explanation of post hoc statistical approaches used can be found within each experimental chapter. All LMM were performed within R Studio [171] using the lme4 [85] package for mixed models and the emmeans package for least squares trend comparisons and marginal mean estimation [172].

3.10.2 Reliability: Coefficient of variation

Variability of CMJ, IMTP and match load measures was assessed via repeated pairwise comparisons between measures and reported as a coefficient of variation (CV%). For CMJ and IMTP measures this variability was calculated during the familiarization period prior to assessment period in the relevant chapters. For chapter four this was done over two repeated trials, for chapters 5a and b variability was calculated from three repeated trials. Variability in match loading measures was calculated in a similar fashion by taking the average pairwise differences represented as a coefficient of variation (CV%) between all games, where no active constraints were placed on playing time for an individual.

Chapter 4: Recovery of Force–Time Characteristics Following Australian Rules Football Matches: Examining the Utility of the Isometric Midthigh Pull.

4.1 PREFACE

The following chapter aims to explore the practical utility and sensitivity of measures collected from the IMTP following elite competitive match play, addressing the first aim of this thesis. The findings from this chapter will give insight into measures that may be of interest for subsequent chapters, and to identify a potential recovery time-point where between-player variation in responses may exist.

The work presented in this chapter has been published and cited as:

Norris D, Joyce D, Siegler J, Clock J, Lovell R. Recovery of Force-Time Characteristics Following Australian Rules Football Matches: Examining the Utility of the Isometric Mid-Thigh Pull. *Int J Sports Physiol Perform.* 2019: vol. 14(6), pp 765-770.

4.2. Abstract

Introduction: This study assessed the utility of force-time characteristics from the Isometric mid-thigh pull (IMTP) as a measure of neuromuscular function (NF) following elite level Australian Rules Football (ARF) matches. It was hypothesized that rate characteristics of force development would demonstrate a different response magnitude and recovery time-course compared to peak force measurements. **Methods:** Force-time characteristics of the IMTP (peak force, 0-50ms rate of force development [RFD], 100-200ms RFD) were collected at 48 h (G+2), 72 h (G+3) and 96 h (G+4) following three competitive ARF matches. **Results:** Meaningful reductions (>75% of the smallest worthwhile change) were observed at G+2, G+3 & G+4 for RFD 0-50ms (-25.8, -17.5 & -16.9%), and at G+2 & G+3 for RFD 100-200ms (-15.7 & -11.7%). No meaningful reductions were observed for peak force at any time point (G+2: -4.0; G+3: -3.9; G+4: -2.7%). Higher week-to-week variation was observed for RFD 0-50ms (G+2: 17.1; G+3: 27.2; G+4: 19.3%) versus both RFD 100-200ms (G+2: 11.3; G+3: 11.5; G+4: 7.2%) and peak force (G+2: 4.8; G+3: 4.4; G+4: 8.4%). **Conclusion:** These findings highlight the potential use of rate characteristics from the IMTP as measures of NF in elite sport settings, and in particular RFD 100-200ms due to its higher reliability. Interestingly, peak force collected from the IMTP was not meaningfully supressed at any time point following elite ARF match-play. This may suggest that rate characteristics from IMTP may provide a more sensitive and valuable insight regarding NF recovery kinetics than peak measures.

4.3. Introduction

In professional team sport, ever-increasing resources are being allocated to quantifying both the existence and extent of fatigue. Quantifying fatigue may provide contextual information regarding injury risk and delivery/prescription of appropriate training [92,173]. However, given that fatigue is a multifactorial construct, a variety of monitoring strategies are often employed within the professional setting, such as markers of muscle damage, neuromuscular function, endocrine responses, immune status and psychological wellbeing [9,58]. While informative, due to cost and time constraints longitudinal measurement of many of these markers is rarely feasible, as is finding a singular metric that is indicative of all fatigue domains. Of these markers however, recovery of neuromuscular function (NF) is accepted as one of the most practically viable due to its relative ease of assessment and reported relationships to performance outcomes, injury risk and training load[4,11,23,39].

Decreases in NF have been observed following a range of elite sporting competitions, with deteriorations evident immediately post-activity, and a return to baseline values usually within 72 hours [10,16,50]. Currently, assessment of NF in field settings has largely utilised a range of dynamic contraction modalities such as sprint and jumping protocols [9,39,58]. In particular, jumping protocols have been considered favourable, given their ease of implementation in elite sporting environments, where time constraints and squad sizes are key factors for consideration.

While a range of studies examining the utility of CMJ exist in elite settings [10,39,53,58], it is now suggested that best inference for quantification of fatigue requires interpretation of both physical output measures and movement strategies deployed during the eccentric and concentric portions of the jump [63,121,122]. This dynamic requirement of jumping protocols however, may preclude athletes who are sore or injured from being able to complete a required trial. A potential solution to this problem may be testing NF with an isometric contraction. Traditionally, these assessments were commonly performed in laboratory settings using expensive and importable equipment such as isokinetic dynamometers. More recently however, the Isometric Mid-Thigh Pull (IMTP) has become increasingly used as a strength profiling tool in elite sport settings [77,78], requiring only a force-platform (which may be portable) and a Smith-machine, which is common to most elite training facilities. The adoption of this test may also stem from the relative ease of assessment, reproducibility, non-fatiguing nature, high correlations to other dynamic explosive and strength measures, and minimal associated injury risk [27,76-78]. Furthermore, explosive force-time measures collected from the IMTP may have a potential advantage of giving insight into the neural and contractile mechanisms of neuromuscular fatigue [12,69,118], with early phase rate of force development (<75ms) being predominantly influenced by neural mechanisms, whereas later phases (>75ms -200ms) are governed by contractile components [12,71,118,174]. This additional information regarding the potential sources of fatigue may be insightful for high performance staff when deciding on appropriate fatigue management strategies.

Currently however, there is a paucity of research examining the recovery time course of force-time characteristics generated from the IMTP following competitive match play. Furthermore, there is limited information regarding the typical week-to-week variation in the recovery time-course of these parameters, which may provide insight for routine NF monitoring in elite team-sports settings. Accordingly, the primary aim of this study was to determine and compare the time course recovery of rate of force development (RFD) and peak force collected via the IMTP. It was hypothesized that different recovery kinetics would be observed between rate characteristics and peak force based on previous laboratory research [14,69,75]. Secondly, week-to-week variation of these markers was also assessed to inform the utility and potential scheduling of routine IMTP assessment within the typical team-sports micro-cycle.

4.4. Methods

4.4.1 Participants–

Eight elite (national competition) ARF players (age 20.7 ± 2.4; body mass 83.5 ± 6.1 kg; stature 188 ± 8.2 cm; seasons played 3 ± 2.3) with an average of 40 competitive playing appearances (range: 0-124) volunteered to participate in this investigation. The players represented a mixture of positional roles (Outside Midfielder, Key Defender, Ruck, Small Forward, and Inside Midfielder). A total of 60/72 (83%) IMTP samples were recorded after three professional in-season competition fixtures. Reasons for missed samples included timing constraints, players being unavailable due to illness, and/or inconsistent pre testing routines.

4.4.2 Design -

IMTP and creatine kinase (CK), as an indirect marker of muscle damage, were collected at 48hrs (G+2), 72hrs (G+3) and 96hrs (G+4) post 3 elite level ARF competition matches. These days were selected based on previous research in elite ARF players who reported recovery of jump kinetic variables between 72-96hours post competitive match play [10]. Immediate and 24-hour post-match measures of NF were not recorded on the basis that players often have time-off following matches, and routine NF monitoring at these time-points may not be feasible in industry practice [175]. To avoid diurnal variations, matches were selected that commenced at similar times (±3 hours) and IMTP and CK samples were collected at the same time each subsequent testing day (8:00-9:30am). Players were made familiar with IMTP and CK testing periods prior to the study commencing. Baseline values were collected *a priori* on two separate occasions following three-day rest periods, with the individual’s average score used as baseline. The average game time for all players during the 3 matches was 106±10 minutes.

4.4.4. Procedures:

Isometric Mid-Thigh Pull Testing:

MTP procedures were followed as outlined within chapter 3 with best of two maximal trials used for inference. Measures of peak force, RFD 0-50ms and RFD 100-200ms were assessed and reported as % of baseline. The typical error from the baseline assessments revealed a 16.4% and 12.2% coefficient of variation (CV) for RFD 0-50ms and 100-200ms respectively, with a CV of 4.8% observed for peak force.

***Indirect muscle damage measurement*:**

Muscle damage was assessed via duplicate capillary blood measures of CK collected from the fingertip and held in heparinised capillary tubes. Samples were then immediately transferred onto regent strips where the concentration of plasma CK was analysed via Reflectance photometry (Reflotron ® Plus / Sprint System, Mannheim, Germany). Prior to each collection day the spectrometer was calibrated using custom calibrated strips from the manufacturer. The mean of the two scores was utilised for subsequent analysis, with the typical error of measurement of CK identified at baseline was 36.5%.

***4.4.4. Statistical analysis*:**

Two outlier data points from CK were removed due to clear deviations away from expected error ranges. Due to the unbalanced and repeated measures design of the study, a linear mixed effects model was used to assess the time course recovery of IMTP and CK variables. Where time (G+2, G+3 and G+4) was cooperated into the model as a fixed effect while repeated observations (3 ARF matches) and individual players were incorporated as random intercept and slope effects, respectively. Estimated marginal means were the identified with 90% confidence intervals (CI) calculated on the difference from baseline scores.

Magnitude based inferences were then calculated to determine the likelihood of a meaningful effect. The smallest worthwhile change (SWC) was classified as 0.2 of the baseline between-subject standard deviation, and then converted to a percentage from the log transformed data (RFD 0-50ms: 11.2%; RFD 100-200ms: 7.7%; Peak force: 2.8%; CK: 30.2%). A meaningful increase or decrease in outcome measures was classified according to the disposition of the 90% confidence interval, when the likelihood of change was greater than 75% (*likely*) with less certain effects classified as trivial[176]. Between match variability for each time-point (G+2, G+3 and G+4) was then quantified as the coefficient of variation, calculated via a customized excel spreadsheet [177].

4.5. Results:

Figure 4a displays the recovery time-course of the IMTP force-time characteristics. RFD 0-50ms showed a meaningful decrease from baseline at all-time points (G+2: -25.8, CI: -33.8 to -18.2%; G+3: -17.8, CI: -24.4 to -10.3%; G+4: -16.9, CI: -24.1 to -9.9%). RFD 100-200ms showed a meaningful decrease from baseline at G+2 and G+3 (G+2: -15.7, CI: -22.7 to -8.7%; G+3: -11.7, CI: -18.6 to -4.8%), with a trivial decrease observed at G+4. Peak Force collected at G+2, G+3 and G+4 were all classified as trivial changes when compared to baseline. Compared to baseline values, CK showed meaningful increases at each time point (G+2: 635, CI: 559 to 711%; G+3: 429, CI: 357 to 502%; G+4: 412, CI: 341 to 484%). A meaningful decrease was also observed between both G+3 (-205, CI: -95 to -314%) and G+4 (-222, CI: -112 to -332%) versus G+2.

Between match variability- Over the three matches examined, the variability of RFD 0-50ms at G+2, G+3 and G+4 was 17, 27, and 19% respectively, while the variability recorded for RFD 100-200ms was lower at 11, 11, and 7% respectively. Peak force showed lower week-to-week variability than both RFD measures at 4.8, 4.4, and 9.4% for G+2, G+3, and G+4, respectively. The variability of CK was 33.4, 23.2 and 25.2% at G+2, G+3 and G+4.

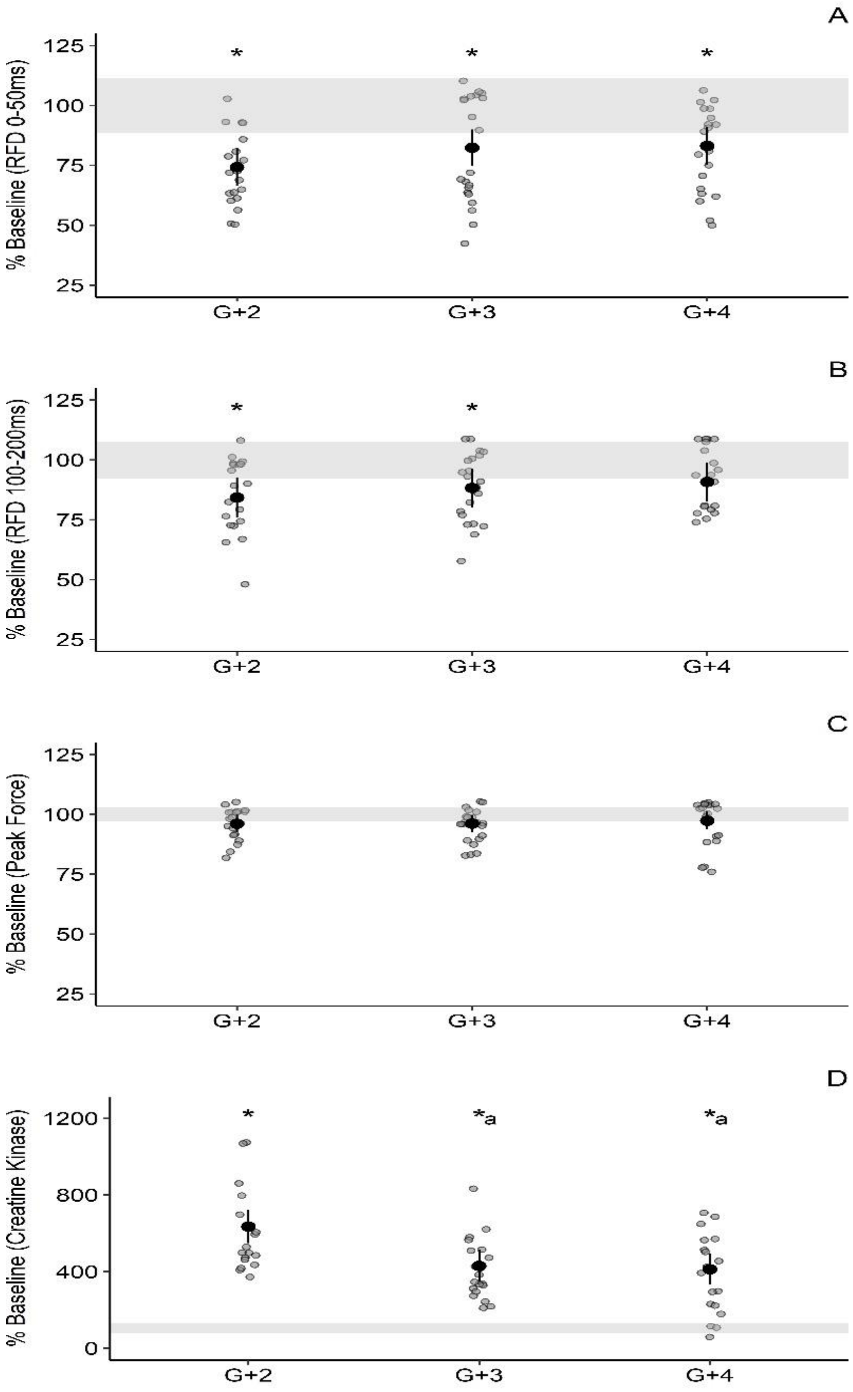

Figure 4a

Figure 4a – Time course recovery of RFD 0-50ms (A), RFD 100-200ms (B), Peak force (C) and (D) creatine kinase. Point ranges indicate the marginal mean and 90% confidence interval for each measure. The shaded grey area represents the predetermined smallest worthwhile change represented as a %. Reductions greater than 75% of the smallest worthwhile change are represented as *. “a” denotes a meaningful difference between G+2.

4.6. Discussion

To this author's knowledge, this is the first paper to examine the time course recovery of force-time characteristics attained from the IMTP following competitive ARF match play. It was postulated that rate characteristics would be influenced to a greater degree than peak force. Indeed, meaningful reductions in early and late phase RFD 0-50ms were observed persisting for 96, and 72 hours post-match respectively, while only trivial reductions were observed in peak force at each time point. Furthermore, higher week-to-week variability was reported with RFD 0-50ms when compared to RFD 100-200ms, whereas peak force was relatively stable. Though limited research on the time course recovery of RFD from isometric contractions following competitive match play exists, RFD 100-200ms recovery observed in this study was similar to other commonly reported dynamic NF measures. These studies have shown that a return to baseline occurs 48-96 hours post competition [10,16,50,51,95]. However, the magnitude of decline observed in our study for RFD 0-50ms (G+2: -25.8%) and RFD 100-200ms (G+2: -15.7%) were somewhat larger than the CMJ (-1.5 to -4.8%) [9,11] and peak isometric force changes (-3.6 to +2.8%) [11,30] reported 48 hours following team-sport activity. Multiple factors such as study design, baseline criteria, variability of outcome parameters, and the differing exercise stimuli may explain between-study discrepancies in both response magnitudes and the time-course of recovery observed. Nonetheless, the rate characteristics collected from the IMTP, and in particular RFD 100-200ms, may be a more sensitive marker of NF when compared with dynamic and isometric peak force assessments [16,50,95].

4.6.1. Univariate

A key finding in this study was the lack of change in peak force measurements at each time point when compared to RFD measures. A potential reason for this may be in the days selected for assessment. Decrements in peak force recorded during isometric knee flexion have been observed immediately post activity to 24 hours after competitive and simulated soccer match play, returning to baseline values by 48-72 hours [50,51]. Hence, it is possible that any reduction in peak force may have transpired before our first IMTP trial administered on G+2. More rapid recovery in peak force versus rate characteristics have also been observed in laboratory studies. For example, Crameri et al[14] observed greater and longer lasting reductions of RFD 0-50ms than isometric MVC following 210 maximal isokinetic eccentric knee contractions. Oliveira and colleagues[75] also reported greater reductions in RFD (0-100ms) than MVC torque after a 35-minute-high intensity running (95% of OBLA) protocol. Collectively, these findings suggest that peak force is not sensitive to NF after 24 hours, which may question its application in professional team-sports where time-off or recovery days are typically scheduled for 24-36 hours post match [59]. It is well documented that different time windows of RFD are influenced by either neural or contractile mechanisms during isometric contractions. In particular, early phase RFD windows (<75ms) are likely more influenced via neural components (e.g. agonist activity, motor unit discharge rate, supraspinal mechanisms), while contractions >75ms influenced by muscular properties (cross bridge kinetics, fibre type) and closer linked to MVC capacity [12,71,118,174,178]. As such, Peñailillo et al[69] observed later phase RFD (100-200ms) to be a better indicator of muscle damage versus early phase RFD and peak force. However, in this study the time-course of CK was concordant with both early- (0-50ms) and late- (100-200ms) phase RFD. The results of this study indicate a lack of recovery in neural components (early phase RFD), with contractile components (late phase RFD) potentially compromised until 96 hours post-match. However, the absence of recovery in early phase RFD may also be explained by the baseline adopted, whereby measures were scheduled following 3-day recovery periods. Considering the high variability and neural mechanisms underpinning early phase RFD, it is possible that the baseline may have over-estimated the decay magnitude and time-course [12]. In support, the post-match restoration in RFD 0-50ms appeared to plateau at 72 (-17.8%) to 96 hours

(-16.9%). Further work may therefore be necessary to examine the impact of baseline scheduling on both the recovery time-course and typical error of NF parameters.

4.6.2. Variation in responses

Although within and between trial variability of IMTP variables have been previously reported within controlled laboratory settings [77,78,114], to this author's knowledge this is the first study assessing between match variability of these measures following elite team sports. Peak force was relatively stable on a week-to-week basis (CV 4.4-8.4%), irrespective of the day assessed (G+2, G+3, G+4), which may further support the notion that it remains insensitive to fluctuations in load. RFD 0-50ms showed the highest between-game and between-day variability, perhaps mediated by the wide variety of neural mechanisms and intra-muscular properties reported to effect early phase RFD. A substantial increase in RFD 0-50ms variability was noted on G+3, and whilst the root cause is unknown, it may represent bifurcation in the recovery rate of NF, and accordingly present as the most appropriate day for NF monitoring post-match. Alternatively, whilst RFD 0-50ms may give insight into neural mechanisms of fatigue, its high degree of variation coupled with the potential confounding influence of the series elastic component in a multi-joint movement [179], renders inference regarding NF challenging. In contrast, RFD 100-200ms had greater week-to-week reliability versus early stage RFD and may represent a suitable NF parameter characterised by sensitivity to load changes with moderate consistency. Finally, an important practical observation in our study was that NF inference from rate characteristics was made from collection of just two IMTP contractions. Given the high degree of variability associated with RFD, an average of 5 samples has been recommended [12], but this protocol is not appropriate in team-sports settings where squads in excess of 20 athletes are commonplace.

4.6.3. Limitations

The main limiting factor of the current study was the absence of other NF modalities such as CMJ to assess the concordance to IMTP peak force and rate characteristics. The absence of acute (0 and 24 h post-match) NF measures was also a confounding factor in the study, albeit their relevance for application in professional team-sports settings has been questioned [175]. Acute and comparative NF measures were traded to gain serial data from athletes performing at the highest level of ARF competition in a repeated measures experimental design. The small sample size available, in combination with the week-to-week variability of IMTP rate characteristics, may challenge the detection of individual changes in NF. Hence, future longitudinal work is certainly necessary to better understand meaningful changes in IMTP force-time characteristics and to examine the impact of match-related physical variables, which were not analysed in the current study considering their very-high degree of match-to-match variation [180]. Finally, without mechanistic data statements on the potential underpinning physiology that distinguishes the recovery time-course between early- and late-phase RFD may be considered speculative.

4.7. Conclusions and Practical applications

The current findings suggest that while RFD measures collected from the IMTP may have lower reliability than peak measures of force, meaningful RFD decreases are detected days after competition where no reductions in peak measures are evident. Importantly, NF recovery kinetics were derived from two IMTP force traces, which may suggest its practicality for use in team environments. Moreover, due to the differing mechanisms that influence rate characteristics, a more detailed understanding of the nature of fatigue may also be inferred, which may be useful to practitioners when deciding on appropriate recovery strategies. Considering the week-to-week noise in early-phase rate characteristics reported, RFD 100-200ms may be the most appropriate parameter to track recovery 96 hours following match-play. Additionally, the static modality may facilitate routine compliance following matches when dynamic protocols may be unsuitable due to soreness or injury. Interestingly, despite greater week-to-week variation, rate characteristics collected from the IMTP may be more sensitive to changes in NF than peak measures of force production. Of these, RFD 100-200ms may offer the most suitable rate measure of NF due to its higher reliability when compared to earlier phase rate of force production.

Chapter 5a: Influence of physical qualities on seasonal trends in dynamic and isometric measures of neuromuscular function.

5a.1: PREFACE

The previous chapter aimed to explore both the sensitivity and practical utility of the IMTP as a deployable measure of NF within a team sport environment. As mentioned within the limitations, the lack of a criterion measure, and accounting for potential co-founding influencers such as load stimulus and physical qualities may add complexity to the interpretation of fatigue. Nonetheless, the long return to baseline levels evident within RFD when compared the peak measures is an interesting finding and will be explored in more detail within the following chapters. In particular, the following chapter 5a will aim to see if differences in force time characteristics are extended to seasonal settings in both isometric and dynamic measures of NF. Additionally, the potential moderating influence of baseline PQ's on seasonal responses will also be assessed (thesis aims 2 & 3).

Findings from this chapter were presented at a peer-reviewed conference proceeding:

Norris D, Siegler J, Joyce D & Lovell R (2019) Influence of physical qualities on seasonal trends in dynamic and isometric measures of neuromuscular function. World Congress of Science and Football (WCSF). Melbourne, Australia.

5a.2 Abstract

Introduction: Seasonal monitoring of neuromuscular function (NF) is now frequent practice in elite team sport settings. While seasonal trends of NF have been previously examined, little evidence assessing the potential moderating influence of physical qualities on these trends is available. Moreover, the impact of physical qualities (PQ) on NF assessments is likely to vary over time. Therefore, the aim of this study was to assess the influence of PQ on seasonal trends in both dynamic and isometric measures of NF. **Methods:** Dynamic (CMJ; Peak Power, Jump Height, flight:contraction time ratio, eccentric duration) and Isometric (Mid-thigh pull [IMTP]; rate of force development [RFD] 0-100, RFD 0-200, RFD 100-200 & Peak force•kg) NF measures were collected from 32 elite-level Australian Rules Football players (seasons played:4±3) 72 hours post-match play (7±2 collections) over a season of the national competition (AFL). PQ indices of aerobic capacity (30:15; V_{IFT} [20.6 ± 1.0 km•h^{-1}]), muscular strength (IMTP; peak force [40 ± 4.3 N•kg]) and dynamic power (CMJ; peak power [56 ± 5.2 N•kg]) were collected prior to start of the season and included as time varying covariates into linear mixed effects models. The impact of PQ was assessed by information criterion and likelihood ratio tests. **Results:** Univariate analysis revealed a significant negative trend of both RFD 0-100 (-80.7, CI: -134.6 to -27.3, p = 0.004, seasonal effect: *d* = -0.83) and RFD 0-200 (-45.5, CI: -84.5 to -7.11, p = 0.02, seasonal effect *d* = -0.75) over an ARF season, with no significant univariate trends observed on IMTP peak force or any CMJ measures. An interaction effect of baseline IMTP strength was observed for seasonal peak force trends ($X^2(1) = 5.91$, p = 0.015), with lower baseline strength associated with greater seasonal improvement. **Conclusions:** Rate characteristics from isometric NF assessments demonstrated reductions across the season, which may be indicative of accumulated fatigue. There was no systemic influence of physical qualities upon seasonal trends of NF, although weaker players in pre-season showed longitudinal strength gains. Rate characteristics derived from standardized isometric assessments may be more sensitive to seasonal NF, but further research is warranted to examine the impact of load upon NF.

5a.3. Introduction:

Monitoring of neuromuscular function (NF) is now a commonly reported practice in elite team-sport settings, where assessments of NF status may be used to inform the choice of subsequent recovery modalities or training stimuli. Indeed, increased injury risk, reductions in both skill and physical performance outcomes, and increased perception of effort have been observed while in reduced NF states [4,11,23,39]. Therefore, a longitudinal understanding of how NF may vary over a season and an understanding of potential moderating influencers may be useful to high performance practitioners, where maintaining optimal NF status over a season offers a unique challenge.

While seasonal trends of NF have previously been examined, the majority of this research has been performed using kinetic and kinematic data collected from the counter movement jump [6,10,123,175,181]. However, as stated in the previous chapter, the dynamic nature of the CMJ may preclude athletes who are sore or injured from being able to perform assessment. To combat this problem, assessment of NF via an isometric modality (isometric mid-thigh pull, IMTP) was proposed and initially explored in the previous chapter. Indeed, other isometric tests have been explored in the literature, for example McCall et al[68] reported high reliability [ICC:0.95] and acute (15 minutes post) sensitivity to soccer match play with a supine hamstring test. Measures collected from isometric knee flexion and extension tasks (MVC and RFD) on a dynamometer have also showed acute sensitivity and longer lasting reductions (48hrs) after competitive match play in both soccer and European handball [2,50,51,95]. Findings from the previous chapter (chapter 4) revealed a longer recovery time-course in both early and later phase RFD (0-50ms, 100-200ms) when compared to peak force measures, which remained stable from baseline between 48-96hrs following elite level ARF competition. While these findings collectively suggest that isometric modalities offer a viable alternative measure of NF following competitive match play, an understanding of the seasonal trends of rate and peak measures collected from isometric assessment are lacking in team-based sports. It is therefore unclear the impact that a season long competition has on isometric rate and peak measures, and whether both dynamic and isometric measures share similar longitudinal variance in their response.

Of further use to practitioners is an understanding of factors that may moderate NF responses, which may improve management of acute recovery strategies or long-term athletic development plans for individual athletes. While it is likely that multiple factors influence recovery responses [35], of particular interest is the influence of physical qualities on NF as they represent a potentially modifiable feature [16]. Indeed, moderating influences of physical qualities have been observed in both acute and longitudinal time frames. For example, higher aerobic capacities were shown to positively influence acute NF (CMJ; Peak power) and muscle damage (CK; creatine kinase) recovery rates in sub-elite rugby league players [16]. In the same study, higher levels of lower body strength as measured by a 1-repition maximum (RM) squat test also showed lower levels of CK following competitive match play, despite performing higher match external loads. Similar findings have also been observed in longitudinal studies, with advanced lower body strength and aerobic capacity reducing CK responses in soccer and ARF [16,30,90]. While informative, using CK as a primary measure to identify influence of PQ on recovery may be questionable, as multiple factors such as hydration status, genetics, ethnicity and age have shown to be potential influencing factors on CK response to exercise [182]. Furthermore current capillary sampling methods deployed within team settings have reported high error rates [chapter 3], and the source of CK (e.g. brain or muscle based) using this technique is unknown [182].

To this author’s knowledge, there is a paucity of longitudinal research that examines the potential moderating influence of PQ on dynamic and isometric NF responses. Furthermore, current available acute NF time-course designs using dynamic measures have applied categorization methods to separate physical qualities into high and low groups. While categorization methods such median-split may allow for easier inference and equal degrees of freedom across groups, this inference comes at the cost of both decreased statistical power, false positive rate, and under- or over-estimation of outcomes between groups, as individuals closer to the cutoff value (median) are treated differently rather than similarly [183-185]. Therefore, the aim of this chapter is two-fold. Firstly, to describe the seasonal trends in rate and peak characteristics collected from the IMTP and CMJ and assess the shared variance of these measures. Secondly, to assess whether physical qualities exert a moderating influence on seasonal NF recovery within isometric and dynamic conditions. It was hypothesized that advanced levels of physical qualities would exert a positive moderating influence on seasonal recovery dynamics.

5a.4. Methods:

5a.4.1 Participants:

Thirty-two elite-level Australian Rules Football players (Height 189.9 ± 7.7 cm, Body Mass 89.5 ± 8 kg, seasons played: 4 ± 3) representing all playing positions volunteered to participate in this study**.**

5a.4.2. *Design:*

IMTP and CMJ were assessed at the same time on the third day following a match (G+3;~72hrs, 08:00 - 09:30AM) on several occasions (7±2 collections; CMJ: 143 samples, 67% possible trials; IMTP: 188 samples, 88% possible trials) throughout an ARF season. This collection day (G+3) was selected as it was consistent with previous research in a similar athletic cohort [10], and as observed in the previous chapter, may represent a potential bifurcation in acute recovery responses between individuals.

5a.4.3. Procedures:

Both the IMTP (isometric) and CMJ (dynamic) were used as markers of NF and were collected according to the procedures outlined in chapter 3. Where the best score from 2 sets of 2 repetitions used for analysis. Multiple measures of NF were collected from both the IMTP and CMJ and are outlined in *table 5a.1* with coefficient of variation reported for each variable. For a more thorough explanation see chapter 3.

Table 5a.1: Indices utilised to identify current NF state from the CMJ and IMTP. CV% represents coefficient of variation from a familiarisation period.

IMTP	CV%	**CMJ**	CV%
RFD$_{0-50}$	12.70%	Jump height (cm)	4.40%
RFD$_{0-100}$	10.20%	Peak power (W/Kg^{-1})	3.60%
RFD$_{100-200}$	9.40%	Eccentric Duration (ms)	8.50%
RFD$_{200}$	7.90%	FT/CT	7.30%
Peak force (N/kg^{-1})	4.40%	Eccentric RFD/kg	17%
		Force at zero velocity (F@Zero) N	5.70%
		Eccentric mean power (W/Kg^{-1})	8%
		Concentric RPD (W.kg^{-1})	11%

5a.4.5. Physical qualities:

Aerobic fitness, lower body strength and power were utilised as measures of physical qualities [table2]. These measures were chosen as they have previously shown impact on recovery kinetics, and also shown to be important discriminators between higher and lower levels of AFL status [7,42]. A more detailed description of the rationale and procedures utilised for PQ assessment was outlined in the methodology chapter (chapter 3).

Table 5a.2: Descriptive statistics and coefficient of variation (%CV) for physical qualities (mean ± standard deviation.).

Quality	Test	Mean ± SD	CV%
Aerobic power (**V_{IFT}**)	30:15; End stage speed	20.6 ± 0.76 km•h^{-1}	1.80%
Lower Body Strength **(LBS)**	IMTP Relative peak force	40 ± 4.3 N•kg^{-1}	4.80%
Lower Body Power **(LBP)**	CMJ Relative peak power	59 ± 5.2 N•kg^{-1}	4.40%

5a.4.6. Statistics analysis:

Univariate and physical qualities interaction:

Linear mixed effects models (*lme4 package*,[85]) were used to assess the influence of physical qualities on seasonal trends of NF. Where the round (fixture) number was incorporated as a fixed effect, with individual level variation allowed for the intercept and slope. Significance of coefficients were assed utilising Kenward Roger approximation degrees of freedom (lsmeans – package)[172] and reported with 95% confidence intervals.

The univariate model was then considered the baseline model from which each additive model was compared via likelihood ratio test, with information criterion scores also reported (AIC: Akaike information criterion). Two levels of additive models were created for each physical quality where level 1 included physical qualities as an intercept only model, while level 2 treated physical qualities as an interaction term with round number. All subsequent model levels for each physical quality were compared to the baseline (univariate) model, where a significant effect was determined when the level 2 model significantly explained the data ($p<0.05$) compared to the baseline and level 1 model. Where two PQ's showed an effect for a NF measure, an additional likelihood ratio test was performed comparing both the level two models. This stepwise approach allowed for the PQ that had the highest probability of explaining the data to be reported.

A post hoc analysis was performed on models with significant interactions, this included categorising the physical quality into groups of <1SD below average, between <1SD and +1SD, and greater than 1SD (>1SD) above average. Comparison of seasonal trend coefficients between these PQ categories was performed via least mean squares (emmeans package)[172]. Seasonal changes over time were then reported as a standardised Cohens D effect size by dividing the observed seasonal change estimate by the baseline standard deviation of that physical quality. Qualitative interpretation of the Cohens unit was interpreted as 0.2-0.6 small, 0.6-1.2 moderate and greater than 1.2 large [168].

Dynamic and isometric interchangeability

To compare the seasonal association between dynamic and isometric NF measures, within subject correlations (rmcorr package, Rstudio [171,186]) were analysed on paired observations of CMJ and IMTP (i.e. performed on the same day during the season). Pearson r-values with 95% confidence intervals were reported (see **figure 5a.5),** with qualitative descriptors of effect size quantified as 0-0.1 trivial, 0.1-0.3 small, 0.3-0.5 moderate and 0.5-0.7 large [168,176]

5a.5. Results:

Univariate seasonal trend: Univariate analysis revealed a significant negative trend for both RFD 0-100 (-80.7, CI: -134.1 to -27.3 N.m.s^{-1}, p = 0.004, seasonal effect: *d* = -0.88; moderate; *Figure 5a.1*) and RFD 0-200 (-45.5, CI: -84.5 to -7.11 N.m.s^{-1}, p = 0.02, seasonal effect *d* = -0.75; moderate) over an ARF season. No significant univariate trends were observed on IMTP peak force, or any CMJ measures table 5a.3 and *figure 5a.2*

Physical qualities: An interaction effect of baseline IMTP strength was observed for seasonal peak force trends ($X^2(1) = 5.91$, p = 0.015), with lower baseline strength associated with greater seasonal improvement (Cohens D: [*<1SD*: 0.76 small], [*±1SD*: 0.09 trivial], [*>1SD*: -0.23 small]; *Figure 5a.2*). An interaction effect was also observed between V_{IFT} and eccentric duration (X2(1) = 7.55, p = 0.005) collected from the CMJ where lower baseline V_{IFT} levels showed seasonal reductions in eccentric duration responses (Cohens D: [<1SD: -1.39 small], [mean±1SD: -0.11 trivial], [+1SD: 1.02 small]; *Figure 5a.3*). While inclusion of both LBS and V_{IFT} significantly improved the model fit, the differences between slope beta coefficients were not statistically significant between the categories (<1SD, mean±1SD and >1SD;table 5a.2).

Within Subject correlations: Small to moderate within-subject correlations were observed for RFD 0-100 and 200ms with CMJ variables (*figure 5a.5*), with the strongest relationships being RFD 0-200ms ~ Peak Power (r = 0.41, CI: 0.21 to 0.57); ~FT/CT (r = 0.38, CI: 0.19 to 0.55), and F@0v (r: 0.38, CI: 0.18 to 0.54)] . Relative peak force, RFD 0-50ms and 100-200ms showed relatively small agreement with CMJ indices (trivial to small relationships).

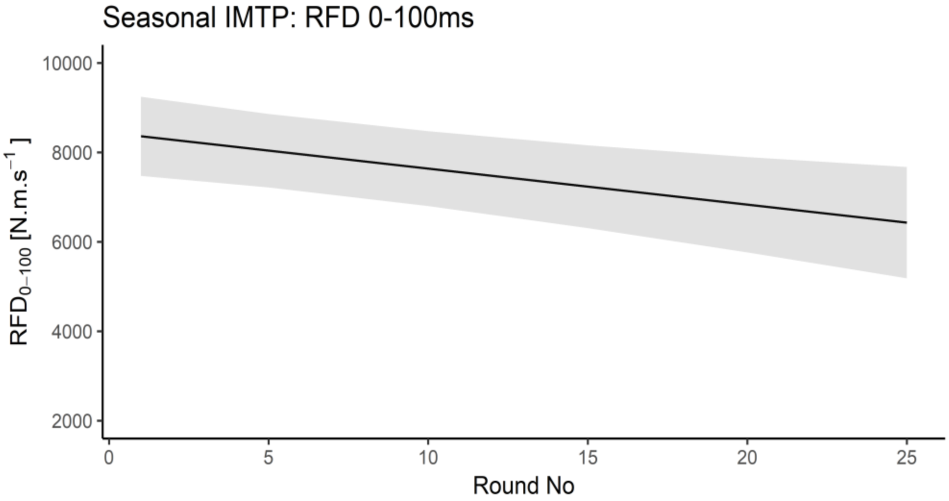

Figure 5a.1: Seasonal RFD 0-100ms univariate trend. The black solid line represents point estimates from the linear trend while shaded grey error represents 95% confidence interval.

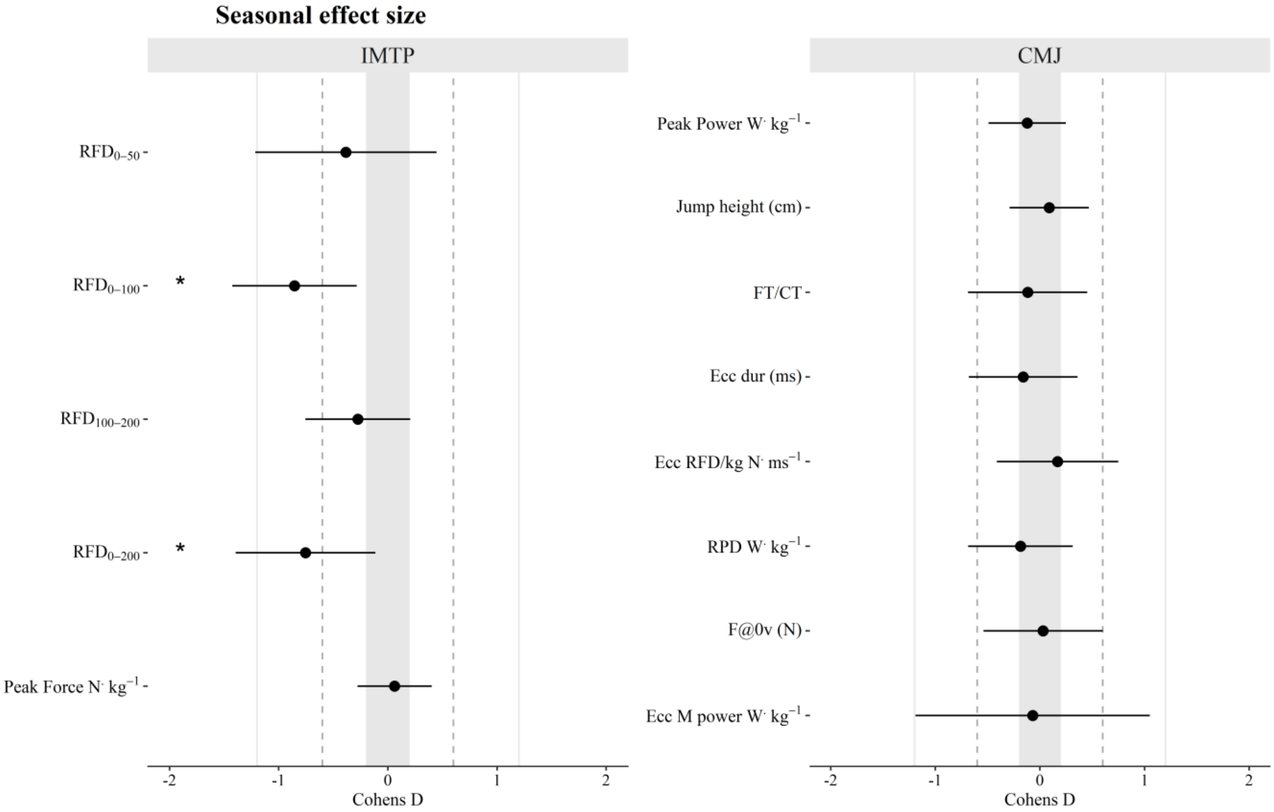

Figure 5a.2. Seasonal effect size for all variables, point range plot represents estimated Cohens d with 95% confidence interval where * denotes a significant effect. The grey shaded region represents a trivial effect (-0.2 to 0.2 SD units), dotted line represents a small effect (0.2 - 0.6 SD units) with the solid line representing a large effect (0.6-1.2 SD units).

Table 5a.3. Univariate fixed effect coefficients (Level 1) observed across both the IMTP and CMJ. Level 2 model diagnostics with AIC values and p-values (* denotes p-value <0.05) from chi square tests.

	Univariate (Variable~Round)						**Level 2 model diagnostics**		
	Coef	*95LL*	*95UL*	*P value*	*AIC*	*Seasonal Cohens D*	*LBS*	*Vift*	*LBP*
IMTP									
RFD 0-50	-19.45	-59.58	20.68	0.334	3232	-0.38	-	-	-
RFD 0-100	-80.69	-134.12	-27.26	0.003*	3314	-0.91	-	-	-
RFD 100-200	-24.78	-70.6	21.04	0.304	3329	-0.26	-	-	-
RFD 0-200	-45.8	-84.49	-7.11	0.028*	3204	-0.74	-	-	-
PF	0.01	-0.07	0.1	0.78	927	0.06	***(0.034,aic = 837)*	-	-
CMJ									
PP	-0.028	-0.11	0.06	0.512	669	-0.13	-	-	-
JH	0.021	-0.05	0.09	0.577	612	0.12	-	-	-
FT/CT	0	0	0	0.65	-224	0.04	-	-	-
Ecc Dur	0.342	1.94	-1.25	0.676	1416	0.13	-	***(0.012, aic =1411)*	-
Ecc RFD/kg	0.25	1.05	-0.55	0.546	1288	0.17	-	-	-
RPD	-0.812	-2.63	1.01	0.394	1507	-0.21	-	-	-
F@0v	0.379	-6.37	7.12	0.91	1809	0.03	-	-	-
Ecc M power	-0.001	-0.02	0.02	0.899	251	-0.06	-	-	-

Table 5a 4: Marginal slopes and least squares contrast between interaction effects. The left panel displays univariate effects for PQ subcategories with 95% confidence limits. The right panel reports the differences in trend coefficients between subcategories.

	Baseline	Category	*Beta Coef*	Lower CL	Upper CL
Seasonal peak force	LBS (Peak Force/kg)	<1SD	0.15	0.01	0.29
		mean ± SD	-0.02	-0.10	0.06
		>1SD	-0.04	-0.21	0.12
Seasonal eccentric duration	Aerobic capacity (V_{IFT})	<1SD	-3.70	-7.46	0.07
		mean ± SD	-0.30	-1.81	1.20
		>1SD	2.71	-1.47	6.89

Contrast	*Beta Coef diff*	Lower CL	Upper CL	p-value
<1SD | > 1SD	0.19	-0.02	0.40	0.179
>1SD | mean ± SD	-0.03	-0.21	0.15	0.955
<1SD | mean ± SD	0.17	0.01	0.33	0.108
<1SD | >1SD	-6.41	-11.79	-1.04	0.067
>1SD | mean ± SD	3.02	-1.25	7.28	0.360
<1SD | mean ± SD	-3.39	-7.24	0.46	0.216

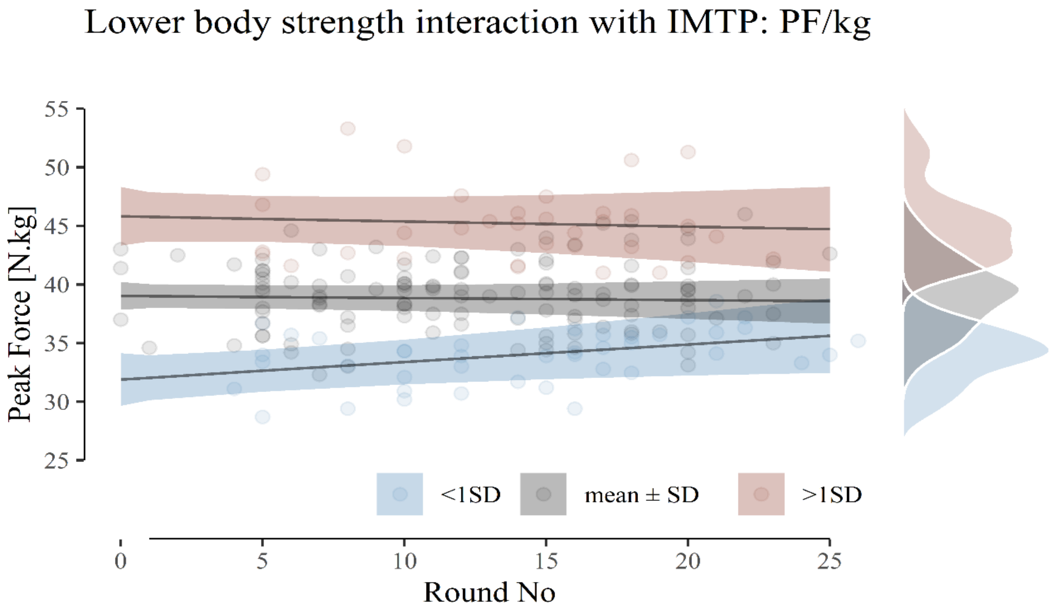

Figure 5a.3: Seasonal peak force/kg trends with interaction of LBS. Baseline LBS segmented into ->1SD (blue), mean ±1SD (grey) and <1 SD (red) to highlight seasonal interaction. Straight lines represent the point estimates while shaded regions represent 95% CI. Marginal distributions represent the sample of scores collected between each subgroup over the collection period.

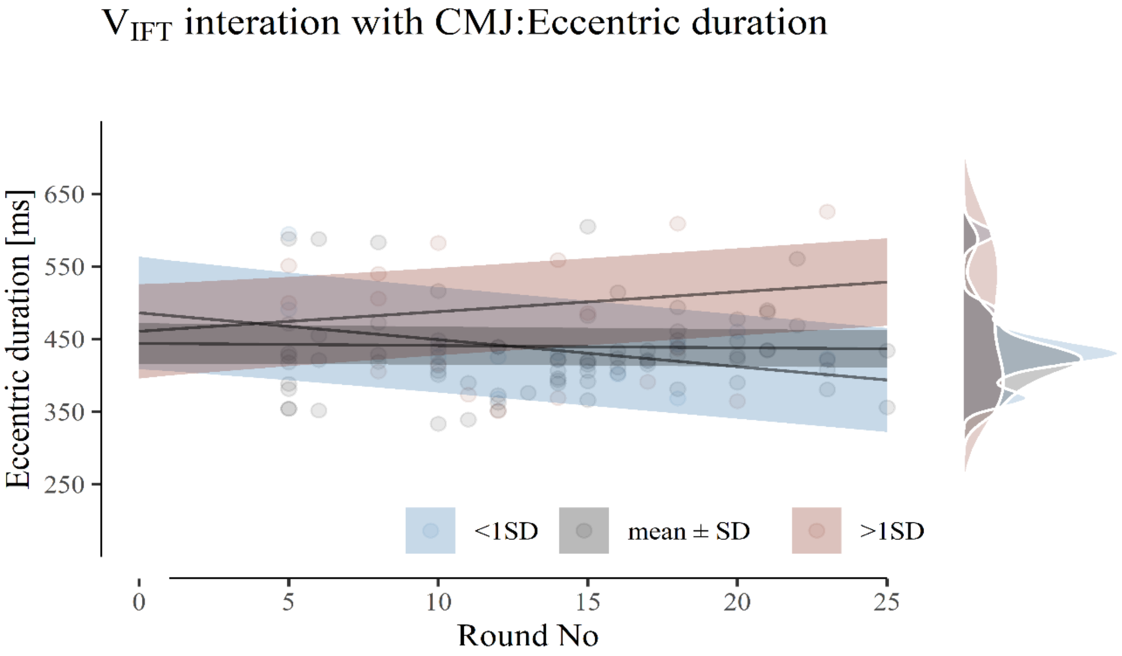

Figure 5a.4: Seasonal eccentric duration trends with interaction of MAS. Baseline MAS segmented into -1SD (blue), mean ±1SD (grey) and +1 SD (red) to highlight seasonal interaction. Straight lines represent the point estimates while shaded regions represent 95% CI. Marginal distributions represent the sample of scores collected between each subgroup over the collection period.

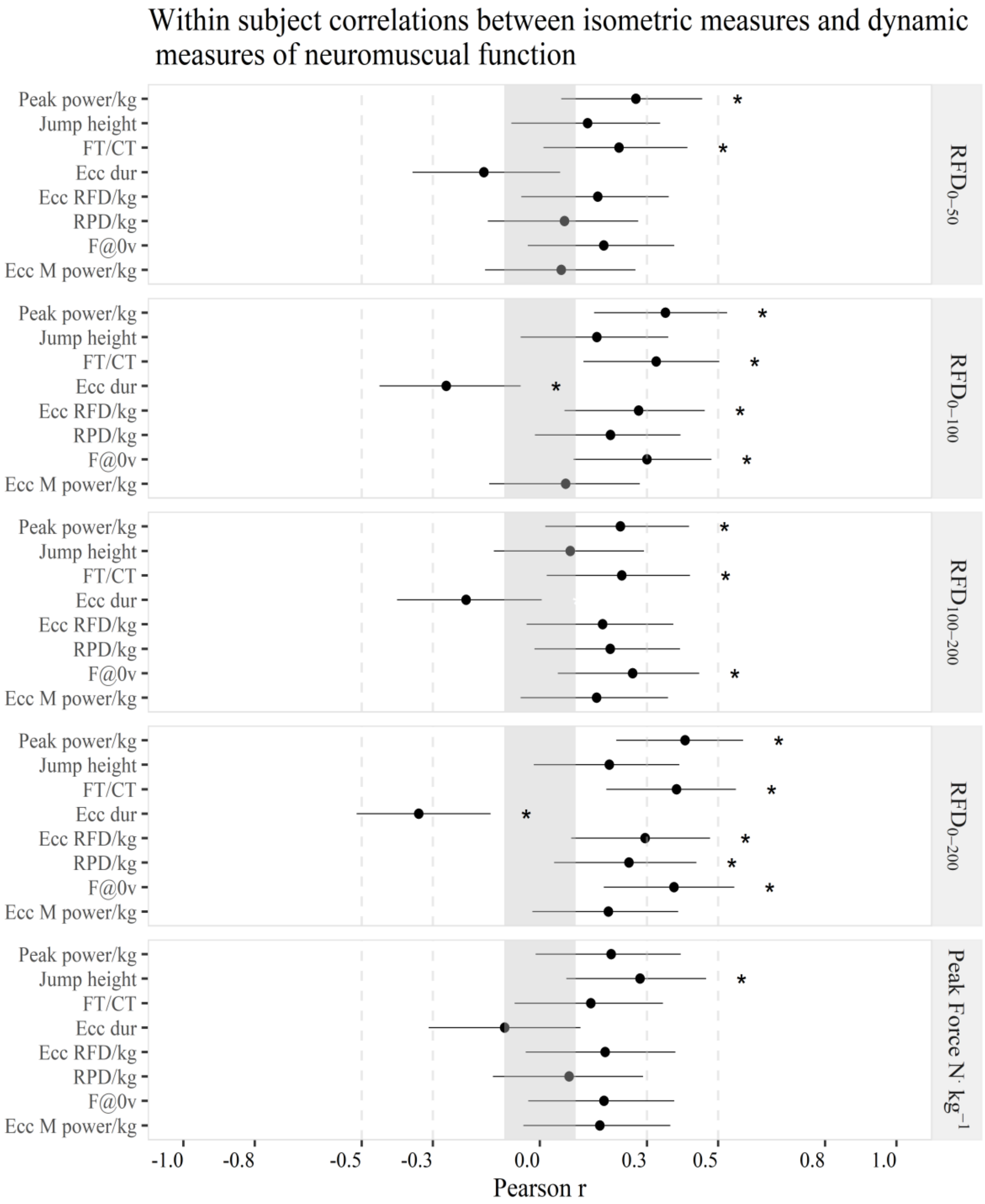

Figure 5a.5: Point estimates with error bars represent Pearson R coefficient with 95% CI. The grey shaded area represents trivial regions with the dotted lines represent small (0.1- 0.3), moderate (0.3-0.5) and large (> 0.5) cutoffs for effect size. “*” denotes measures which were deemed statistically significant $p < 0.05$.

5a.6. Discussion:

This chapter examined the second aim of this thesis, examining both the influence of physical qualities on seasonal trends in NF, and identifying the interchangeability or association between isometric and dynamic measures of NF. Moderate seasonal decreases in rate characteristics collected from IMTP (RFD 0-100ms & 0-200ms) were observed regardless of physical quality development, while no univariate seasonal effect was observed with peak force. In contrast to rate characteristics collected from the IMTP, no univariate seasonal influence was observed on any of the CMJ indices collected. Seasonal changes in IMTP peak force was better described when considering baseline lower body strength levels, with weaker players showing greater seasonal improvements. A similar effect was also observed with baseline V_{IFT} and eccentric duration, where players with lower V_{IFT} levels showed reductions in eccentric duration over the season, while opposing observations were reported in players with higher baseline V_{IFT}. Finally, higher associations were reported with RFD 0-100ms and 0- 200ms from the IMTP and a host jump related indices, while only small to trivial relationships were observed between IMPT peak force and CMJ measures.

5a.6.1. Seasonal Trends:

A key finding of this study was the moderate seasonal decrements observed in RFD 0-100ms and 0-200ms from the IMTP, where no seasonal changes were observed in other NF indices collected from either the IMTP or CMJ. Furthermore, this decrement was independent of physical qualities, with no moderating influence observed with lower body strength, power or aerobic capacity. While limited season-long studies exist, reductions in NF measures were observed by Argyus et al[187] who reported small decreases in Jump squat performance [peak power at 55% of 1rm] over a season in elite-level rugby union players. Similarly, an increased magnitude of pre- to post-match CMJ (cm) fatigue was also observed over a season in rugby union [188].

However, due to the differing cohort of athletes and days of NF assessment it is unclear whether the mechanisms underpinning the NF reductions observed in the aforementioned studies are transferable to the rate reductions that were observed within the IMTP in this study. This assertion is additionally supported by the lack of seasonal change observed with any CMJ measure observed in our study. Indeed, longitudinal research in a similar cohort of athletes observed meaningful reductions (group mean response) in 60% of samples collected of FT/CT over an ARL season [17]. While this may suggest a negative response, a post hoc regression analysis of the week-to-week results within their study revealed no increase in magnitude of difference to baseline over the season ($b= -0.001$, $p = 0.518$), which is similar to the FT/CT findings in this study. Additionally, a study of sub-elite basketball players also reported trivial changes in range of eccentric and concentric based CMJ measures over a season [189]. Given the results from our study, this may indicate that while CMJ related measures have reported associations with fatigue [10,64,95], these indices are generally maintained over season long competitions. Reasons for this contrast between CMJ measures and isometric RFD may be due to time intervals over which these measures are collected. In particular, it has been suggested that the loading period within the CMJ (>400ms) may give athletes time to attenuate / identify movement strategies to counter any potential reductions in performance [23,190]. This assertion is further supported by the peak force responses (maximal peak force within 3 seconds) collected from the IMTP in this study, which showed similar stability as CMJ measures over the season, suggesting that longer duration contraction modalities may identify only certain aspects of neuromuscular function within fatigue monitoring. In contrast, the longest RFD interval recorded was 200ms in this study design, which within a static position reduces the erroneous contribution of movement strategies and may provide additional mechanistic information regards the origin of NF perturbations.

Discrepancies in seasonal trends between CMJ and IMTP rate characteristics may be explained by the varying mechanisms that have been proposed to influence different phases of the force-time curve. For example, research via nerve stimulation and electromyography has observed different levels of contribution between neural and contractile mechanisms throughout isometric contractions, with neural mechanisms (motor unit recruitment/discharge rate, firing frequency) predominately influencing early phase RFD (<100ms), whereas intrinsic muscle properties (fibre type, size and architecture) showed greater influence upon later phase windows (RFD 100-200ms) [2,12,71,118]. As no significant seasonal effect was observed with RFD 100-200ms, it may be suggested that the decrements observed in RFD 0-100 & 200ms may be driven by neural components. This is further supported by post hoc analysis where a stronger association was observed between RFD 0-100ms and RFD 0-200ms (r = 0.71, CI: 0.62 – 0.87) versus RFD 100-200ms (r = 0.50, CI: 0.37 – 0.61), suggesting that the decrements observed in RFD 0-200ms were largely driven by early phase RFD (RFD 0-100ms). Whilst these suggestions are not supported by RFD 0-50ms (no seasonal effect), this is likely due to the high-degree of week-to-week of variability observed in the previous experimental chapter (Chapter 4), which may limit the ability to identify meaningful trends.

It is important to note that as central and peripheral nerve activity were not directly measured in this study, it is not possible to directly infer neural involvement, however a possible reason for the RFD decrement over a season may be down to an ‘unwillingness’ to produce force as fast possible despite being cued to. While this may in itself indicate a fatigue mechanism [9], it is also likely to reflect the challenges of collecting multiple maximal samples over a season in team-based sport, where observed deficits may not reflect actual capacity of the physiological system.

Another potential explanation for the seasonal decrement observed in RFD 0-100ms may be the differing resistance training exposures in the pre-season versus in-season training programs. Pre-season training consisted of two key lower body resistance training days a week, compared to a single key exposure during in-season micro-cycles. Indeed, neural adaptations have reported moderate to strong contribution to RFD increases derived from strength training ($r^2 = 0.46$-0.81) [12,71,119,179,191], therefore it is plausible that the reduction in early phase RFD may be reflective of a decrease in lower body strength stimulus from pre-season to in-season. Nonetheless, as no other measures showed meaningful seasonal decreases and as RFD has been linked to performance decrements and injury risk [12] [11], this finding may be of interest to high performance practitioners looking to monitor NF status over a season.

5a.6.2. Physical Qualities:

Whilst moderating influences of PQ on NF has been previously reported [16], less available research exists that examines this influence over a seasonal setting and with two NF testing modalities. Indeed, an effect of baseline LBS was observed on peak force trends, where players with lower baseline LBS showed greater seasonal improvements compared to players with higher baseline values (*figure 5a.2*). Although limited evidence exists regarding within season improvements of strength in AFL, improvements of LBS as measured by a box squat have been observed in elite-level Rugby Union players over a competitive season [187]. Baker [192] also reported a similar effect between elite level and sub-elite rugby league players, reporting seasonal strength improvements (Bench Press) in sub elite level players, while elite level players' strength remained relatively stable. It is therefore plausible that IMTP peak force improvements may be made over a season, however the magnitude and direction of this change may be influenced by initial LBS, with lower baselines shower greater improvements while higher starting baselines may have reduced scope for improvement [187,192,193]. Inspection of PF.kg trends between subgroup categories (<1SD, mean ±SD and >1SD) in figure 5a.3 support this notion, where it can be seen that players in the mean ±SD and >1SD categories show relative stable responses over the season. This may have important implications for practitioners when designing training programs where, for example, a greater emphasis on maximal strength development may not be needed to maintain this quality for individuals above certain thresholds over a season.

An effect of baseline V_{IFT} was also observed on seasonal eccentric duration responses from the CMJ, with lower baseline levels showing reductions in eccentric duration over the season (*figure 5a.4*). Eccentric duration has been previously suggested to be an important variable to monitor throughout CMJ trials as it may represent a change in movement strategy [10,53,122]. Interestingly, this moderating influence was not observed with FT/CT, which suggests that the decrease in loading time over the season likely corresponded with a small decrease in flight time. This disparity across measures makes interpretation of this observed effect of V_{IFT} difficult and represents one of the challenges when the evaluation of fatigue is dependent on two phases of contraction (eccentric and concentric). Another possible explanation for this finding however, may be related to the assignment of baseline V_{IFT} values to individuals. Indeed, these values were collected from one maximal 30:15 attempt but given individual variations in acute loading schemes prior to the time of testing, it is possible that the assigned value may under represent some participant's true fitness. This potential underrepresentation in fitness is further compounded as a change of only two levels during the 30-15 would have moved an individual from below 1SD to within the mean in the sample distribution collected in this study. Examination of the marginal distribution between subgroups in *figure 5a.4* also suggests a high degree of variability between subgroup responses and reduces our confidence in the effect observed. This in turn may explain the lack of clear effect of V_{IFT} on other NF indices, considering that previous research has inferred a positive influence of aerobic capacity upon recovery [16,35]. Indeed, a similar constraint may question our ability to identify a “true” baseline of LBS from IMTP, where for example research in AFL athletes reported a very large negative correlation (r = -0.82) with weekly training load and IMTP PF responses [194]. However, due to a larger spread within baseline LBS responses it is likely that this effect would have less influence on the subsequent analysis utilised for our study.

5a.6.3. Relationships:

While, associations between isometric and dynamic measures of strength and power have been previously examined [27,76,195,196], to this author’s knowledge, limited literature assessing longitudinal within-subject association between rate and peak characteristics collected from the IMTP to key CMJ variables over a season in elite level AFL athletes exist. Findings revealed small-to-moderate associations between RFD 0-100 & RFD 0-200 and CMJ indices (figure *5a.5*) were observed, while only trivial to small associations were found between peak measures and jump indices. These findings may suggest that seasonal PF.bw changes may not be indicative of associated NF changes measured via the CMJ.

While limited lower body seasonal strength and power trends exist, similar findings were found by Argus et al [187] who reported trivial relationships between improvements in LBS as measured by box squat and LBP measured by load squat jump in rugby union players over a competitive season. However, the testing of strength and power within their study was not matched on the same day, which is likely to make comparison to our findings difficult. These findings suggest that rate measures collected from the IMTP in particular RFD 0-200ms may explain more variance in seasonal CMJ responses, however as explored within the univariate results, this shared variance may not be indicative of the same underling fatigue mechanism. In turn the ability to interchange IMTP and CMJ measures of NF for monitoring may be limited within team settings, and if possible systematic testing of both measures may give better insight into NF than one test alone.

5a.6.4. Limitations:

While this study was able to further the current understanding of both the seasonal dynamics of isometric and dynamic measure of NF, and the potential moderating influence of physical qualities on these trends, some important limitations do exist. Firstly, our sample size precluded us from appropriate sensitivity to assess the influence of two-way interactions between PQs for example advanced aerobic capacity and lower body strength on seasonal trends. Indeed, an understanding of this interaction may further inform recovery and training prescription. Secondly, the lack of multiple aerobic assessments within this design is a limitation and may limit our ability to accurately assess the influence of aerobic capacity on NF seasonal trends. Indeed while limited research exists, variability in maintenance of aerobic endurance has been reported from both field- and laboratory-based measures [197,198], it is therefore clear that further research is warranted to more accurately assess the impact of this variable.

Thirdly, as a moderating influence of external load on NF recovery has previously been reported [4,6,50,96], the exclusion of these variables within this chapter's analysis may limit potential inference. This potential moderating interaction between load, NF and PQ will however be explored in the following chapter. Finally, as central and peripheral measures of NF were not directly measured it is only possible to infer the potential mechanisms behind the responses observed within this study.

5a.6.5. Conclusion and practical applications.

The results of this study indicated that NF inference may be influenced by assessment type, indices from the collected modality, time of season, and physical qualities. Rate characteristics (RFD 0-100, 0-200ms) collected from the IMTP may give additional information into an athletes current NF status that is not measured by peak measures from the CMJ or IMTP, nor CMJ rate indices. In particular, early phase RFD may give insight into potential neural underpinnings of NF that may be missed by other measures. These findings are similar to the previous chapter, where inclusion of rate characteristics from isometric assessment was able to give additional insight into NF capacity that was not detected by peak force measures. Furthermore, no systemic effect was observed of physical qualities on seasonal trends, however consideration of baseline lower body strength may be important when assessing seasonal NF adaptations of PF on the IMTP. Therefore, assessment of rate characteristics collected via isometric assessment may offer a viable solution to identify NF over a season in team-based sport settings.

Chapter 5b: Do physical qualities have a moderating influence on the load-fatigue response?

5b.1: PREFACE

Chapter 5a aimed to extend the acute isometric findings from chapter 4 to a longitudinal setting and assess whether NF rate and peak responses from the IMTP showed similar responses to CMJ measures of NF. Indeed, similar to chapter 4, monitoring of rate characteristics from the IMTP was shown to provide additional insight into neuromuscular state (negative seasonal decay) that was not identified by assessment of peak measures from the IMTP or any CMJ measures alone. Additionally, findings from this chapter revealed that inclusion of baseline PQ's may allow for a better description of observed seasonal trends. In particular, inclusion of baseline LBS as a time varying covariate was shown to better explain direction of observed seasonal results for IMTP PF.kg. While these results may be of interest to practitioners, they provide limited insight into the mechanisms that may influence weekly dynamics of NF recovery. Therefore, the following and final experimental chapter 5b aims to explore whether game loads preceding NF testing can better describe observed NF in isometric and dynamic responses. Similar to chapter 5a potential moderating influences of PQ's on this load-fatigue response will also be explored (Thesis aim 4).

Findings from this chapter were presented at a peer reviewed conference proceeding:

Norris D, Siegler J, Joyce D & Lovell R (2019) Do physical qualities have a moderating influence on the load fatigue response. World Congress of Science and Football (WCSF). Melbourne, Australia.

5b.2 Abstract

Introduction: A key component of monitoring neuromuscular function (NF) in elite sport settings is to gain insight into how an athlete may be responding to a given external load, which may inform subsequent training decisions. The moderating impact of physical qualities (PQ) on this relationship may also be of interest given their potentially modifiable nature. To date however, limited longitudinal studies exist assessing the impact of PQ on NF responses to external load. **Methods:** 32 national competition Australian Rules Football (ARF) players' NF was assessed in both isometric (isometric mid-thigh pull [IMTP]) and dynamic conditions (counter-movement jump [CMJ]) 72 hours after competitive match-play (7±2 collections). Neuromuscular responses (peak and rate characteristics) to standardized external load measures collected during matches (GPS; Total Distance, high-speed running [HSR; $\geq$17.0 km·h^{-1}] & sprinting [VHSR; $\geq$23.0 km·h^{-1}] were assessed using linear mixed effect models. Physical qualities of lower body muscular strength (IMTP; relative peak force [N•kg]), aerobic capacity (V_{IFT}) and dynamic lower body power (CMJ Peak Power) assessed in pre-season were then incorporated as interaction terms, with the significance of their inclusion assessed via information criterion and likelihood ratio tests. **Results & Discussion:** No practically meaningful effects were observed with any univariate neuromuscular responses to match load measures. Pre-season lower-body power and strength had a moderating influence upon NF responses to VHSR and HSR, with higher baseline levels associated with enhanced NF recovery (CMJ: Jump height & eccentric mean power/kg) following higher standardized loads. **Conclusion:** There were no meaningful relationships between NF peak and rate characteristics collected 72 h post ARF matches, versus match-play external loads. While no systemic moderating influence of PQ were observed, enhanced levels of lower body strength and power in particular may positively influence an athlete's NF response to match-play load fluctuations.

5b.3. Introduction

As was identified in the previous chapter, monitoring of neuromuscular function across a variety of modalities may give additional insight into acute and seasonal NF states, versus a single stand-alone assessment modality. In particular, rate measures collected from the isometric mid-thigh pull (IMTP) were shown to give additional information in terms of both magnitude and direction of decay of neuromuscular status in both an acute (chapter 4) and seasonal setting (Chapter 5a). A limitation of the previous two chapters, however, was the exclusion of external load measures from the analysis. Indeed, previous research has shown small to moderate impacts of external load measures on acute and longitudinal NF recovery [17,66,94,99,199]. For example, Rowell et al[66] observed small to moderate impacts of match load on acute NF recovery (CMJ; Jump height and FT/CT) following three competitive soccer games. Similarly, Russell et al[94] , reported small to moderate correlations between a variety of game loads and CMJ peak power at 24-48 hours post match. Within longitudinal frameworks, Cormack et al[17] observed a small correlation between match time played and FT/CT responses over elite level ARF season. Furthermore, Mooney et al[4] in a similar cohort of athletes reported a mediator effect of neuromuscular state (CMJ; FT/CT) on within-game load profiles, where a reduced NF state pre-match lessened the contribution of high intensity running on game load. While informative, the primary tool for inference of NF within the literature has been jump based, with little literature examining the influence of external loads on rate and peak measures collected during an isometric assessment. As mentioned within the previous two chapters, while jumps have reported ecological validity and shown to be sensitive to loading stimuli [66,94,122], it may not always be possible to perform dynamic assessment of NF on athletes. Additionally, the dynamic nature of a CMJ makes inference on underlying fatigue mechanism more difficult as multiple components may influence eccentric and concentric contraction speed [23,190]. Therefore, given the findings from the previous two chapters and the ability to better infer mechanisms influencing isometric force-time performance, an understanding of the impact of load on this contraction modality is warranted.

Indeed, a study of elite soccer players reported a moderately negative effect between match total distance and voluntary activation during an isometric knee extension test, while no effect was observed for High Intensity Running (>15km.hr) after one competitive match [51] . A longer-term study in elite ARF players monitored peak force responses from the IMTP on three occasions over a pre-season and reported a strong negative (r= -0.82) relationship between distance covered and the subsequent peak force response. Neither of the above studies however, reported on the potential influence of loads of rate characteristics which, given the findings from the previous two chapters, may have allowed for additional inference into neuromuscular state. Furthermore, given the high week-to-week variability reported in competitive match play loading [180], longer term within-subject designs are needed to better examine the nature and magnitude of this load-NF relationship.

As explored in the previous chapter, an understanding of how PQ's interact with NF responses may be of interest to practitioners as PQ's represent a potentially modifiable trait. Moreover, identifying the magnitude of interaction between of PQ and external load on NF responses may allow for earlier intervention strategies for athletes who may be at risk of neuromuscular fatigue given a certain external load and fitness status. Indeed, previous work by Mooney et al[4] reported a mediating influence of neuromuscular status on the relationship between aerobic fitness (YoYo IR2) and match output, with a fatigued state weakening the influence of aerobic fitness on match output. Furthermore, Malone et al[91] reported a moderating influence of lower body physical qualities (Strength; 3RM trap bar deadlift, repeat speed ability; 6*35metre repeat shuttle, maximum speed: 5,10,20 metre) on injury risk for given arbitrary workloads, with advanced capacities showing greater ability to tolerate higher workloads. While NF was not directly measured in this study, it is plausible that advanced physical qualities may exert a similar moderating influence through enhanced NF recovery.

To date however, relatively little research exists examining the influence of PQ on neuromuscular responses to external load within a longitudinal within-subject design. Therefore, the aims of this chapter are two-fold: 1) to describe the impact of different measures of external load on dynamic and isometric NF responses; and 2) to assess of the influence of PQ's on these responses.

5b.4. Methods:

This chapter's methodology can be seen as an extension of the previous chapter. Key differences in study design will be discussed, in particular external load measures and subsequent analysis.

5b.4.1. Procedures:

Both the IMTP (isometric) and CMJ (Dynamic) were utilised as markers of neuromuscular status and were collected according to the procedures outlined in chapter 3. The same force and time variables assessed for dynamic and isometric NF modalities as in chapter 5a are explored within this chapter (see table 5a.1 from the previous chapter).

5b.4.2. External Load measures

Assessment of external load procedures were outlined within the methodological chapter (chapter 3), where the key measures and descriptive statistics of load collated from GPS units can be seen in table 5a.2. These measures were collected from competitive match play and transformed into individual level z-scores using the equation below, before subsequent analysis.

$$Z\ score = \frac{Game\ value_i - \mu\ of\ full\ completion\ games_I}{\sigma\ of\ full\ completion\ game_i}$$

Where "μ" *(mu)* denotes the mean within-participant (i) game score over the season and "σ"*(sigma)* denotes the standard deviation of games utilised within *"mu".* Average game time over the season was 98 ± 13 minutes for participants.

5b.4.3. Measures of external work:

Table 5b.1: Descriptive statistics and %CV for external loads in competitive ARF (mean ± standard deviation). CV% represents seasonal game-to-game variation.

Measure	**Thresholds**	**Distance (m)/ Efforts**	**CV%**
Total distance		12608±1983	6.9
High speed running (HSR)	>17km.hr^{-1} (>4.7m.s^{-1})	2253±597	14.8
Very high speed running (VHSR)	>23km.hr^{-1}(>6.39m.s^{-1})	400±186	38.5
Acceleration load (Accel + Deceleration load) efforts (AccDecc)	Acceleration > 2.5m.s^{-2}, Deceleration <-2.5m.s^{-2}	110±27	18.8

Physical qualities:

Physical qualities and descriptive statistics used for the analysis can be seen in the previous chapter (table 5a.2).

5b.4.4. Statistical analysis:

Univariate and physical qualities interaction:

A linear mixed effects model (*lme4 package,*[85]) was employed to assess the influence of physical qualities on NF responses to load. Firstly, univariate models incorporated standardised load scores as fixed effects with individual level variation allowed for the slope and the intercept. Kenward Roger approximation from the emmeans[172] package was used to assess the significance of the fixed effects (Load measure) on NF responses, where significance was denoted as $p < 0.05$.

This model then formed the subsequent baseline model from which each additive model was compared via information criterion (AIC: Akaike information criterion) likelihood ratio test with information criterion also reported. Two levels of additive models were created for each physical quality where level 1 included physical qualities as an intercept only model, while level 2 treated physical qualities as an interaction term with each measure of load. All subsequent model levels for each physical quality were compared to the baseline model, where a significant effect was maintained when the level 2 model significantly explained the data ($p<0.05$) compared to the baseline and level 1 model. Where two PQ's showed an effect for a NF measure an additional likelihood ratio test was performed comparing both the level two models via likelihood ratio test. This approach allowed for the PQ that had the highest probability of explaining the data to be reported.

In the event of a significant interaction model, *post hoc* analyses were performed by categorising the physical quality into groups of below average (<1SD), between <1SD and +1SD, and greater than 1SD (>1SD) above average. Comparison of trend coefficients between these PQ categories was performed via least mean squares (emmeans package)[172] and reported with 95% confidence intervals. Cohen D effect size units were assessed by dividing the coefficient by the pre-baseline SD for that measure. An effect was considered practically meaningful when a unit change in within subject load (1 SD) was very likely (75%) greater than 0.2*baseline SD for that measure and had a reported p-value <0.05. This approach was also extended to contrast differences in slope coefficients between subgroups of PQ's at a given 1 SD load with calculations performed via a custom excel spread sheet [200].

5b.5. Results:

Univariate seasonal trend: A significant increase was observed with Force at Zero velocity (F@0v) and total high speed running distance (HSR) (coef: 34.05, 95% CI; 0.55 – 67.55, p-value = 0.048, *Cohens D* = 0.12) per 1 SD increase within-subject load. Contrastingly, a significant decrease was observed in Eccentric deceleration RFD/kg and the sum of Acceleration and Deceleration movements performed (coef: -6.53, 95% CI; -11.6 to-1.39, p-value = 0.014, *Cohens D*: -0.18). While significant, no NF measures were meaningfully impacted by load. A list of all univariate effects can be seen in tables 5b.4 and 5b.5, with a graphical representation provided within the appendix.

Physical qualities: Model explainability was improved when baseline LBS (IMTP PF/kg) was included with CMJ: eccentric mean power/kg responses to high speed running volume (AIC = 237, $X^2(1)$ =7.85,p = 0.0050), with a positive moderating effect observed of LBS on this response (HSR*LBS = 0.035, 95% CI: 0.011 – 0.06, p-value = 0.0057). Inclusion of LBP (CMJ: Peak Power/kg) also improved explainability of CMJ: Jump height responses to very high intensity running (AIC = 588, $X^2(1)$ = 4.24 ,p = 0.0390), with higher levels of LBP positively moderating JH responses to VHSR (VHSR*LBP = 0.078, 95% CI: 0.004 – 0.148, p-value = 0.0386). Finally, a moderating influence of baseline V_{IFT} on CMJ: F@0v responses to the sum of acceleration and deceleration efforts was also observed (AIC = 1785, $X^2(1)$ = 4.21, p-value = 0.040), with higher levels of baseline V_{IFT} being less influenced by AccDecc loads than participants with lower baseline V_{IFT} (AccDecc*V_{IFT} = 37.08, 95% CI: 1.99 – 72.16, p-value = 0.0407). Practically meaningful effects between subcategories were observed for LBP and JH responses to VHSR, where a difference between slope coefficients was observed between players categorised <1SD Peak power/kg and players >1SD Peak power/kg (slope differential: -1.57, 95% CI: -2.71 to -0.43, p-value = 0.022, cohens d: -0.35, 84% likely greater than 0.2 between-subject SD). Finally, a practically meaningful effect was observed with LBS on CMJ: Ecc mean power responses to HSR (<1SD | >1SD; slope differential: -0.46, 95% CI; -0.76 to -0.16, p-value = 0.001, Cohens d: -1.02, 99% likely worse response). Data and relevant visualisations of these findings are available in tables 5b 2-4, and *figure 5b.1*.

Table 5b.2 Univariate fixed effect coefficients (Left panel) observed across both the IMTP and CMJ for Total distance and HSR external load measures. Right panel represents the model diagnostics of interaction models with AIC and p-values (* denotes p-value <0.05) from LRT test.

	Univariate response (NF measure ~Load measure)						**Level 2 model diagnostics**		
Total Distance	*Beta*	*95LL*	*95UL*	*Pvalue*	*AIC*	*Std beta*	*LBS*	*V_{IFT}*	*LBP*
IMTP									
RFD 0-100	33.30	-217.58	284.18	0.7950	3254	0.01	-	-	-
RFD 100-200	116.70	-175.34	408.74	0.4340	3282	0.05	-	-	-
RFD 0-200	15.40	-173.66	204.46	0.8727	3142	0.01	-	-	-
PF/kg	-0.05	-0.40	0.30	0.7545	909	-0.01	AIC 826, p =0.10	-	-
CMJ									
Peak power/kg	-0.44	-0.88	0.00	0.0528	662	-0.08	-	-	-
JH	-0.08	-0.44	0.28	0.6749	610	-0.02	-	-	-
FT.CT	-0.01	-0.03	0.00	0.2061	-225	-0.09	-	'-	-
Ecc Dur	5.32	-2.26	12.90	0.1718	1402	0.08	-	-	-
Ecc RFD/kg	-4.59	-9.16	-0.03	0.0520	1275	-0.13	-	-	-
F@0v	-30.67	-61.83	0.49	0.0570	1790	-0.11	-	-	-
Ecc M power/kg	-0.08	-0.18	0.01	0.0980	244	-0.19	-	-	-
RPD	-7.24	-17.96	3.48	0.1878	1496	-0.08	-	-	-
HSR (>17km.hr)	*Beta*	*95LL*	*95UL*	*Pvalue*	*AIC*	*Std beta*	*LBS*	*V_{IFT}*	*LBP*
IMTP									
RFD 0-100	-110.00	-359.51	139.51	0.3891	3254	-0.05	-		-
RFD 100-200	-177.00	-463.16	109.16	0.2270	3282	-0.08	-	-	-
RFD 0-200	-65.65	-252.63	121.33	0.4927	3142	-0.05	-	-	-
PF/kg	0.06	-0.29	0.42	0.7310	911	0.01	-	-	-
CMJ									
Peak power/kg	-0.15	-0.62	0.32	0.5243	666	-0.03	-	-	-
JH	-0.13	-0.51	0.25	0.5068	610	-0.03	-	-	-
FT.CT	0.01	-0.01	0.03	0.2610	-225	0.08	-	-	-
Ecc Dur	-7.45	-15.50	0.61	0.0732	1401	-0.11	-	-	-
Ecc RFD/kg	3.80	-1.10	8.70	0.1330	1267	0.11	-	-	-
F@0v	34.05	0.55	67.55	0.0488*	1496	0.12	-	-	-
Ecc M power/kg	0.09	-0.01	0.18	0.1070	247	0.20	AIC:237,p =0.003	-	-
RPD	3.82	-7.53	15.17	0.5110	1497	0.04	-	-	-

Table 5b.3 Univariate fixed effect coefficients (Left panel) observed across both the IMTP and CMJ for VHSR and Accel and Decell count external load measures. Right panel represents the interaction model diagnostics with AIC and p-values (* denotes p-value <0.05) from a likelihood ratio test reported.

	Univariate response (NF measure ~Load measure)						**Level 2 model diagnostics**		
VHSR (>23km.hr)	*Beta*	*95LL*	*95UL*	*Pvalue*	*AIC*	*Std beta*	*LBS*	*V_{IFT}*	*LBP*
IMTP									
RFD 0-100	-57.90	-298.98	183.18	0.643	3255	-0.03	-	-	-
RFD 100-200	188.00	-83.85	459.85	0.177	3281	0.08	-	-	-
RFD 0-200	63.30	-115.06	241.66	0.490	3142	0.04	-	-	-
Peak Force/kg	0.11	-0.22	0.44	0.494	910	0.02	-	-	-
CMJ									
Peak power/kg	0.09	-0.38	0.56	0.750	666	0.02	-	-	-
Jump height	0.27	-0.12	0.65	0.170	608	0.06	-	-	AIC: 588, p = 0.039
FT.CT	0.01	-0.01	0.03	0.340	-225	0.07	-	-	-
Ecc Dur	-7.09	-15.20	1.02	0.090	1401	-0.11	-	-	-
Ecc RFD/kg	1.01	-3.97	5.99	0.690	1286	0.03	-	-	-
F@0v	8.67	-25.59	42.93	0.620	1805	0.03	-	-	-
Ecc M power/kg	0.07	-0.02	0.17	0.162	245	0.17	-	-	-
RPD	-0.75	-12.16	10.67	0.898	1496	-0.01	-	-	-
Sum AccDec (>2.5ms)	*Beta*	*95LL*	*95UL*	*Pvalue*	*AIC*	*Std beta*	*LBS*	*V_{IFT}*	*LBP*
IMTP									
RFD 0-100	-62.28	-332.76	208.20	0.650	3318	-0.03	-	-	-
RFD 100-200	293.00	-14.72	600.72	0.064	3279	0.13	-	-	-
RFD 0-200	15.08	-186.80	216.96	0.880	3141	0.01	-	-	-
Peak force/kg	0.06	-0.31	0.43	0.756	911	0.01	-	-	-
CMJ									
Peak power/kg	-0.48	-0.98	0.01	0.059	668	-0.09	-	-	-
Jump height	-0.11	-0.51	0.30	0.616	609	-0.03	-	-	-
FT.CT	-0.01	-0.03	0.01	0.150	-225	-0.08	-	-	-
Ecc Dur	5.59	-3.01	14.19	0.206	1403	0.09	-	-	-
Ecc RFD/kg	-6.53	-11.66	-1.39	0.014*	123	-0.18	-	-	-
F@0v	-35.30	-70.99	0.39	0.055	1790	-0.13	-	AIC: 1785,p = 0.04	-
Ecc M power/kg	-0.07	-0.17	0.04	0.244	245	-0.15	-	-	-
RPD	-8.05	-20.16	4.06	0.195	1494	-0.09	-	-	-

Table 5b. 4 Trend assessment of different levels of standardised physical qualities to load constraints. Panel 1 (left) represents univariate response of PQ subcategory level while panel 2 (right) represents the difference in trend coefficients between groups. * denotes a significant effect ($p>0.05$) after controlling for multiple comparisons with 95% confidence intervals reported.

Measure	*Load measure*		*PQ*	*Category*	*Beta Coef*	*Lower CL*	*Upper CL*	*Contrast*	*Coef diff*	*Lower CL*	*Upper CL*	*Pvalue*	*Cohen D*
Ecc. Mean power/kg	HSR	*	LBS	<1SD	-0.16	-0.39	0.06	<1SD | >1SD	-0.46	-0.76	-0.16	0.0012*	-0.64
				Mean ±SD	0.06	-0.07	0.20	<1SD | Mean ±SD	0.23	-0.02	0.48	0.1623	0.32
				>1SD	0.29	0.08	0.51	<1SD - Mean ±SD	-0.23	-0.48	0.03	0.1956	-0.32
Jump Height	VHSR	*	LBP	<1SD	-0.30	-1.08	0.47	<1SD | >1SD	-1.57	-2.71	-0.43	0.0218*	-0.35
				Mean ±SD	0.19	-0.31	0.70	>1SD | Mean ±SD	1.07	0.09	2.05	0.0871	0.24
				>1SD	1.27	0.41	2.12	<1SD | Mean ±SD	-0.50	-1.41	0.41	0.5311	-0.11
F@0v	AccDec	*	V_{IFT}	<1SD	-52.87	-160.95	55.21	<1SD - +1SD	-87.04	-226.41	52.34	0.4416	-0.32
				Mean ±SD	-46.78	-90.11	-3.46	>1SD | Mean ±SD	80.95	-18.18	180.09	0.2498	0.29
				>1SD	34.17	-56.22	124.56	<1SD | Mean ±SD	-6.08	-121.29	109.1	0.9941	-0.02

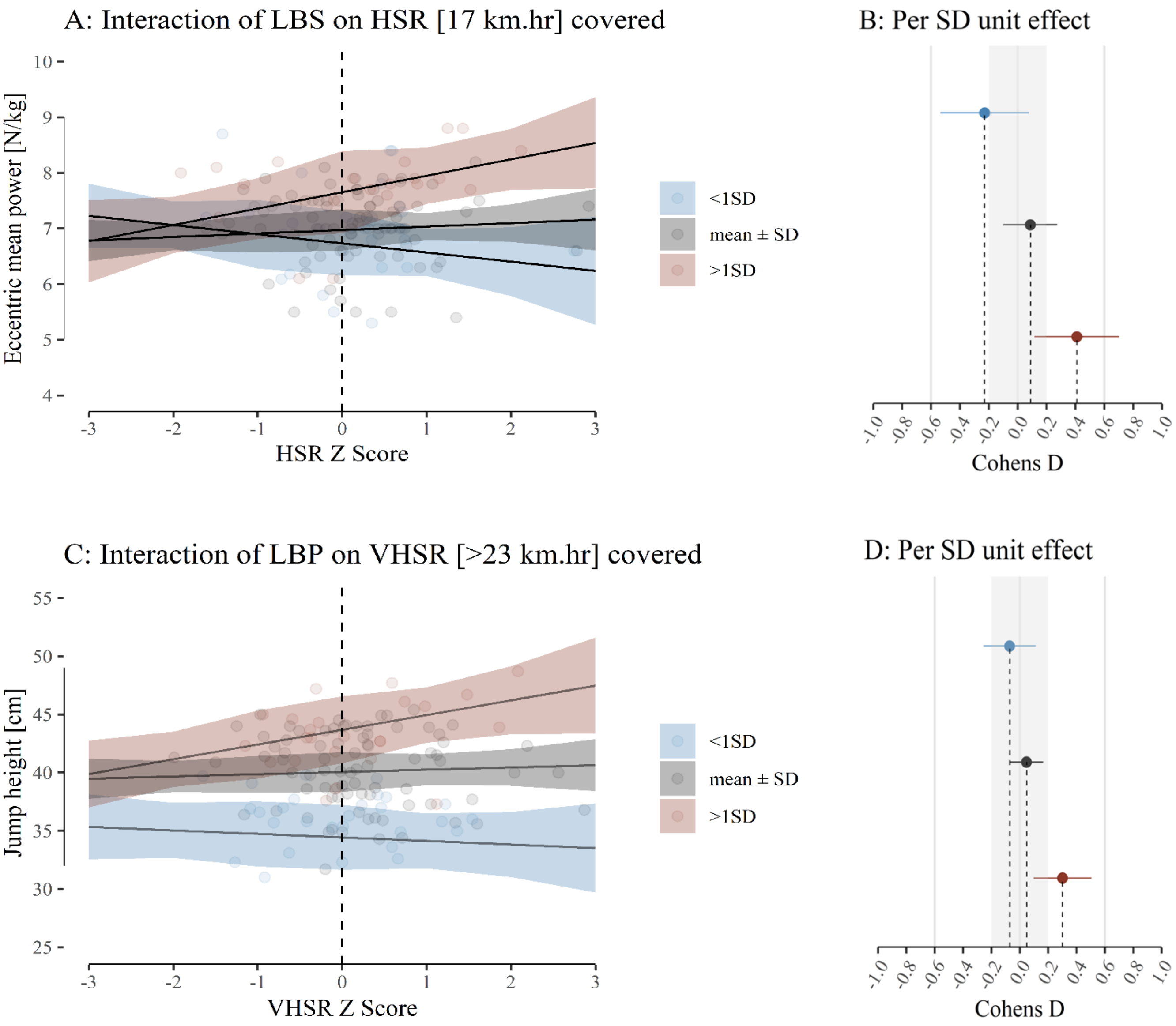

Figure 5b.1. Moderating influence of physical qualities on NF responses to load conditions. Plots **A** and **B** represent linear estimates of NF responses to differing load volumes between baseline physical qualities subgroups. The grey line represents mean estimate effect, and filled ribbons represent 95% CI of the estimate. Plot **B and D** represent the standardised effect of each subgroup per 1 SD response for the given the load with the shaded grey region representing a trivial range (-0. 2 to 0.2) between subject SD. *LBS = baseline lower body strength (IMTP: PF/kg), *LBP = baseline lower body power (CMJ: PP/kg)

5b.6 Discussion.

The aims of this chapter were to identify the influence of external load measures on NF responses in both isometric and dynamic conditions, and to explore the potential moderating influence of baseline physical qualities on these responses. Findings from this chapter observed no statistically or practically meaningful relationships between measures of external load and isometric rate and or peak measures of NF. While, statistically significant effects were observed between some CMJ measures and external load, the magnitude of the observed effects were not deemed practically meaningful. Finally, accounting for baseline lower body strength, power and fitness (V_{IFT}) were found to improve model explainability across certain CMJ indices, with advanced capacities showing a positive moderating influence on these responses.

5b.6.1 Univariate responses: IMTP

Findings from chapter 4 revealed that residual fatigue when compared to baseline was still likely evident for early and late phase RFD at 72 hours post-match. It was therefore postulated that variance in RFD measures collected at this time pointed may be explained by the acute match load 72 hours prior. Interestingly, findings from this chapter revealed no significant or practically meaningful effect of external load measures on RFD responses collected from the IMTP. While this may question the utility of RFD as a measure of NF, potential explanations for this lack of observed relationship exist. Firstly, while fatigue symptoms may remain evident for up to 72 hours as observed in chapter 4, it is possible that the influence of load behind these decrements may have dissipated prior to 72 hours, and that the variations evident are driven by other latent variables not reported on in this chapter. Secondly, it is possible that the seasonal decay effect as observed in the previous chapter, reduced our ability to identify any relationship between these measures. Finally, while no agreed limits of acceptable reliability exist, this lack of relationship may be indicative of the high week-to-week variations reported (see table 5b.3) in rate characteristics collected from the IMTP, which coupled with the high week to week variations in loading measures in particular HSR, VHSR and AccDecc Load, reduced the ability to identify meaningful associations.

Similar results were also observed with peak measures collected (IMTP: PF/kg), with no meaningful effect observed across any condition. The results of peak force are consistent with the findings observed in the previous two chapters, which highlighted the lack of change in peak force in both acute and longitudinal settings. In contrast, Garrett et al[194] reported a very large negative effect between conditioning load (distance) and IMTP Peak force/kg during a pre-season in elite ARF players. A reason for this discrepancy may be in the differences in loads observed within the pre-season design (21 – 43 km), which were several orders of magnitude greater than the variations observed within the seasonal match data collected in this chapter (average within game variation: 870m). These findings along with the results from the previous two chapters suggest practitioners should be cautious when interpreting Peak Force from the IMTP as a primary measure of neuromuscular fatigue, as despite its reported high reliability this measure does not seem to show any meaningful relationships to loading constraints.

5b.6.2. CMJ:

While the influence of external load on CMJ performance has previously been examined in acute and longitudinal settings [4,17,53,66,201], this study adds value by reporting on the effect of a range of external load measures on both rate and peak measures collected during both the eccentric and concentric portion of the CMJ. Findings from this paper revealed a significant positive influence of HSR volume on F@0v, and a significant negative influence of the sum of acceleration and deceleration counts (>2.5ms) on eccentric RFD produced during the CMJ. Whilst considered significant, the magnitude of these observed effects and all other effects were not considered of practical relevance (< 0.2*between subject SD). In contrast to our findings, research by Rowell et al[66] reported an influence of external load output (Player load; low, medium, high group) on the recovery time-course of CMJ indices (Jump height, FT/CT) following 3 elite competitive soccer matches. Interestingly, this reported association between match load and NF response was only evident acutely (0.5 to 18 hour post), where subsequent longer-term responses (42 and 66 hour post) were not shown to be dependent on match load. These results give further credibility to the influence of external load on a given NF response being largely dissipated by 72 hours after competitive match-play. While not practically meaningful, the significant opposite effects observed in eccentric RFD to the sum of AccDec efforts, and F@0v to high speed running volume, may be of interest to practitioners and require future investigation. Traditionally, due the high eccentric contribution required for acceleration, deceleration and sprinting it has been reported that performing higher workloads of these actions would be associated with higher levels of muscle damage and reduced NF [31,94,202]. Indeed, the decrements observed in eccentric RFD to the sum of acceleration and deceleration load gives added support to this notion, suggesting that high intensity AccDec movements in games may cause reductions in the eccentric force producing capabilities of the muscle up to 72hours post-match play. In contrast however, an opposite effect was observed with F@0v and HSR load, with higher loads having a significant positive influence on F@0v velocity. Previous research assessing the recovery time course of this measure has shown it to be both reliable and a sensitive marker of acute fatigue [53,121], with interpretation of this measure similar to that of other eccentric markers where a fatigued state would be indicated by a reduction in force at this point [121].

Indeed, while not significant, other eccentric markers collected during the CMJ were concordant with the results observed with F@0v, giving added support of higher within-player HSR loads being associated with a positive response in subsequent NF testing. This finding, despite being only a small effect, may have important implications for practitioners when deciding on appropriate recovery and training stimulus following competitive match play

5b.6.3. Physical qualities:

Similar to the univariate responses for IMTP based measures, no significant improvements in model explainability were observed when assessing possible interaction effects of PQ's on any rate or peak measure response to external load. It is therefore possible that the limitations outlined within univariate response, such as the observed high variation in RFD and game load measures, seasonal decay masking relationships, and/or fatiguing effects from load being largely dissipated by 72 hours, have more impact versus the level of physical quality.

In contrast to IMTP responses, inclusion of LBS, LBP and V_{IFT} significantly improved model explainability for CMJ: eccentric mean power/kg, Jump Height, and F@0V respectively.

Of these measures, only baseline LBS and LBP showed a practically meaningful influence on CMJ: eccentric mean power responses to HSR and JH responses to VHSR loads when performing 1SD above within subject loads. While it is not possible to directly infer the mechanisms at which these covariates exerted their influence, a rationale for the observed effect between LBP and JH responses may be explained by the previously identified relationship between LBP and maximum speed qualities [05,10], and the use of arbitrary thresholds to identify VHSR in this study. It is possible that the threshold used for VHSR (>23km.hr^{-1}) represented a higher relative intensity for individuals with lower levels of LBP and are therefore less able to produce and tolerate accumulated running loads at this velocity, which is represented in a longer fatigue response. In contrast, players with above average levels of LBP may find VHSR less physiological demanding, and given the observations reported within this chapter, performing higher amounts of VHSR may positively influence NF function 72 hours post-match.

Similarly, the observed moderating effect of LBS on eccentric mean power responses to HSR may also be indicative of an enhanced ability to tolerate eccentric forces associated with high speed movements. While, the influence of strength levels upon NF response to load was not directly measured, Johnston et al[16] observed similar NF responses (CMJ; Peak power) between high and low strength groups (3rm Squat; Median split technique) despite the high strength group performing significantly more total distance and high speed distance (>18.3 km.hr). A moderation effect has also been observed between LBS (3rm; Trap bar deadlift) and training load on injury risk, where advanced levels of LBS showed mitigated injury risk profiles to both higher chronic loads and magnitude of load changes [91]. Interestingly, results from this chapter indicate that LBS assessed via an isometric modality (IMTP; Peak force/kg) may be a useful tool to identify an individual's ability to tolerate eccentric demands from high speed running loads.

5b.6.4. Limitations:

While this chapter was able to report on findings previously lacking in the literature, some important limitations do exist. Firstly, due to reported effects of strength and power training on both isometric and dynamic neuromuscular performance [63,71,192,203-205] the exclusion of data representing this stimulus is a limitation and future research should aim to include a representation of this load when identifying influencers on NF. Secondly, as identified within PQ's section, use of arbitrary cut off zones to identify high and very high intensity running zones may potentially over- or underestimate the intensity of these load measures for a given individual. Therefore, future research should assess whether similar findings exist when utilising individualized load threshold methods. Similar to the previous chapter, the lack of multiple assessments of aerobic capacity throughout the season limits our ability to accurately quantify the impact of this physical quality on NF. Finally, while direct assessment of central and peripheral contribution to NF remains difficult in weekly monitoring designs seen in team-based settings, the lack of a criterion laboratory-based measure of either central of peripheral fatigue limits our ability to confirm mechanisms influencing NF in this chapter. Consequently, future research is still needed to better quantify the agreement between laboratory and field-based measures of fatigue and their ability to infer contributing mechanisms.

5b.6.5. Conclusion and practical applications.

This final experimental chapter revealed that the magnitude of decay in NF response in either isometric or dynamic measures is not well explained by the dose of acute external load at 72 hours post competitive match play. Contrastingly to the findings from the previous two chapters, where rate characteristics from the IMTP gave additional insight into both acute and seasonal NF that was not identified by peak- (chapter 4) or CMJ measures (chapter 5a), findings from this chapter revealed no meaningful relationships between load and IMTP rate measures. Significant effects were observed between some CMJ measures and external load measures however the magnitude of the observed effect questions the practical relevance of the finding. Given the findings from the previous chapter, and the reported findings from this chapter, assessment of NF in both a dynamic and isometric capacity may give better inference into current NF state than one modality alone.

Similarly, to the previous chapter, inclusion of PQ’s as an interaction allowed for better explanation of the observed effects for some variables, namely LBS and LBP may better explain responses seen in CMJ measures to both HSR and VHSR loads. Importantly, dependent on baseline physical status direction and magnitude of response to different loading measures may be observed between these categories. This indeed, may have important practical applications for high performance staff when identifying appropriate training and recovery protocols.

Chapter 6: Thesis summary

In professional team sport, ever-increasing resources are being allocated to quantifying both the existence and extent of fatigue. Quantification of fatigue in particular that relates to the neuromuscular system, may provide important contextual information into an athlete's capacity to cope with a new stimulus. Hence, a continued focus on identifying test modalities and indices that allow for reliable and valid inference of neuromuscular function are being explored, with additional interest of identifying cofounding or moderating influencers on the recovery of this capacity. This thesis therefore aimed to further the current understanding of NF recovery in team-based settings by assessing the aims below.

1) Assess the practical utility and acute sensitivity of force-time measures collected from the IMTP as a measure of NF following competitive matches in elite ARF players (Chapter 4).
2) Identify whether accounting for baseline physical qualities allowed for a better description of observed seasonal trends in both dynamic and isometric measures of NF (Chapter 5a).
3) Establish the degree of association between dynamic and isometric measures of NF (Chapter 5a).
4) Identify whether baseline physical qualities moderate NF responses to within subject load changes (Chapter 5b).

As mentioned, the first aim of this thesis was to identify the sensitivity and practical utility of the IMTP as a measure of NF in team-based settings. Force-time measures collected from the IMTP have been previously assessed for its ability to identify favourable physical qualities [76,78], however limited literature examining it's utility as a measure of NF existed in team based settings.

Due to its static nature and ability to give inference into possible sites contributing to reductions in NF via assessment of RFD intervals, further examination of this test was warranted. Indeed, findings from this chapter revealed that rate characteristics (RFD 0-50 and 100-200ms) collected from the IMTP may offer additional information into neuromuscular state, versus peak measures of force production which remained unchanged at 48,72 and 96 hours post competitive match play. This finding is interesting because despite having higher week-to-week variability than peak measures, larger and longer lasting negative changes were still evident in rate measures up to 72 hours post-match. Importantly, this identification of a reduced NF state was able to be inferred from the better of two maximal contractions, which gives added credibility to the use of this test as a measure of NF within team-based settings.

Chapter 5a then looked to extend the findings from chapter 4 and examine the seasonal dynamics of rate and peak measures collected from the IMTP against CMJ measures of NF. This chapter also looked to explore whether accounting for individual physical qualities allowed for better description of seasonal trends observed across these measures. Indeed, similar to chapter 4 rate measures collected from the IMTP provided additional information into neuromuscular status over the season when compared to peak measures collected from the IMTP and CMJ indices, where no seasonal effect was observed. In particular, a moderate seasonal decay was observed with RFD 0-100ms with a similar effect also observed for 0-200ms. However, as little seasonal effect was observed for RFD 100-200ms, it is suggested that the primary reduction evident was within early phase RFD 0-100. Given the neural underpinnings that influence early phase RFD and the reported influence of resistance training on neural adaptations, it is possible that the reductions observed may be indicative of reductions in the frequency of resistance training sessions seen from pre-season to within season. It is interesting however, that this potential influence was only observed within RFD measures collected from the IMTP and not extended to CMJ based measures. Indeed, the observed seasonal CMJ responses are similar to previously reported longitudinal designs [17,189] suggesting relative maintenance of NF over a season.

It was postulated that differences in contraction duration between key measures collected from the IMTP (RFD 0-100, 0-200) and CMJ may contribute to the observed differences in seasonal responses. In particular, longer contraction durations as seen in measures assessed via the CMJ and Peak Force from the IMTP, may miss initial decrements in the ability of the neuromuscular system to produce force. Interestingly, despite being small to moderate in association strength, RFD intervals (0-100, 0-200) from the IMTP showed higher agreement with a host of CMJ variables versus peak force from the IMTP, where only trivial to small associations were observed.

This chapter also revealed little systematic influence of baseline physical qualities on observed trends throughout the season across IMTP or CMJ measures. Only inclusion of baseline lower body strength (IMTP; Peak Force/kg) as an interaction term allowed for a better description of the observed responses in that measure, where players with lower starting levels of baseline strength showed greater seasonal improvements than those with more advanced baseline levels.

Together the findings from both chapter 4 and 5a suggest that monitoring RFD windows may provide context into neuromuscular state not identified by assessment methods with longer testing durations. A key limitation of both these chapters was the exclusion of load variables. Indeed, the impact of load on NF is likely of interest to high performance practitioners and similarly to chapter 5a, an understanding of how baseline physical qualities moderate this relationship may be of interest to practitioners.

The final experimental chapter therefore aimed to assess the limitations from the previous seasonal chapter. Surprisingly, little systematic influence or meaningful impact was observed between external load variables and measures of NF from either the CMJ or IMTP. Only the volume of HSR and count of acceleration and decelerations efforts were shown to negatively influence markers of NF collected throughout the eccentric phase (F@0v and Ecc RFD) of the CMJ. The magnitude of this change however questions the sensitivity within applied settings, where within athlete load values of greater than 2SD were needed to elicit a small (0.2*between subject SD) response in NF. Interestingly, in contrast to the findings from the previous chapters where additional insight in NF was observed with inclusion of RFD variables, results from this chapter revealed no meaningfully influence of external load on any RFD measure. Possible reasons for this may be the seasonal decay evident from the previous chapter masking any effect and / or the inherit variability in both game loads and RFD measures limiting the capacity to identify meaningful relationships.

Finally, this chapter revealed that inclusion of baseline PQs as interaction terms may enhance the ability to describe observed NF responses under different loading conditions. Advanced levels of lower body strength, power and aerobic fitness all showed favourable moderating influences on some measures of NF responses to external load. In particular, advanced levels of lower body strength and power may meaningfully influence the direction of NF response following a given dose of external load. For example, favourable NF (CMJ: eccentric mean power) responses were observed in players with advanced lower body strength when performing higher amounts of within-player high-speed running. Similar findings were also observed in players with greater baseline lower body power where favourable NF responses (CMJ: JH) were observed when performing higher amounts of VHSR. These findings may have important implications for practitioners when inferring an expected NF response to a given external load, where the direction of NF recovery may be dependent of both the load performed but the baseline physical quality of an athlete.

Together the experimental chapters revealed that identifying true NF status is difficult and may be influenced by testing modality (isometric vs dynamic), measure of NF (rate vs peak), time of the season, external load and physical qualities. A complex interaction between these effects on NF responses is likely evident and indeed a host of other latent structures not reported on in this thesis also likely contribute to a given NF response such as age, resistance training volume, internal load and subjective wellbeing. This is supported by the relatively small systematic improvement in model explainability across NF measures when accounting for load and PQ's, suggesting that other potential influencers should also be explored. Despite this, an understanding of an athlete's baseline physical qualities, time of season and match loads may still be important considerations when identifying the expected impact of match loads on the subsequent fatigue response.

6.1. Practical applications

Based on the summary findings from this thesis, several practical recommendations may be of interest to practitioners.

1) Force time measures collected from the IMTP may offer a viable solution to the assessment of neuromuscular function in team-based settings, with potential inference being made available from the better of 2 maximal contractions.

2) In particular rate measures, monitoring of RFD 0-100, RFD 100-200 and RFD 0-200ms may give additional insight into current neuromuscular function that are not identified within peak measures of capacity in dynamic or isometric measures.

3) Despite the inherit variability associated with RFD, magnitudes of decay may be large enough to warrant investigation following acute match play within a group level response. The ability to identify individual level responses for RFD however may be limited, and reliable inference may require measurements over several collections to be confident of a change in function.

4) 72 hours following competitive match play may be indicative of a period during the recovery time-course where both high between-subject and within-subject variability exist, and may represent an appropriate day for NF testing in elite AFL athletes.

5) Maintenance of seasonal neuromuscular function may be dependent on the method or measure used to identify neuromuscular function. Therefore, if plausible monitoring of both isometric and dynamic measures of NF should be considered within elite team-based settings. In particular, monitoring of early phase RFD (0-100ms) from isometric assessment may give additional insight into neural mechanisms of NF that are not captured in other variables collated from the CMJ and IMTP.

6) Consideration of baseline physical qualities, in particular lower body strength and power may allow for a more accurate description of neuromuscular response considering both the time within-season and match load preceding assessment. In particular, advanced levels of lower body strength and power may facilitate improved tolerance of higher doses of external work, which may expedite NM recovery.

6.2. Limitations and recommendations of future research:

While this research has extended on the current literature in NF responses following competitive match play, further research building on the concepts discussed and limitations within this thesis would be of additional benefit to practitioners:

1) Throughout this thesis the IMTP was used as the key isometric measure of NF, while findings from this thesis give support to the use of this test, the need for a specialized rig design for scalable testing may represent a limitation to easy adoption in team-based environment.

Additionally, as it has been suggested that multi-joint isometric assessment as seen with the IMTP may increase potential for noise [12], future research should continue to explore other isometric modalities of testing that may require less additional equipment and reduce the degrees of freedom.

2) Given the acute reductions and high variability observed in RFD in the first experimental chapter, future within-subject designs with larger sample sizes are needed to confirm these results. Secondly, the lack of a criterion measure or other commonly used field-based assessments of neuromuscular function to compare and contrast the findings observed in this chapter is a limitation and should be a focus of future research.

3) Within chapters 5a and 5b certain statistical limitations and assumptions existed which may not best describe the true response within these models. Firstly, all univariate and interaction effects were assumed to be linear in nature, and secondly, these chapters lacked appropriate power to assess the influence of two-way interactions of physical qualities (e.g. lower body strength and fitness) on both seasonal and external load influence on NF responses.

Indeed, while sample sizes required for modelling of nonlinear multilevel interaction terms can exceed numbers often seen in team-based settings, factors such as increasing precision of measurement, numbers of trials of both NF and physical quality testing, and/or multi-centre or multi-seasonal approaches may offer potential strategies for designing appropriately powered studies to detect these complex relationships.

4) As just mentioned, increasing the frequency of testing of physical qualities may allow for a more accurate understanding of the moderating influence exerted on recovery of NF. While multiple measurements of both lower body strength and power were utilised to identify baseline levels within chapters 5a and 5b, aerobic endurance was estimated from only one maximal attempt during the pre-season. This represents a limitation in accurately estimating the potential influence of this variable on NF recovery where previous research has suggested an influence [16]. Indeed, measuring maximal aerobic capacity multiple times throughout a season may represent a challenge in applied settings. Utilising other monitoring estimates such as prior loading history or submaximal estimates of aerobic fitness (e.g. heart rate recovery test, submaximal ramp tests) may represent a potential approach to inferring aerobic fitness without the need for multiple maximal assessments. Further research however would be needed to examine these strategies.

5) While the influence of external load on NF responses was explored within chapter 5a/5b, the key measure of load here was based on volume and intensity measures collected from GPS. While in line with common practice seen in this field, monitoring of load via these external load measures alone, likely limits the ability to explain observed NF responses. In particular, as resistance training-based methodologies have shown to influence both force and rate characteristic adaptations, its exclusion as potential moderating influence is a limitation. Though methods for monitoring resistance training load have been previously proposed [206] , recent increases in technology including software database systems and measures of intent throughout training (velocity based assessment) may allow for easier quantification and monitoring of volume and intensity measures throughout resistance training sessions. Future research assessing NF should therefore aim to include measures assessed within resistance-based training session.

6) As previously identified in the literature [6,123], a focus on giving context to the effect of NF on skill related key performance indicators may allow for furthered relevance across key stakeholders within team-based settings e.g. coaches, sport scientists, medical staff. Therefore, future research assessing NF via isometric assessment should aim to identify the implications of NF state across other relevant key performance indicators.

7) Finally, the practical utility of laboratory measurements of NF, including central and peripheral based stimulation techniques, remain difficult within team-based sports. The lack of a criterion measure of NF limited our ability to support proposed mechanisms or sites contributing to fatigue. Future research should therefore continue to explore potential strategies to better quantify the agreement in responses between laboratory and field-based recovery of neuromuscular function.

6.3 Final remarks

Gaining insight into an athlete's neuromuscular function continues to be of interest to high performance staff in team-based settings. Current methodologies for assessing neuromuscular function have shown mixed results between acute and longitudinal designs and, may allow for limited inference regarding the origins contributing to decrements in neuromuscular function. Additionally, a limited understanding of factors which may influence NF following competitive match play also existed.

This thesis therefore aimed to give a further insight into these limitations by assessing two modalities of neuromuscular function (isometric and dynamic) whilst also examining moderating influences of external load and physical qualities in acute and longitudinal designs. Indeed, findings from experimental chapters reveal that inferring neuromuscular function may depend upon which modality of testing is used, the stage of the season, and baseline physical qualities. Additionally, an interaction may exist between baseline physical qualities and certain external load measures, where in particular enhanced lower body strength and power may favourably influence the relationship between load and NF. Therefore, it is suggested that assessment of both dynamic and isometric measures of neuromuscular function may give a more holistic understanding of current capacity versus one test alone. Development of physical qualities likely also exert favourable effects on recovery of neuromuscular function and should be a continued focus of development in high performance settings. Importantly, this thesis has highlighted the complexity in inferring neuromuscular responses following competitive match play, and it is clear that continued research is needed within this area to better understand the recovery process of NF.

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APPENDIX

i) Ethics Approval

ii) Information forms

iii) Initial Communication

iv) Additional stats

APPENDIX i)ALocked Bag 1797
Penrith NSW 2751 Australia
Research Engagement, Development and Innovation (REDI)

REDI Reference: H11987
Risk Rating: Low 2 - HREC

HUMAN RESEARCH ETHICS COMMITTEE

15 March 2017

Doctor Richard Lovell
School of Science and Health

Dear Richard,

I wish to formally advise you that the Human Research Ethics Committee has approved your research proposal H11987 “Factors influencing recovery of Neuromuscular function post Australian Rules football matches“, until 31 December 2018 with the provision of a progress report annually if over 12 months and a final report on completion.

In providing this approval the HREC determined that the proposal meets the requirements of the National Statement on Ethical Conduct in Human Research.

This protocol covers the following researchers: **Richard Lovell, Jason Siegler, Dean Norris**

Conditions of Approval

1. A progress report will be due annually on the anniversary of the approval date.
2. A final report will be due at the expiration of the approval period.
3. Any amendments to the project must be approved by the Human Research Ethics Committee prior to being implemented. Amendments must be requested using the HREC Amendment Request Form: https://www.westernsydney.edu.au/__data/assets/word_doc/0012/1096995/FORM_Amendment_Request.docx
4. Any serious or unexpected adverse events on participants must be reported to the Human Research Ethics Committee via the Human Ethics Officer as a matter of priority.
5. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the Committee as a matter of priority
6. Consent forms are to be retained within the archives of the School or Research Institute and made available to the Committee upon request.

7. Project specific conditions:
There are no specific conditions applicable.

Please quote the registration number and title as indicated above in the subject line on all future correspondence related to this project. All correspondence should be sent to the e-mail address humanethics@westernsydney.edu.au as this e-mail address is closely monitored.

Yours sincerely

Professor Elizabeth Deane
Presiding Member,
Western Sydney University Human Research Ethics Committee

ppendix

APPENDIX ii)

School of Science and Health

Information for Participants

Project title

"Assessing the validity and reliability of the Isometric Mid-Thigh Pull as a measure of Neuromuscular Fatigue in elite Australian Rules Football players”

Who is carrying out the study?

You are invited to participate in a study conducted by the following listed researchers from the School of Science and Health.

- Mr Dean Norris (PhD candidate)
  University of Western Sydney – School of Science & Health

  Ph: 0434 109 172 Email: dean.norris@gwsgiants.com.au

- Dr Ric Lovell (Senior Lecturer and Researcher)
  University of Western Sydney – School of Science & Health

  Ph: 02 4620 3304 Email: r.lovell@uws.edu.au

- A/Prof Jason Siegler (Senior Lecturer and Researcher)
  University of Western Sydney – School of Science & Health

  Ph: 02 4620 3381 Email: j.siegler@uws.edu.au

- Mr David Joyce (GWS High Performance Manager)
  GWS Giants – Athletic Performance Unit

  Ph: - Email: David.Joyce@gwsgiants.com.au

What is the study about?

This document provides information to potential participants for a research project examining the acute effects of an AFL match on muscular force and blood related markers of muscle damage.

Details regarding the specific requirements of participants, potential risks and benefits and other information are contained below.

Note: To be eligible to participate in this research you must:

- Pass a pre-exercise health screening.
- Be free from injury which may adversely affect your performance or ability to complete required tasks.
- Currently be participating at an Elite level of AFL Football.
- Be aged between of 18 - 35 years of age.

What does the study involve?

Experimental testing will take place at the Great Western Sydney Giants Training Facility – Homebush.

As a participant you will be required to wear team training kit. Firstly you will be asked to perform a brief warm-up to prepare you for the exercise tasks. Initially you will be give 2 warmup repetitions of the Isometric Mid-Thigh Pull (see figure below) to examine how your body reacts.

This exercise requires you to stand on a force plate. You will then bend at the hips and knees to lower your hands to hold on the bar which will positioned roughly at your Mid-thigh. You will then be asked to pull the bar as fast and as hard as you can whilst staying in a static position for 3 seconds.. During this contraction, we will measure how much force is measured over periods of time. It is expected that this testing procedure will take 3minutes.

Secondly a pinprick of capillary blood will be required from your fingertip, this will be performed by one of the principle researchers (pic 2)_. This blood sample will be used to identify blood measures of muscle damage. We expect this to take 2-3minutes of your time.

How much time will the study take?

As a participant you will be required for approximately 10 minutes a day for a *total of 12 days over a 4 week period*.

Will the study benefit me?

The information collected from this study will give insight into your individual recovery rate post competition. Each participant will be given a individual recovery profile from the results of this study. The risk associated with the experimental protocol for this research is considered minimal to low. The Isometric Mid-Thigh Pull which may give symptoms acute fatigue lasting for up to 3 minutes. Similarly, collection of the capillary blood sample may cause some minor discomfort for 3 -5 seconds and be associated with low to negligent levels of bleeding for the following 2miutes. If you meet the eligibility criteria for this research you are considered to be at low risk of injury as you will be regularly exercising at or beyond the intensity required during the test trials.

All trials will cease immediately if at any time you are feeling ill, are uncomfortable, sustain an injury or voluntarily decide not to continue participating. Nonetheless, every effort will be made to minimise any associated risk to the participant risk by:

- Evaluation of preliminary information relating to your health & fitness;
- Continuous monitoring of your physiological response to the exercise task
- Observation of your technique during the experimental trials.
- Having all necessary medical first aid equipment on standby.

In the unlikely event that injury does occur during the testing, the attending researchers will initiate an appropriate first aid treatment and action plan.

How is the study being paid for?

This research project is funded by the Greater Western Sydney Giants and Western Sydney University. Your involvement in this project will be on the basis of an unpaid volunteer, participation will be at no additional cost to you and the researchers will try to ensure the experimental testing will cause minimal inconvenience to you.

Will anyone else know the results? How will the results be disseminated?

All aspects of the study, including results, will be confidential and only the researchers will have access to information on participants except as required by law. As a participant, all information collected from you will be coded by numbers and lettering and stored separately from any listing that includes your name to ensure the maintenance of privacy and confidentiality. Throughout this investigation all data will be securely maintained in the possession of Mr Dean Norris (Principal Researcher).

Furthermore, your personal details and data will not be released or revealed to any other party without your written consent. The de-identified and aggregated results from this investigation are intended to be used for publication in a scientific domain (presentation and journal publication). You are assured that this will be achieved whilst maintaining your right to privacy and confidentiality. Data may be used for further publications or investigations in the future.

Can I withdraw from the study?

Participation is entirely voluntary. You are not obliged to participate and if you do participate you can withdraw at any time without giving any reason. Whatever your decision there will be no consequences and it will not affect your relationship with the researchers or the club in any way. This includes any perceived impact between or on the player – researcher and coach relationship.

Can I tell other people about the study?

Yes, you can tell other people about the study and provide them with researcher contact details. They are then welcome to contact one of the researchers to discuss their potential participation in the research project and obtain the information sheet.

What if I require further information?

When you have read this information Mr Dean Norris, Dr Ric Lovell, Dr Jason Siegler and Mr David Joyce will discuss it with you further and answer any questions you may have. If you would like to know more at any stage please feel free to contact any of the above mentioned researchers from the information on the first page.

What if I have a complaint?

This study has been approved by the University of Western Sydney Human Research Ethics Committee. The Approval Number is……….

If you have any complaints or reservations about the ethical conduct of this research, you may contact the Ethics Committee through the Office of Research Services (Ph: +61 2 4736 0229 or Fax +61 2 4736 0013; Email: humanethics@uws.edu.au).

Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome. If you agree to participate in this study, you may be asked to sign the Participant Consent Form.

The information sheet is for the participant to keep and the consent form is retained by the researcher.

Appendix ii)

WESTERN SYDNEY
UNIVERSITY

School of Science and Health

Information for Participants

Project title

Factors influencing Recovery of Neuromuscular Function post Australian Rules football matches.

Who is carrying out the study?

You are invited to participate in a study conducted by the following listed researchers from the School of Science and Health.

- Mr Dean Norris (PhD candidate – Principle Researcher)
  University of Western Sydney – School of Science & Health

  Ph: 0434 109 172 Email: dean.norris@gwsgiants.com.au

- Dr Ric Lovell (Senior Lecturer and Researcher)
  University of Western Sydney – School of Science & Health

  Ph: 02 4620 3304 Email: r.lovell@uws.edu.au

- A/Prof Jason Siegler (Senior Lecturer and Researcher)
  University of Western Sydney – School of Science & Health

  Ph: 02 4620 3381 Email: j.siegler@uws.edu.au

- Mr David Joyce (GWS High Performance Manager)
  GWS Giants – Athletic Performance Unit

  Ph: - Email: David.Joyce@gwsgiants.com.au

What is the study about?

This study aims to identify what factors influence recovery of muscular force output (Neuromuscular Function) post Australian Rules football matches.

Details regarding the specific requirements of participants, potential risks and benefits and other information are contained below.

Note: To be eligible to participate in this research you must:

- Pass a pre-exercise health screening questionnaire.
- Be free from injury which may adversely affect your performance or ability to complete required tasks.
- Currently be participating at an Elite level of AFL Football.
- Be aged between of 18 - 35 years of age.

What does the study involve?

Experimental testing will take place at the Great Western Sydney Giants Training Facility – Homebush.

As a participant you will be required to wear team training kit. Firstly you will be asked to perform a brief warm-up to prepare you for the exercise tasks. Initially you will be give 2 warmup repetitions of the Isometric Mid-Thigh Pull (see figure below) to examine how your body reacts. If any pain exist on warmups the trial will be stopped immediately.

This exercise requires you to stand on a force plate. You will then bend at the hips and knees to lower your hands to hold on the bar which will positioned roughly at your Mid-thigh. You will then be asked to pull the bar as fast and as hard as you can whilst staying in a static position for 3 seconds. You will be required to perform two repetitions of this movement with a two minute recovery between bouts. During this contraction, we will measure how much force is measured over periods of time. It is expected that this testing procedure will take 3-5minutes.

Information collected from preseason and midseason testing of physical qualities along with physical output as measured by GPS units from competition will be collected for analysis and use of this paper.

How much time will the study take?

As a participant you will be required for approximately 5 minutes once a week, 3 days after Elite Australian Rules competition for a maximum of 26 weeks.

Will the study benefit me?

The study aims to further knowledge of human performance with results potentially influencing future research questions and directions. This process may give valuable insight into important recovery measures post an Australian Football game.

The risk associated with the experimental protocol for this research is considered minimal to low. The Isometric Mid-Thigh Pull exercise requires a maximum amount of effort though over a short period of time. This has the potential to give symptoms acute fatigue lasting for up to 3 minutes. This fatigue will alleviate after this time and there is a very low risk of any permanent muscle damage. If you meet the eligibility criteria for this research you are considered to be at low risk of injury as you will be regularly exercising at or beyond the intensity required during the test trials.

All trials will cease immediately if at any time you are feeling ill, are uncomfortable, sustain an injury or voluntarily decide not to continue participating. Nonetheless, every effort will be made to minimise any associated participant risk by:

- Evaluation of preliminary information relating to your health & fitness;
- Continuous monitoring of your physiological response to the exercise task
- Observation of your technique during the experimental trials.

In the unlikely event that injury does occur during the testing, the attending researchers will initiate an appropriate first aid treatment and action plan

How is the study being paid for?This research project is funded by the Greater Western Sydney Giants and Western Sydney University. Your involvement in this project will be on the basis of an unpaid volunteer, participation will be at no additional cost to you and the researchers will try to ensure the experimental testing will cause minimal inconvenience to you.

Will anyone else know the results? How will the results be disseminated? All aspects of the study, including results, will be confidential and only the researchers will have access to information on participants except as required by law. As a participant, all information collected from you will be coded by numbers and lettering and stored separately from any listing that includes your name to ensure the maintenance of privacy and confidentiality. Throughout this investigation all data will be securely maintained in the possession of Mr Dean Norris (Principal Researcher).

Following completion of the study, all information collected for, used in or generated by this project will be disposed of after 5 years.

Furthermore, your personal details and data will not be released or revealed to any other party without your written consent. The de-identified and aggregated results from this investigation are intended to be used for publication in a scientific domain (presentation and journal publication). You are assured that this will be achieved whilst maintaining your right to privacy and confidentiality. Data may be used for further publications or investigations in the future. Therefore it will not be possible for individual participants to be identified in any publications arising from this study. .

Can I withdraw from the study? Participation is entirely voluntary. You are not obliged to participate and if you do participate you can withdraw at any time without giving any reason. Whatever your decision there will be no consequences and it will not affect your relationship with the researchers or the club in any way. This includes any perceived impact between or on the player – researcher and coach relationship.

Can I tell other people about the study? Yes, you can tell other people about the study and provide them with researcher contact details.

What if I require further information?

When you have read this information Mr Dean Norris, Dr Ric Lovell, Dr Jason Siegler and Mr David Joyce will discuss it with you further and answer any questions you may have. If you would like to know more at any stage please feel free to contact any of the above mentioned researchers from the information on the first page.

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Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome. If you agree to participate in this study, you may be asked to sign the Participant Consent Form.

The information sheet is for the participant to keep and the consent form is retained by the researcher.

APPENDIX iii)

WESTERN SYDNEY
UNIVERSITY

Dear GWS Team,

We are interested in understanding how quickly you recover from
a match. From here, we hope to be able to understand what factors make you a quick (or slow) recoverer. In turn, we hope that this information may help us develop more individualized training plans for you.

To explain how we hope to answer these questions an educational seminar before the afternoon training session block at 1pm. This seminar will roughly take 10 minutes of your time where we will go through the following.

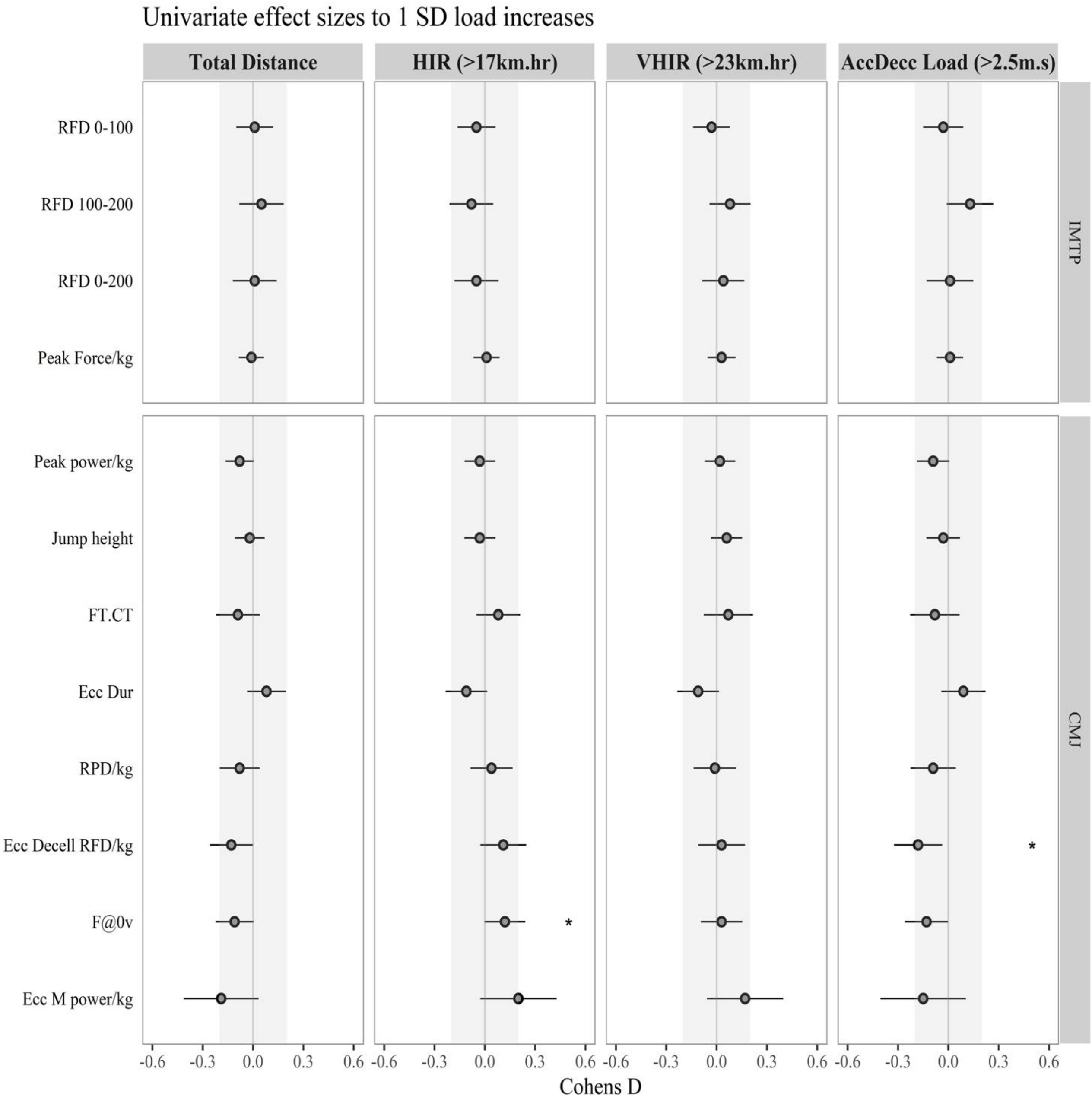
1) What would be required of you
2) How to get involved
3) answering any questions you may have

Please note that this is not a compulsory seminar to attend and no attendance record will be taken. Secondly, if you are unable to make it and what further information please feel free to email another of the following people below.

Thank you for your time.

ric.lovell@westernsydney.edu.au
Dean.norris@gwsgiants.com.au
David.joyce@gwsgiants.com.au

APPENDIX IV)


Univariate effect sizes to 1 SD load increases
Total Distance
HIR (>17km.hr)
VHIR (>23km.hr)
AccDecc Load (>2.5m.s)
IMTP
CMJ
RFD 0-100
RFD 100-200
RFD 0-200
Peak Force/kg
Peak power/kg
Jump height
FT.CT
Ecc Dur
RPD/kg
Ecc Decell RFD/kg
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