Monitoring wellness, training load and neuromuscular performance:

Implications for assessing athlete training status

By

Wayne Lombard

MPhil (Bio), BSpSc (Hons), CSCS, RSCC

(LMBWAY001)

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Supervisor:

Prof. Michael I. Lambert, *PhD*

HUB
Department of Human Biology
Physiological Sciences

UNIVERSITY OF CAPE TOWN
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“Education is not the learning of facts, but the training of the mind to think”

— **Albert Einstein** —

Declaration

I, **Wayne Lombard,** hereby declare that the work on which this dissertation is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other university.

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Signed by candidate

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Definitions of terms

For the following working definitions, I do acknowledge some of the current conjecture round the use of the term's "load", "work", "bodyload" and "playerload" to name a few. However, for the purpose of this thesis I have opted to use these definitions as they are still commonly used within the field of sports and exercise science[1].

1. **Bodyload:**

   Is an arbitrary measurement of a player's external mechanical stress. It is calculated as the sum of all accelerations, decelerations, changes of direction as well as impacts a player accumulates over a period (i.e., training or match).

2. **Fitness and fatigue relationship:**

   A bout of exercise training has two consequences; 1) fitness which represents a positive physiological response, and 2) fatigue which is a negative physiological response to training.

3. **Motivation-to-train:**

   Subjective rating of an individual's psychological and physiological internal drive *to train or compete.*

4. **Neuromuscular training status:**

   An athlete's objective neuromuscular profile as determined through either improvements or decrements in countermovement jump performance.

5. **Readiness-to-train:**

In general, the recovery from the previous training sessions and 'readiness' for subsequent training sessions may affect the training response. In this thesis readiness-to-train is represented by an accumulative subjective score out of 35. The score comprises various wellness questions incorporating, fatigue, stress, sleep, mood, recovery, motivation-to-train, and general muscle soreness.

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Publications associated with this thesis

Sections of the following published papers have been included in Chapters 3 and 4.

Chapter Three:

Wayne Lombard; Sorrel Reid, Keagan Pearson & Michael Lambert; **Reliability of metrics associated with a counter-movement jump performed on a force plate**; Measurement in Physical Education and Exercise Science Journal 2017, Vol 21, No 4, 235-243; http://doi,org/10.1080/1091367X.2017.1354215

Author contributions:

1. **WL:** Primary researcher, Study plan, data collection, data analysis and manuscript preparation
2. **SR:** Data collection, data analysis
3. **KP:** Data collection, data analysis
4. **ML:** Primary supervisor, data analysis, manuscript preparation

Chapter Four:

Wayne Lombard; Lindsay Starling, Luke Wewege & Michael Lambert; **Changes in countermovement jump performance and subjective readiness to train scores following a simulated soccer match**; European Journal of Sports Science 2020, Vol 14, No 2, 1-9; https://doi.org/10.080/17461391.2020.1757764

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1. **WL:** Primary researcher, Study plan, data collection, data analysis and manuscript preparation
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4. **ML:** Primary supervisor, data analysis, manuscript preparation

Abstract

Background: Athletes training for peak performance have periods of systematic overload followed by recovery. The balance between overload and recovery is important to avoid unexpected fatigue or underperformance. The relationship between overload and recovery is unique for each athlete. Thus, programmes designed to monitor fitness and fatigue should consider the inter-athlete differences.

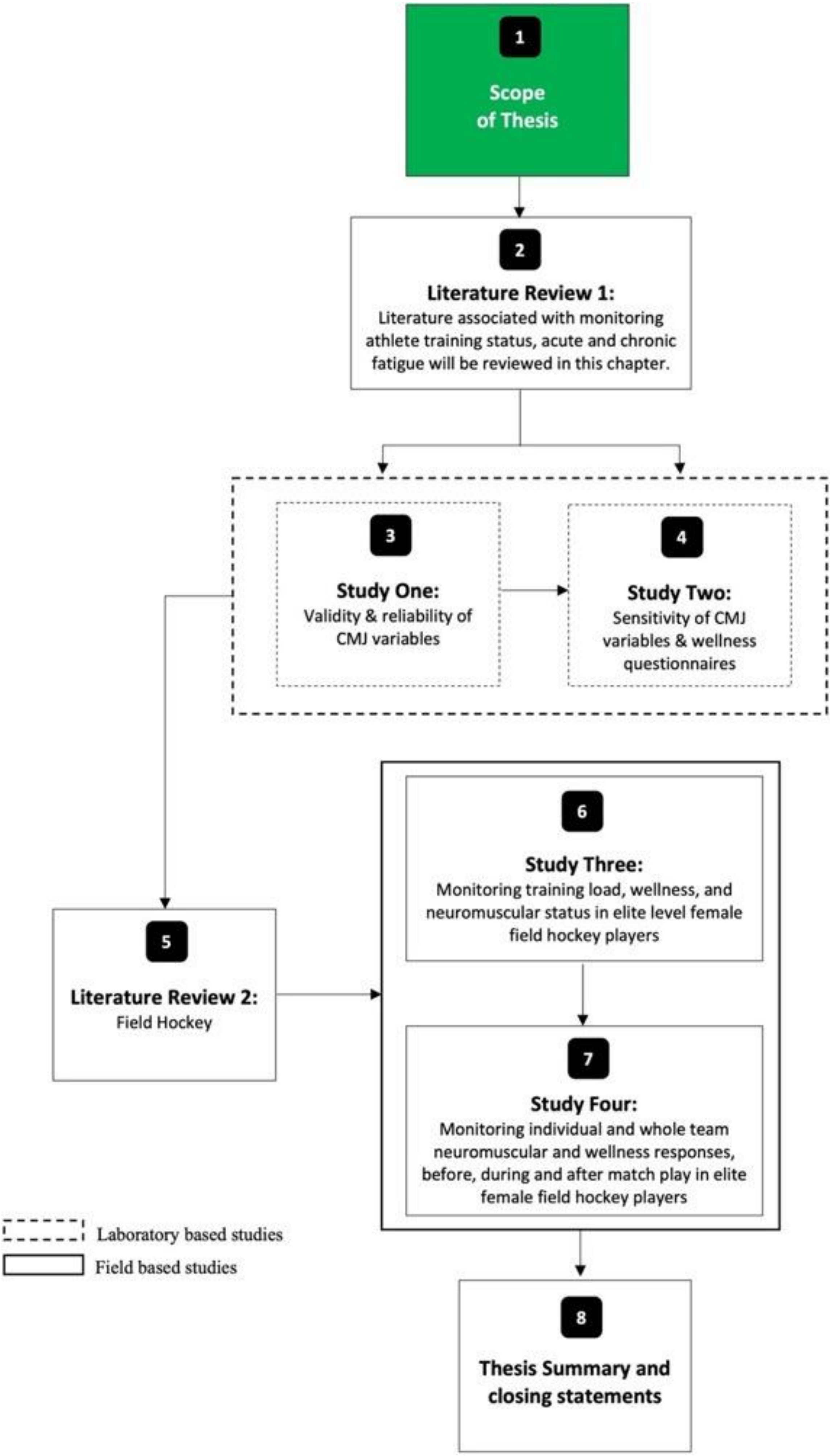
Aim: The broad aim of the PhD thesis was to assess the relationships between various tools for monitoring fitness and fatigue in elite level athletes. Subjective and objective training/match demands, questionnaires to assess wellness and readiness-to-train as well as countermovement jump variables to assess neuromuscular performance were investigated within 4 inter-related studies.

Methods: Four inter-related studies were designed to determine; 1) the validity and reliability of countermovement jump variables measured on a force plate in the laboratory; 2) the relationships between countermovement jump variables, responses to a wellness and readiness-to-train questionnaire and exercise-induced fatigue in the laboratory; 3) the relationships between training load, responses to a wellness and readiness-to-train questionnaire and neuromuscular performance in elite level female field hockey athletes measured in a “real-world” situation, and 4) the relationships between these same variables for each athlete and whole team before, during and after international match play.

Primary findings: The findings for each inter-related study were as follows; 1) Maximum force, rate of force development, jump height, flight time and time to maximum force, as measured on a force plate during a countermovement jump were valid and reliable. The typical error of measurement was defined for each variable.

The validity and reliability were best in participants who had more strength training experience. In most cases the precision of the variables was sufficient to detect "*small*" changes. 2) Subjective measures (wellness questionnaire) were more sensitive to acute exercise-induced fatigue compared to objective measures of neuromuscular performance; 3) The relationship between variables differed between players. Multiple variables should be collected to better understand a player's subjective and objective fitness and fatigue status in response to subjective and objective measures of match and/or training demands; 4) Pre, intra and post-match related data should be collected to better understand individual player responses between matches. Variables such as jump height, rating of perceived exertion, total distance during the match, bodyload (a derived measure of the total external mechanical stress from accelerations, decelerations and change of direction) and subjective wellness should be considered when monitoring athlete training status.

Conclusions: Firstly, there is no set standard battery of tools that can be used to monitor fitness and fatigue of athletes as the relationship between variables is not consistent between athletes. Variables such as jump height, rating of perceived exertion, total distance, bodyload and wellness responses should be considered in a monitoring system. Secondly, this thesis proposes the novel concept of "monitoring specificity". This suggests that different tools, based on their responsiveness, should be used at an individual level. Thirdly, identifying which athletes are most sensitive to certain variables will reduce the "noise" within a team's monitoring system. This will enable better informed decisions to be made about the athlete's fitness/fatigue status.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1. Chapter One:

Scope of Thesis

1.1 Introduction

Elite level athletes are required to train hard to improve their performance. Consequently, athletes, but even more so sporting organisations have started utilizing the services of exercise scientists to monitor them daily, to ensure that their training programmes are appropriately structured[2]. Training for peak performance requires the athlete to be systematically overloaded to induce adaptations associated with performance[3]. Athletes must avoid a prolonged imbalance between training stimuli and recovery to avoid underperformance and an increased risk of injury[2,4,5] . Hence, the relationship between training stimulus (training load) and recovery (individual responses) is essential for developing peak performance[6]. Athletes respond differently to a similar dose of exercise, therefore, the relationship between training stimulus and recovery is unique for each athlete[7].

During the process of manipulating overload and recovery, athletes may be exposed to various phases of training, which include 1) a phase of functional overreaching, in the off-season, where training loads and intensities are generally at their highest, 2) taper (before a phase of competition) 3) competitive phase 4) and an active rest phase, (after a phase of competition)[8].

The concept of monitoring variables associated with training load and the athletes' response is important. These data identify any deviations from expected responses and based on the context the training programme can be adjusted. The long-term consequences are that the risk of undertraining and overtraining can be reduced[2,9].

Exercise affects the whole-body homeostasis, leading to a wide spectrum of physiological disturbances, which require multiple integrated responses to maintain homeostasis and recover or even get better (i.e., supercompensation)[10]. There are several factors that contribute to an athlete's adaptation or maladaptation to a training dose (whether that be an acute or chronic dose). Examples of factors associated with the training programme include the psychological state of the athlete, nutritional factors, recovery, and sleep[11–13]. Therefore, the process of monitoring variables associated with training through subjective questionnaires and objective measurements has become popular in a high-performance environment. Commonly used objective markers include heart rate recovery after exercise, heart rate variability (HRV), time-to-completion tests, performance tests for peak power output (e.g., countermovement jump) and biochemical measures (e.g., testosterone vs. cortisol ratios)[2,14,15]. Monitoring these variables provides data for making informed decisions about training prescription and early identification of athletes with maladaptation or super-compensatory patterns.

With the advancement of technology in elite sport, it is now possible to use subjective and objective tools to monitor athlete training responses on a daily basis with minimal intrusion on their training or time. The goal being to use the data to manage an athletes' training more specifically[16–18]. The interpretation of the data remains speculative when analysed on an isolated basis (i.e., only using one monitoring tool) as the relationships between the variables are unclear. A more contemporary approach is to analyse more than one variable, usually a subjective variable (e.g., Wellness questionnaires) and an objective marker (e.g., Countermovement jump) to better understand the individual athlete dose response relationship in an individual or team training environment.

The development of a monitoring protocol for elite level athlete to assess their training status would be helpful for both coaches as well as high performance support staff. A longitudinal study assessing the relationship between training loads, athlete wellness questionnaires as well as neuromuscular performance would bode well for further insight into practical monitoring strategies in elite sport. Furthermore, scarce research is available from a real-world setting involving elite level female athletes. Thus, data associated with this specific cohort will prove novel and useful for all involved with elite sports athletes. Furthermore, the individualised approach of the data analysis within this thesis is novel and leads to the importance of the concept of monitoring specificity that will be discussed within the individual studies conducted.

1.2 Research questions

1.2.1 Question 1

Establishing the validity and reliability of various countermovement jump variables while using a force plate.

The validity and reliability of countermovement jump variables, through identifying the technical error of measurement and intra-class correlation coefficient for participants of varying training age are explored in detail in Chapter Three.

1.2.2 Question 2

Are countermovement jump variables and responses to subjective wellness questions sensitive enough to detect changes induced by acute exercise fatigue.

The responsiveness of countermovement jump variables and responses to subjective wellness questions, to acute exercise fatigue are explored in detail in Chapter 4.

1.2.3 Question 3

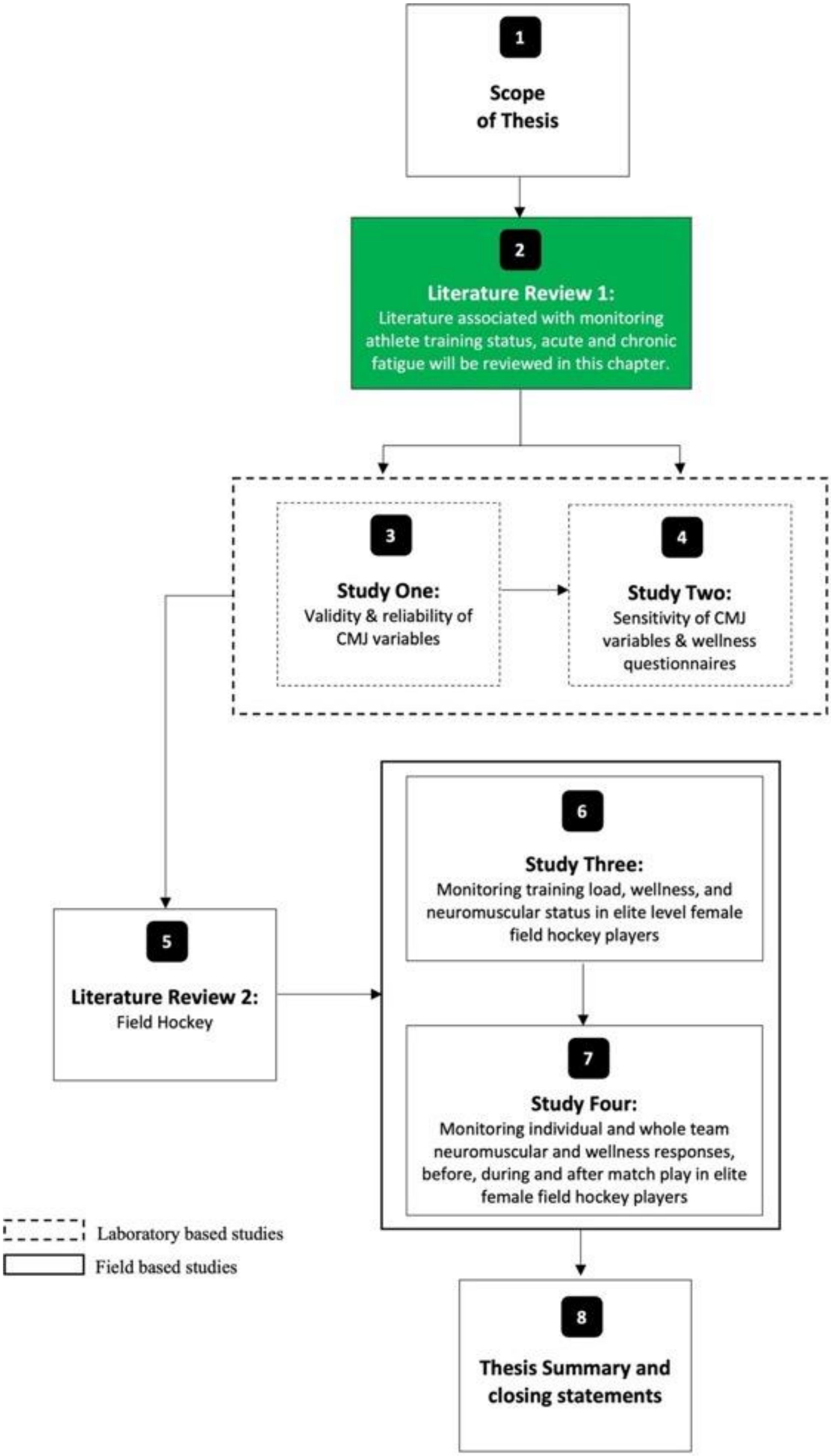
Understanding the intra-individual relationships between training load, wellness, and neuromuscular performance in female athletes in a real-world elite level sporting environment. How do these relationships help support staff understand players readiness-to-train?

A detailed analysis of various intra-individual relationships of each monitoring tool were explored in Chapter Six.

1.2.4 Question 4

How can monitoring data be used to inform decision-making before, during and after match play in elite level field hockey players?

The intra-individual relationships between various monitoring tools before, during and after match play are explored in Chapter Seven.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2. Chapter Two

Literature Review

2.1 Challenges in managing the training, fatigue, and adaptations of high-performance athletes

Sport scientists, strength and conditioning specialists and exercise physiologists have been interacting with high-performance athletes for many years (for ease of use they will be referred to collectively as high-performance support staff). Their roles within team sport environments vary depending on the country and sport in which they work. In many countries and sporting disciplines they may not be considered an integral part of the athletes' support system. Moreover, once these high-performance practitioners find their way into a team environment, their ability to apply the science of their craft practically may be hindered by the head coaches more "traditional" beliefs. Additionally, many high-level teams invest in new technologies with "fancy" interfaces which in most cases measure variables which have not undergone scientific scrutiny. In such cases emphasis is placed on the measurements of the new technology at the neglect of fundamental aspects such as individuality, human relationships, content and context, cultural beliefs to name a few[19].

In a recent opinion piece by Le Meur and Torres (2019), they outlined 10 challenges facing high performance staff[19]. Although it is beyond the scope of this section to detail all 10 challenges, highlighting a few pertinent aspects from this paper may prove useful. For example, it is important to understand the context of the environment of the team and questions the coaches want answered. Responses to these questions need to be communicated to the coaches and players in a meaningful manner. Many high-performance staff make the mistake of "science dumping" on their teams. Coaches and players generally do not understand the science jargon, therefore communicating the science in a practical way is important. This leads into the next concept. High-performance staff need to develop trust and support of the coaching staff and the players. Once the trust has been developed the ability to make a positive impact is greater. The last concept is to keep the message simple. Too often the numerous sources of data are not integrated and communicated in a meaningful way. Thus, doing the "simple things savagely well" should be the mantra of all high-performance staff to ensure they maximise their impact in the teams they are working[19].

Lastly, it is important to understand that the environments of team sports are generally chaotic in nature. However, this is paradoxical, because in amongst the chaos we can make assumptions and predictions with relative accuracy to aid in performance enhancement[20]. Thus, we need to be able to assess, plan, re-assess and adjust at all times. By collecting data and monitoring players simply and effectively on a daily basis, high performance staff are able to find some degree of "stability" within the "chaotic" environment. These types of data serve as identifiers of adaptation or maladaptation of individuals within a complex ecosystem. A primary aim of offering practical and implementable feedback to coaches is to ensure the health and performance of the athletes are upheld. Finding the "art" within the science allows high performance staff to build that trust and support of the coaches which is needed to make meaningful changes.

Thus, the purpose of this underlying section, is to present the various pieces of a complex ecosystem, known as high performance sport. By understanding how each piece fits in to the next, high-performance staff can build and adjust the content according to the context in which they work.

2.1 Periodisation strategies for high performance athletes

Training organization or periodisation has been a fundamental process in the success of highly competitive modern-day sports[8]. However, the concept of periodisation is not new and has been around since the ancient Olympic games[21]. The trainers from the Soviet Union laid the foundations of modern-day periodisation by suggesting dividing stages of training into general, preparatory and specific stages[21,22]. However, around these fundamental principles there are different periodisation strategies[23]. A traditional periodisation model allows for long-term planning, intertwined with short-term goals for multiple peak performances in individual athletes. The model for team sport athletes caters for the demand of having to maintain peak performance for prolonged periods due to competition or league-based formats. Other models must cater for athletes who are required to peak for major tournaments such as the Olympic games[24,25]. Although there is no universally accepted definition of contemporary periodisation, it can be described as the systematic and purposeful approach to planning short-term and long-term training cycles by varying training loads, intensities, and recovery to allow peak performance at pre identified periods in the training cycle[24,26–28]. It is important to note that periodisation goes beyond just the physical aspect of training. Examples of periodisation occur for nutrition[29], psychological training[30,31] and tactical and skill training[32]. This implies there should be an integrated approach, where the physical aspects of training are aligned with dietary, skill (technical and tactical) and psychological components of the sport[24,32–34].

The integrative approach may assume many forms to best fit the context. Training organization for elite performance is governed by the principles of progressive undulating overload. This stimulus enhances super-compensatory training adaptations that are facilitated by various restorative methods[22,26–28]. The training-induced adaptations associated with performance are due to the cumulative effects of repetitive acute exercise stimuli. These adaptations are a specific response to the type of stimuli (demands) placed on the athlete[35] and recovery time periods differ according to the system that is being stressed[36].

2.2 The relationship between fitness, fatigue, and recovery

Training organisation and peak performance are governed by the relationship between fitness and fatigue. The fitness-fatigue model was proposed by Banister in 1982[6,37–39]. The fitness-fatigue model is governed by two factors following exercise; (i) fitness, which positively affects performance, or (ii) fatigue, which negatively affects performance. The interaction of these factors results in performance changes[38]. Fitness has a low magnitude, but long duration and fatigue has a high magnitude but short duration. High performance support staff can plan training to ensure that fatigue after-effects are diminished before competition and athletes peak (fitness after-effect) through super-compensatory patterns to the imposed training demands[10]. This model is preferable to the general adaptation syndrome proposed by Selye in 1956[39–41]. The general adaptation syndrome model does not specifically account for the interplay between stress (exercise stimulus) and recovery. Furthermore, most of the research defining the general adaptation syndrome has been derived from animal models and the extrapolation to sports and exercise training in athletes is limited[42,43]. A primary differentiation between the fitness-fatigue model and the general adaptation syndrome, is that the fitness-fatigue model proposes that different training stressors result in different physiological responses[39]. The fitness after-effects are largely neural in nature, whereas fatigue after-effects can be both neural and metabolic[38]. Vanrenterghem et al (2017) have suggested that the load-adaptation response differs according to the biomechanical stress and the physiological stress placed on the athlete[35]. For example, higher volume training results in an acute decrease in circulating testosterone, whereas higher intensity training increases circulating testosterone[44]. When considering Growth Hormone responses to training, higher volume at moderate intensities stimulates an increase, but low volume at maximal intensities has little to no affect[44,45].

The fitness – fatigue response is defined by the absolute load, intensity, and the total work done in a single bout. This is known as the training impulse[46]. As with the type of stimulus, both the amount and magnitude of training have their own fitness-fatigue response[38]. Peak performances are dependent on the training being balanced between the fitness and fatigue after-effects. Failure to get the balance correct, may result in an athlete underperforming or experiencing some degree of distress[9,47]. Furthermore, it has been shown that the fitness-fatigue model is able to relate an athlete's training load to their performance with a high level of agreeability[48]. Thus, the influence of training load on an athlete's subsequent performance should be well documented over time.

2.3 Overtraining

Athletes regularly have periods of overload to induce training adaptations followed by a period of recovery to allow for performance enhancement. However, if the period of recovery is insufficient the athlete may exhibit signs of fatigue or non-functional overreaching[2]. If there is no change in either training or recovery the symptoms may progress to represent a state of overtraining. Besides the negative impact on performance, overtraining can have negative health consequences. For example, there may be a dysfunction of the hypothalamic-pituitary-adrenal axis[49], suppressed immune system[50,51] and psychological changes including decreased vigour, increased feelings of fatigue[52]. Suffice to say overtraining is a complex phenomenon that is represented on the fatigue continuum[2]. It follows that depending on the phase of training an athlete may find themselves somewhere along a continuum ranging from acute fatigue to functional/planned overreaching, non-functional overreaching, and eventually full overtraining syndrome[2]. It has been suggested that maladaptation is a key concept of the overtraining syndrome where homeostasis is downregulated in several biological, neurochemical, and hormonal mechanisms[2,17]. Chronic tissue trauma has also been proposed as a possible cause of the maladaptation[53].

For many years the overtraining syndrome was poorly defined and as a result progress in research was limited. The following definitions of overreaching and overtraining have consolidated and improved the understanding[2,54,55];

1. **Overreaching:** *"an accumulation of training and/or non-training stress resulting in short-term decrement in performance capacity with or without related physiological and psychological signs and symptoms of maladaptation in which restoration of performance capacity may take several days to several weeks."*

2. **Overtraining:** *"an accumulation of training and/or non-training stress resulting in long-term decrement in performance capacity with or without related physiological and psychological signs and symptoms of maladaptation in which restoration of performance capacity may take several weeks to months."*

Some researchers have suggested that overtraining cannot be confirmed in the absence of an underlying medical condition related to underperformance[2,56]. Consequently, the term "unexplained underperformance syndrome" has been recommended as an alternative definition[9].

Team sport athletes have attributed the overtraining syndrome to increases in training load and intensity with insufficient rest periods[57]. Van Borselen et al, described the overtraining syndrome in athletes as a four-staged process[58], including;

- **Stage 1:** No decrease in performance but an altered neuron function may be present.

- **Stage 2:** Likely to have no negative performance effects but altered motor unit recruitment, sympathetic activity and hypothalamic control may be noticed.

- **Stage 3:** probable decrease in performance associated with a decrease in motor coordination, altered excitation contraction coupling, muscle glycogen, increased resting heart rate, mood disturbances as well as altered immune function.

- **Stage 4:** A definite reduction in performance due to a decrease in force production, glycolytic capacity, sickness, and infection as well as emotional and sleep disturbances.

While the details of this model have not been confirmed, it broadly supports the concept of the state of training/overtraining being on a continuum. Suggesting that athletes may lie anywhere along this continuum depending on multiple factors such as training volume, intensity, and monotony, to name a few. This is summarised in Figure 2.1, which has been adapted from Meeusen et al[2].

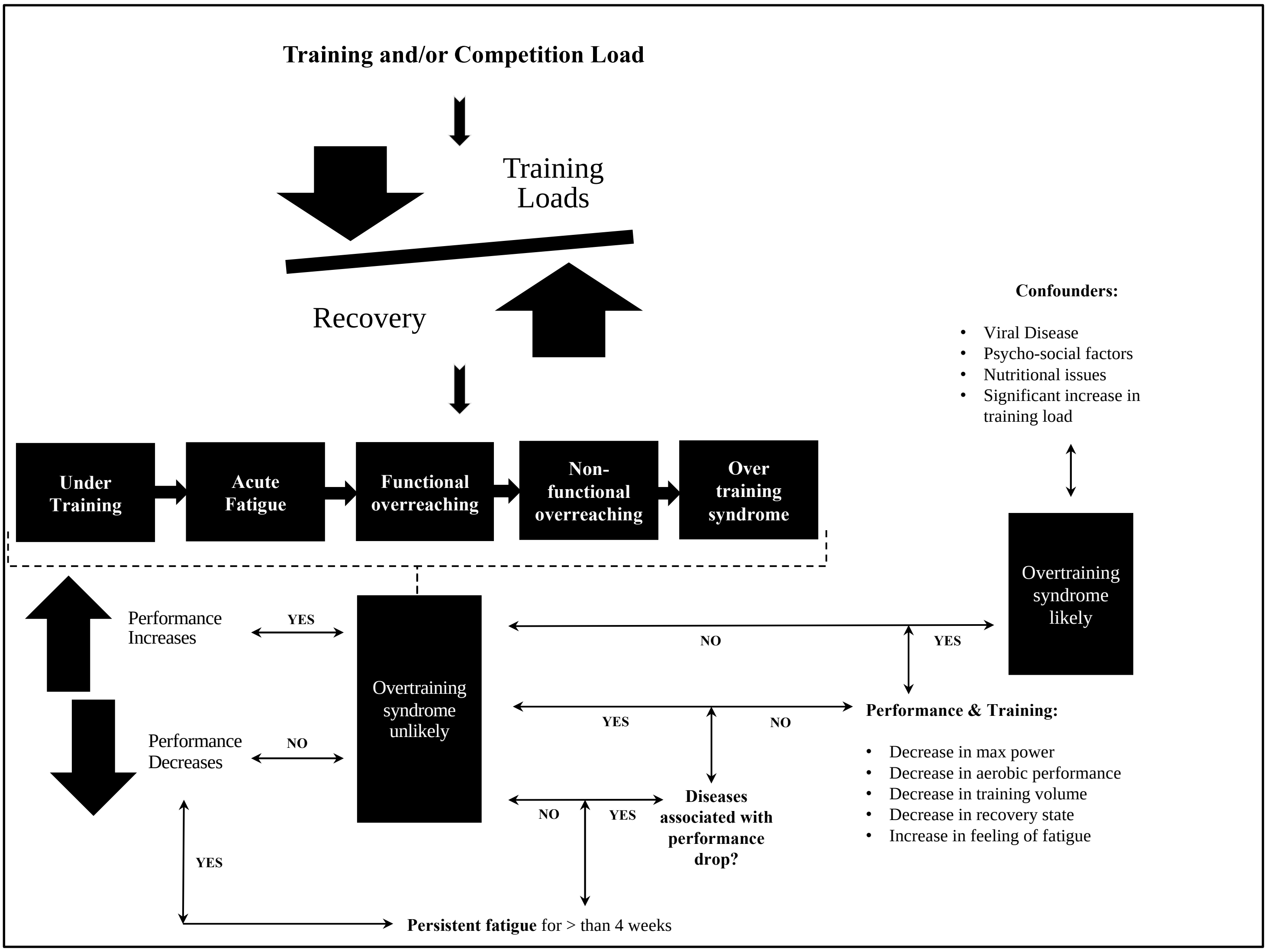


FIGURE 2.1: A conceptual model adapted from Meeusen et al (2013) for diagnosing the likelihood of an athlete presenting with the overtraining syndrome[2].

Hence, during the monitoring process it is important that the tools used are sufficiently sensitive to detect the location on the continuum and to act as early warning signals of non-functional overreaching or unexplained underperformance syndrome. Furthermore, as there are no exact tools to diagnose the overtraining syndrome, the process of exclusion through differential diagnosis should be considered to rule out other possible causes of performance decrements[2,9,56,59].

There seems to be a need to enhance the process of monitoring in team sports environments. However, the “take-home” message in the monitoring process should be that acute or chronic fatigue always manifests along a continuum. There is no single marker that can define where an athlete is on the continuum[4]. Therefore, to detect where an athlete is on the continuum requires a wide variety of tests and exclusion criterion for various confounders such as viral diseases and psycho-social issues that may manifest as the overtraining syndrome[2].

2.4 Fatigue

For many years the causes of fatigue have been explained as being associated with changes occurring between the brain and the muscle fibres[60]. One of the most common definitions of fatigue is “the muscles reduced force generating capacity” [61]. According to this definition the reduced force generating capacity may be linked to both central and/or peripheral fatigue. Changes at the level of the muscle fibre have been referred to as peripheral fatigue and any changes in the supraspinal regions have been referred to as central fatigue[60]. Neuromuscular fatigue is a combination of both central and or peripheral fatigue factors.

2.4.1 Peripheral fatigue models

Peripheral fatigue is characterised by the decrease in function of the peripheral factors, including muscle activation, transmission of the action potential and neuromuscular junction transmission[62]. Peripheral fatigue can also be mediated by intra-muscular biochemical processes, which adversely affect [ADP], [Pi], [H+] acting on the muscle's contractile kinetics[63,64]. A consequence of peripheral fatigue is a decline in muscle force generating capacity, that originates in peripheral tissues and not via the brain or spinal cord[65].

2.4.2 Central fatigue models

It has been suggested that fatigue during exercise is a protective mechanism governed by the central nervous system to avoid "catastrophic system failure" such as irreparable exercise-induced muscle damage or systemic failure[60,66]. Furthermore, central components related to a decreased force generating capacity, would mean that the central nervous system has the inability to recruit the motor neurons, thus reducing motor neuron drive, leading to an attenuated force generating capacity[61].

2.4.3 Neuromuscular fatigue

Mechanisms causing neuromuscular fatigue can develop anywhere along the chain from the brain to the spinal cord and ending at the muscle fibre and motor neuron level[65,67]. Fatigue has been defined as the inability of the muscle to sustain the required level of force at a given exercise intensity[67,68]. Further to this, Boyas et al (2011), suggest that fatigue is also associated with "the notion of a "break point" and the sudden appearance of fatigue and inability to sustain the exercise"[69]. Thus, neuromuscular fatigue is either the decrease in maximal voluntary muscle contraction due to the lowered number and discharge rates of motor units recruited (i.e., a centrally originated fatigue) or a decrease in the contractile strength of the muscle fibres due to various phenomenon mentioned earlier (peripherally originated fatigue)[69]. Peripheral fatigue usually presents earlier then central fatigue, during both maximal and submaximal exercise[70]. But the differentiation between the central and peripheral contributions to neuromuscular fatigue are difficult to determine. For example, Enoka et al. have stated that a decrease in maximal voluntary muscle contraction that develops during sustained low-intensity activity is largely due to a reduction in activation signalling, whereas for high intensity activity it would be largely due to a reduction in contractile function[67]. However, they have also suggested that the distinctions between the different “types” of fatigue are too small or vague to be meaningful and suggest that fatigue be inspected as a single entity rather than a particular type[67].

2.4.4 A working definition of fatigue

As has been detailed in previous sections, the definitions of fatigue vary according to the environment and context in which they are applied[71] and do not adequately account for fatigue associated with the fitness and fatigue paradigm.

Enoka and Duchateau (2016) attempted to translate the classical definitions of fatigue to be relevant to performance and suggested that fatigue should be defined acknowledging two key attributes: performance fatigue and perceived fatigue[67]. According to this definition performance fatigue is governed by the contractile capabilities of the working muscles and the ability of the nervous systems to provide the appropriate activation signals to the working muscle. The perceived fatigue is considered the rate of change in the sensations experienced by athletes that regulate the performance by maintaining homeostasis[67].

It is evident that reducing fatigue to one “global” definition is futile, as the concept itself is a complex issue involving multiple systems and affected by various aspects related to training and recovery[72].

Considering the variety of theories and lack of congruency regarding the definition of fatigue, for the purpose of this thesis the following working definition of fatigue as experienced by athletes, has been adapted from previous research.

"Fatigue can be defined as the physiological response to an increased exposure to a particular training or competition "dose" that results in acute (due to a single exposure which may induce positive adaptations) or chronic (due to prolonged exposure which may induce negative adaptations) decrements in performance relating to neuromuscular components affected by both central and peripheral models of fatigue as well as subjective perceptions of overall wellness".

This definition considers that fatigue exists along a continuum from acute fatigue to chronic fatigue (FIGURE 2.2). Chronic fatigue includes the symptoms of overreaching (non-functional and functional) and overtraining[2]. An athlete's state of fatigue may lie anywhere on this continuum during a training/competition cycle. Improvements or decrements in performance are dependent on how the athlete recovers from training-induced acute and/or chronic fatigue[9,56].

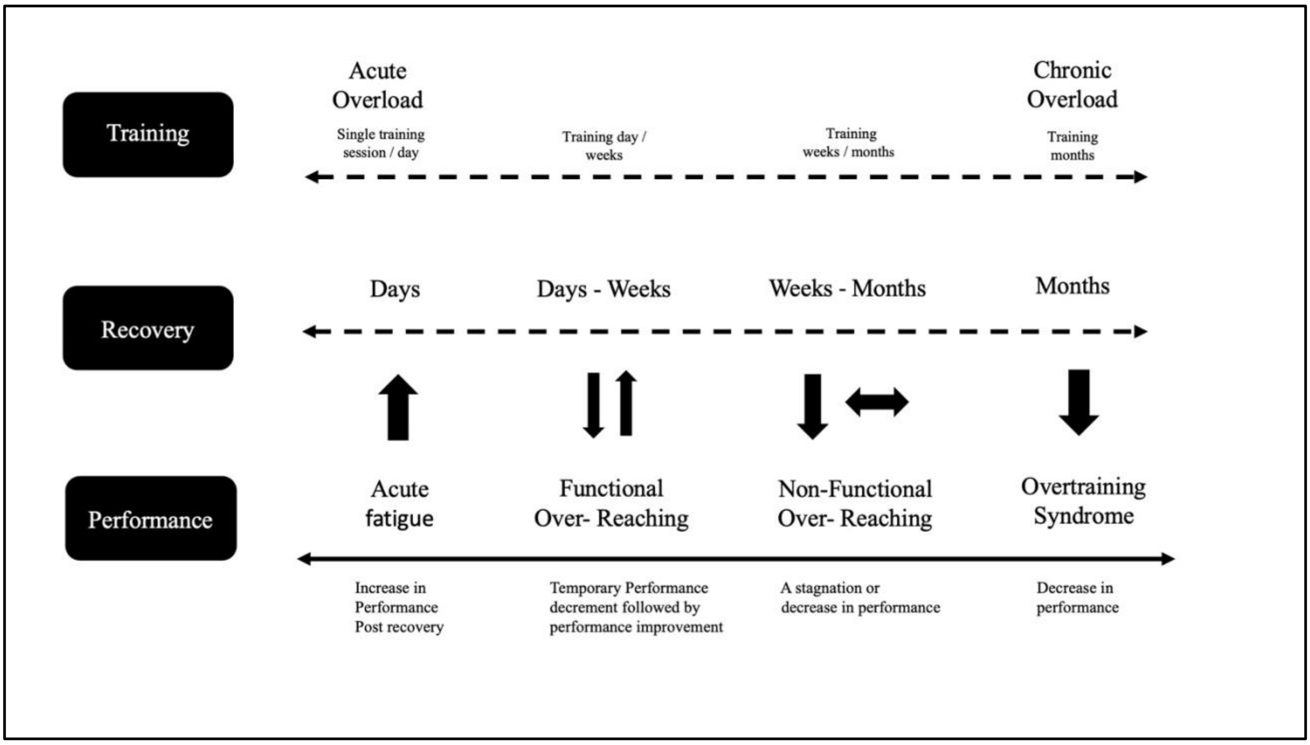


FIGURE 2.2: A schematic of the fatigue continuum representing the timeline for recovery and the effect on performance. Adapted from Meeusen et al, 2013[2]

2.4.4.1 Assessing Neuromuscular fatigue and its effects on performance

Neuromuscular fatigue has been extensively studied over the past century, with the most common definition being “a decrease in the muscle force generating capacity”. Numerous non-invasive techniques have been used to examine neuromuscular fatigue (NMF), including maximal voluntary contractions and surface electromyography (EMG) measures. As there are numerous methods of assessing neuromuscular fatigue as well as its possible effects on performance. I have detailed some of these within the below sections to gain a better understanding of the concept in its entirety.

For example, it has been suggested that global critical neuromuscular fatigue thresholds can be used in determining the extent or onset of neuromuscular fatigue. A proposed threshold of ~30-40% of maximal voluntary contraction force loss at any given intensity has been observed in sustained isometric contractions of the knee extensors[73]. Similar findings have been found in other muscle groups such as the elbow flexors[73,74].

In another study conducted on elite level national rowers, changes in surface EMG activity were extrapolated to establish the power intercepts, to interpret the neuromuscular fatigue threshold. This finding suggests that the neuromuscular fatigue threshold may represent local accumulation of fatigue in the exercising muscle, whereas surface EMG thresholds are closely related to the aerobic-anaerobic transition phase during maximal effort time trials[75].

In another study with fatigue-induced using an uphill running protocol, maximum voluntary contraction (MVC) of knee extensor muscles decreased by an average of 7.0% ($p<0.05$). But there were no changes in maximal activation or torque following nerve stimulation at 80Hz[76]. This suggests that this type of exercise-induced fatigue is due to alterations in excitation-contraction coupling rather than central mechanisms.

When looking at performance tests to identify neuromuscular fatigue, numerous studies have used different measures. An example of such a study was conducted on rugby players, where the researchers used the CMJ as well as a plyometric push up to assess upper and lower body neuromuscular fatigue[77]. They found that after repeated high intensity efforts as well as small-sided-games, both lower body and upper body neuromuscular fatigue were present. The neuromuscular fatigue was dependant on the type of small-sided-game played. For example, in running dominant games lower body fatigue was more evident, but for contact dominant games upper body fatigue was higher[78]. Numerous other studies have been conducted using the CMJ as a method of assessing neuromuscular fatigue These studies will be discussed in detail in the coming sections. More recently it has been suggested that running load index, as derived via micromechanical electrical systems using a standardised running protocol is a practical method to measure neuromuscular fatigue. The responsiveness of the test was very likely small to a most likely large changes being detected during a two-week training block[79].

Another consideration that needs to be understood, is the effects of neuromuscular fatigue on athlete performance. An example of negative effects of neuromuscular fatigue on performance was shown in a study of Australian rules footballers[80]. In this study players with a higher degree of neuromuscular fatigue, identified by flight time: contraction time ratio, had a reduced load per minute. They also tended to perform more running at lower speeds with less accelerations[80,81]. Furthermore, in a study on recreationally active males, landing performance, measured by ground reaction forces and impulse variables, were altered post exercise-induced fatigue[82]. The consequence of this finding is that neuromuscular fatigue may alter biomechanical strategies possibly leading to a higher risk of injury. It has also been shown that neuromuscular fatigue decreases the rate of force development in task specific muscles, which may increase an athlete's risk of injury[83]. Similar findings were shown for the risk of anterior cruciate ligament (ACL) injuries, especially in female athletes[84]. In this study there were modifications in lower limb control when landing with fatigue, which increased their risk of non-contact ACL injuries[84]. Finally, one of the most common "performance defects" in fatigued athletes are exercise-associated muscle cramps. It has been suggested that an increase in neuromuscular fatigue due to exercise intensity and duration, may alter muscle contraction and relaxation kinetics, i.e., decrease inhibitory afferent activity of the golgi tendon organs and increased excitatory afferent activity of the muscle spindles, inducing strong uncontrollable muscular contractions known as exercise-associated muscle cramps[85,86].

Lastly, apart from various assessments that can be used to assess neuromuscular fatigue, we must consider the task dependency characteristics of fatigue. For example, single vs multi vs whole body exercise or intermittent vs continuous exercise or exercise in hot vs cold environments have different manifestations of fatigue[62,67,71]. Also, the mode of contraction, (isometric vs concentric vs eccentric vs ballistic or plyometric muscle actions) have different neuromuscular fatigue outcomes[65,69,83,86–88].

Another consideration when identifying neuromuscular fatigue is that the assessment can occur before, during and after exercise[68]. Therefore, it is important that researchers and practitioners choose the type of measurement they are going to use according to their research question. They also need to consider the type of exercise that leads to the measurement being the most valid, reliable, and responsive, while also considering the time points at which they will be assessing the neuromuscular status of their athletes.

2.5 Recovery in Athletic performance

Most training programs focus on the content and context of the load, intensity, frequency, and duration of the training sessions the athletes are exposed to, with less focus on recovery between training sessions. However, the time spent recovering has a pivotal role in performance enhancement through physiological and psychological mechanisms[5]. Earlier, the fitness-fatigue relationship was addressed, explaining that fitness has a low magnitude but long duration, while fatigue has a high magnitude but short duration. Thus, specific recovery planned around training sessions bodes well for positive adaptations[89]. Recovery has been defined by Kellmann et al as follows;

"Recovery is an inter-individual and intra-individual multi-level process in time, for the re-establishment of performance abilities. Recovery includes an action orientated component, and those self-initiated activities can be systematically used to optimize situational conditions and to build up and refill personal resources and buffers" [5]

It is important to note that this multifaceted process incorporates both physiological and psychological factors related to fatigue. For example, there are various active and/or passive recovery techniques that can be used to address physical factors associated with fatigue after training or competition. Furthermore, there are various relaxation techniques that are used to recover from mental or cognitive fatigue[4,5,90,91]. Thus, the planning of these active (e.g., cooldown), passive (e.g., cold-water immersion) and proactive (e.g., relaxation strategies) recovery modalities will ensure athletes avoid under-recovery from both physical and psychological stressors to which they are exposed[2,9,36,56]. Consequently, monitoring the symptoms associated with the recovery-fatigue continuum may inform coaches of the training status of their athletes, allowing them to optimise training load and maximise performance. As with training, recovery should be individualised and periodised in the training schedule[24]. In accordance with periodisation models, recovery modalities should be planned to accommodate the current stressors placed on the athletes, the individual athlete response to chosen recovery modalities, and whether the peaking index is high or low[24]. Short-term interventions such as power naps, massage, contrast bath etc, can be applied during periods of heavy training to help athletes maintain training quality[5]. However, an over reliance of recovery modalities (e.g., cold-water immersion) may affect the signal associated with training-induced adaptations and cause “blunting” of metabolic and physiological adaptations[5,36,92,93]

Over time various methods of assessing an athlete’s “recovery status” have been implemented by sports scientists. Ideally the signal representing a change in training status needs to be detected before sports performance starts to decline. So, the ability to identify any performance-related decrements or under-recovery through regularly monitoring the recovery status, enables more time for intervention before the problem becomes serious. As a consequence, the use of various physiological and psychological measures are implemented to determine an athlete’s recovery and physiological balance[5]. These proxy-performance measures represent the accumulated “wear and tear” or allostatic disruption that may be caused by training and competition and enable the high-performance support staff to make informed decisions and intervene appropriately[36]. Also, these proxy measures, allow a greater understanding of individual athlete interaction between training, recovery, and performance, allowing specific recommendations to be made in accordance with the fitness-fatigue model discussed earlier.

2.6 Monitoring the training response in team sport athletes

2.6.1 A brief history

The concept of designing a training program to enhance sports performance has been known for decades. In the past coaches relied on their experience and subjective feelings to manipulate training. As sport has evolved so has the science of exercise performance. In the early 1970's exercise physiology became more popular, and the understanding of various concepts of sports science and exercise physiology improved[36]. In particular, the training principles of progressive overload, specificity and supercompensation were applied to the training program of athletes[22,94]. This led to coaches understanding that successful training had to incorporate periods of overload followed by adequate recovery between sessions.

Another concept that grew in popularity was the dose-response-relationship between training load and training adaptations[95]. The "dose" can be defined as any training stimulus, acute (a single training session) or chronic (multiple training sessions over a training cycle), to which the athlete is exposed. The "response" in the dose-response relationship is the physiological outcome to the stimulus. Thus, in any training program the dose-response-relationship plays a pivotal role when designing programs to enhance sports performance. With all things considered it becomes evident that without exposing an athlete to "supramaximal" or unaccustomed loads and/or intensities (known as overload) at some stage in the program, they will likely not improve[55,96,97]. Thus, the concept of chronic training adaptations is a result of the various physiological effects arising from the acute training stimuli. However, the dose-response relationship is more complex than simply assuming that an increase in dose leads to continuous adaptations.

2.6.2 A contemporary view

Considering, the improved knowledge in applied exercise physiology, it is not surprising that support staff of high-performance teams have examined strategies to get information from athletes to determine how they are responding to the training demands[37,98]. Consequently, monitoring strategies have become an integral part of daily activities in high performance sport. It is believed that through monitoring systems, support staff can better understand the dose-response-relationships for each athlete. Various monitoring systems offer both subjective and objective markers of recovery or fatigue, enabling support staff to make informed decisions about their training programme[18,92,99].

A few ideologies need to be considered for monitoring practices to be useful, valid, and reliable. For example, markers of fatigue need to be reliable, easy to administer, non-invasive and able to distinguish between acute and chronic changes[18,100–102]. Further to this it is important that teams have a clear rationale for using a monitoring system and a need to identify key features of a sustainable monitoring system. For example,[37]

1. Why is the monitoring required?
2. What will be monitored?
3. Frequency of the monitoring?
4. Individual or groups responses?
5. How will data be interpreted and presented to the relevant coaching staff and/or athletes?

Through the identification and implementation of these ideologies, monitoring practices can be used to help guide coaches and support staff on the individual athlete responses to various training modes, intensities, and volumes. This notion has been supported in the literature for several decades[37]. Furthermore, many studies have been published on team sports showing the efficiency and usefulness of implementing monitoring systems in these environments[6,80,103–108]. For example, it has been shown in rugby league[109], rugby union[103] , Australian rules football[80], soccer[100,110,111] and field hockey[104], to name a few, that monitoring fatigue, wellness, and recovery, helps better understand the athletes' training status.

Robertson et al (2017) wrote about the implementation of a "red, amber and green" decision-making system, whereby data are collated and represented in a simple and easy to interpret manner[112]. Although easily communicated to coaches and athletes the validity of this method is questionable as the interpretation of the "traffic light" system and the thresholds set may vary from team-to-team and sport-to-sport.

An important concept in monitoring is that the precision of the measurements needs to be known, so changes can be interpreted. This can be described as the "noise" and "signal" of the measurement[113]. The signal can be defined as the "minimal detectable change" (MDC)[114] or "smallest worthwhile change" (SWC)[115]. The noise can be described as the typical error of measurement[116]. By identifying these "benchmarks" for each measurement the support staff can understand the relevance of the changes that are observed. They are then in a better position to make informed decisions about whether to adjust the training programme or not.

In summary, monitoring systems are important in elite sports teams so the support staff can get relevant information about training load, fitness, fatigue, and recovery for each player. It is also important that support staff and coaches understand that there is no single "silver bullet" that can be used to make informed decisions on an athlete's training status. Thus, the selection of which tools, both subjective and objective, that will be used is crucial and needs to meet the requirements of the environment of the team.

2.6.3 Subjective monitoring strategies in elite athletes

As indicated in the preceding section, the notion that athletes need to train hard to improve performance is not novel. However, the approach of training harder and smarter has recently been popularised[117]. With this approach it is important that the athlete's response to the demands placed on them are carefully monitored to ensure the desired outcomes are attained. It is well documented that training imposes stress on the athlete as a "system", including both physiological and psychological wellbeing. It stands to reason that monitoring the manifestation of the exposure to psychological stress in addition to physiological stress has become an integral part of everyday athletic training programs.

2.6.3.1 Self-report questionnaires

For pragmatic reasons sports scientists adopt simple yet effective methods to understand athlete adaptations to training loads. However, it must be noted that not all these approaches are valid and reliable, and organisations should undertake their own validation studies to ensure their data is reliable[118]. One such method, is the self-report questionnaire which probes into aspects of the athlete's wellbeing. Self-report questionnaires that are sensitive to exercise-induced psychological changes have been shown to be useful in early identification of non-functional overreaching[119]. Some of the earliest work on mood state changes in athletes dates back to 1974, where it was shown that the "profile-of-mood-states" (POMS) questionnaire was sensitive to mood changes in athletes[52,119]. The POMS showed that elite level athletes could be characterised by above average scores in the category defined as "vigour", but below average scores in the categories of "tension", "depression", "anger", "fatigue" and "confusion". This profile was referred to as the "iceberg profile"[120].

In the early stages of research on the POMS, researchers tried to identify differences between successful and less successful athletes according to their pre-competition

POMS responses. For example, Olympic level speed skaters and wrestlers who qualified for their teams scored lower for “tension”, “anger”, “depression”, “fatigue” and “confusion” but higher in “vigour” compared to the athletes that did not qualify[121]. However, these findings were inconsistent, with some researchers showing no significant differences between the two groups (successful vs unsuccessful) in marathoners and ultramarathoners, field hockey players, basketball players, and netball players[119,120,122]. Due to the lack of individuality that exists in the POMS, a tool such as the “individual-zone-of-optimal-functioning” (IZOF) has also been researched to identify individual variations to psychological aspects of elite performance[123]. The IZOF attempts to describe the relationship between an athlete’s emotional experiences relative to competition success. The evidence suggests that a multimodal approach is the best approach in response to the complexity of these psychological models. Thus, researchers have shown that psychobiosocial states manifest in at least eight different interrelated modalities, namely[124];

1) Cognitive
2) Affective
3) Motivational
4) Volitional
5) Bodily
6) Motor-behaviour
7) Operational
8) Communicative

For these reasons, it seems as though the future direction of wellness-monitoring, will move towards the assessment of emotional and non-emotional athlete experiences related to their performances.

Much like the POMS, other tools such as the “Daily-Analyses-of-Life-Demands” (DALDA) and the Brunel mood scale also assess the emotions and mood states of athletes[122,125]. The DALDA consists of two parts. Part A assesses the “sources of life stress", whereas Part B assesses the "symptoms of stress". Each item requires an answer of "a" (worse than normal), "b" (normal) or "c" (better than normal). The score is represented by the number of "a" responses from the two sections. Monitoring the number of "a" responses provides coaches and support staff with an indication of the day-to-day stress an athlete is experiencing[122]. Researchers have also shown that an increase in "symptoms-of-stress" may occur before a decrease in immune function during periods of intensified training. These changes in DALDA scores can serve as an early warning signal for coaches and athletes[126]. For example, a study of endurance trained cyclists undergoing two weeks of high intensity training, showed that their POMS scores of "tension", "fatigue" and "confusion" increased while "vigour" decreased. Moreover, they also showed that the cyclists' Part B of the DALDA (rest, recovery, irritability, general weakness, and training effort) worsened during this same period[127].

Similarly, the Brunel Mood Scale (BRUMS) also assesses the mental health of various populations that are physically active including athletes[128]. The BRUMS evolved from the POMS. It was designed to be a simpler version of the POMS test that would identify athletes with the overtraining syndrome[125,128]. However, as a consequence of these tools being non-specific, they have not always met the needs of each team. Consequently, support staff have often developed their own wellness and self-report questionnaires that are designed to be more specific to their environment[129].

2.6.3.2 Athlete subjective wellness questionnaires

The elite sporting world has become more competitive, and each team environment requires different approaches. However, the majority of athlete subjective wellness questionnaires are "built" around the same principles, incorporating questions about sleep quality and duration, muscle soreness, perceived fatigue and recovery ratings, symptoms of illness and mood state to name a few[130–133].

Numerous studies have reported positively on the use of athlete subjective wellness questionnaires. For example, Thorpe et al showed that when players were exposed to a greater volume of high intensity running, their self-reported fatigue increased[18,100]. Furthermore, many researchers involved with various sporting codes have reported an increase in subjective fatigue and decrease in athlete overall subjective wellness ratings, as athletes are exposed to an increase in training volume and intensity[6,18,100,134]. An increase in muscle soreness and a decrease in athlete ratings of mental and physical strength have also been shown to change with acute training loads[113]. Moreover, perceived wellness scores decrease while circulating creatine kinase activity increases with intensified training blocks[135,136]. Also studies of rugby union and rugby league players have shown a relationship between low perceived wellness scores, an increase in muscle soreness scores and a reduction in a neuromuscular performance[78,101,109,134]. Additionally, Fields et al showed that external load can predict an athlete's perceived wellness and wellness can further predict the external load outputs in the subsequent training sessions[137].

It is evident that the use of athlete subjective wellness questionnaires may provide useful information to the support staff associated with high performance athletes. They appear to measure factors that are sometimes missed by objective tests[132]. These questionnaires are easy to implement, inexpensive and allow support staff to effectively monitor their athletes' wellbeing and readiness-to-train or compete[138,139]. Indeed, Saw et al (2015) showed that monitoring through self-report questionnaires may be more beneficial than other objective or performance measures[132]. However, this consensus is not shared by all. For example, Campbell and colleagues, have suggested that wellness responses should be interpreted with caution, when trying to use them in a predictive capacity in relation to internal and external load variables[140]. Furthermore, some researchers have suggested that the validity of some questionnaires require further investigation[129]. Thus, it is plausible to suggest that including a self-report wellness questionnaire that is tailored to the environment in which the data are being collected, may be beneficial and should be considered an important tool for effective monitoring. However, the interpretation of these data should be used in conjunction with other monitoring variables, and possibly not in a predictive capacity.

2.6.3.3 Measuring subjective exercise intensity

The measure of training intensity is not a new concept and dates back several decades where early concepts of periodisation were associated with undulating loads (volume of training) and intensities (effort level) during different phases of training. Intensity was often measured as a percentage of the maximum load for one repetition (1RM) for strength training purposes[22]. However, this method only caters for weight training exercises.

In the late 1960's, Gunnar Borg developed the "Borg Scale" that allowed coaches and athletes to report the individual rating of perceived exertion (RPE) levels of various training sessions[141]. This represented the perceived intensity of the training session. The RPE scale was constructed to increase linearly with intensity on a scale of 6 – 20. The foundations of the score were based on a heart rate range of 60 – 200 bpm[141]. The Borg Scale has generally been used for steady state exercise and for deriving the exercise intensity. The measurement was useful for coaches who required a single measure of the intensity. The 6-20 scale was later modified to the Borg Category Ratio 10 (CR-10) Scale[142]. Foster subsequently modified this scale (session-RPE) to develop a score athletes could provide at the end of a session to represent the rate of perceived intensity of the session[37,143]. Furthermore, the product of the session-RPE score and the duration of the session (min), provided a measure of training load (see next section).

Although RPE scales have been used as a surrogate measure of physiological strain, there are some methodological concerns with their use[142,144]. One of the main concerns with RPE scales are the varying definitions of perceived effort / exertion. For example, Borg defined perceived exertion as “the feeling of how heavy and strenuous a physical task is”[144]. Whereas other researchers have defined perceived effort as “the subjective intensity of effort, strain, discomfort and/or fatigue that is felt during exercise”[144]. Furthermore, the varying semantic descriptors and ratio scales between the CR-10 and Fosters 0-10 scale further highlight the need for standardisation of these scales[145]. At the very least the scale that is selected should be used throughout the trial or monitoring period and not interchangeably with another version of the scale.

Regardless of the concerns with the various scales, perception of effort scores has proved effective and useful in quantifying training intensity and subsequently training load for a variety of exercise modes[146–149]. For example, it was shown that RPE is a valid and reliable measure in rugby union across various training modalities[147]. Moreover, RPE has also been shown to be effective in monitoring the load and intensity of varying levels in resistance training[149], incremental and interval cycle ergometer training[150] and speed training intensity[146].

Some researchers have expressed concern about using RPE[144]. However, when the scales are kept consistent and implemented correctly, RPE is a valid and reliable method of assessing the intensity of several sports and physical activities in both genders, in all age groups and across various levels of sporting expertise[151–153].

2.6.3.4 Subjective quantification of training load

From the early writings of Yuri Verkhoshansky and Mel Siff in Supertraining (1993), training load was described as the summation of the effects of the contents, volume, and organisation of training[154]. This embodied the principles of specificity, overload, and progression, which laid the foundations for exercise prescription. As knowledge in the field of exercise prescription progressed, coaches have better understood the importance of the training-performance continuum. In particular, coaches try to determine the optimal dosage (training volume) required to improve an athlete's performance[155]. Thus, training load or volume can be defined as a quantitative input variable that is manipulated by the coach to elicit the desired training effect. Furthermore, training loads can be characterised by being either internal or external depending on which measure is being used[98,156]. Coaches and support staff usually try track both internal and external loads as these measures need to be interpreted in context, to determine if athletes are coping with their training programs. Furthermore, training load data also helps coaches to periodise their training through the season to help athletes peak at the expected times. Adjustments to the training can be made based on the athlete's response to the training load[98]. Given that athletes respond differently to the same stimuli, coaches can modify their programs in a customised way, based on each individual athlete's response[157].

There are many ways to quantify both internal and external load. For the purpose of this section, we will focus on quantifying training load using a combination of subjective and objective means. In the previous section the effectiveness of RPE as a measure of internal load was discussed. Foster et al have used this concept to develop the session-RPE (sRPE) as a method to quantify session training loads[158]. They asked high level athletes to record their training over a 6 month to 3-year period. Athletes were asked to record the intensity of their training session, within 30 minutes of training cessation. The training load was calculated as the product of intensity and duration[158].

$$\boldsymbol{Training\ Load = RPE\ (1-10) \times\ Duration\ (min)}$$

Furthermore, other researchers have shown that the sRPE can be a useful way to quantify training load in a variety of sports or modes of training, such as swimming

[159,160], resistance training[161,162], team sports[163,164], soccer[165], combat sports[166] and water polo[167]. Due to its ease of use and low cost, many practitioners use sRPE in the high-level sport setting, replacing the TRIMPS method originally proposed by Banister[164].

2.6.3.5 The training-load- injury paradox

The causes of injuries are multifactorial. Training load is one contributing factor[168,169]. It is generally accepted that athletes need to be exposed to high volumes of training over their careers to attain elite level performance. Athletes that are systematically exposed to higher training loads are more resilient overall[155]. However, exposure to high training loads has associated risks. For example, they have, 1) an increased risk of overuse injuries, and 2) an increased risk of overtraining[170–172]. Athletes who are "under-exposed" to training loads, may also have an increased risk of injury. This confirms why studying the relationship between training load and injuries is an important topic for managing athletes.

Dr Tim Gabbett has been at the forefront explaining load-injury relationships through work on the acute: chronic workload ratio (ACWR)[170]. He describes the acute load as the sum of the training load over a week and the chronic load as the rolling average of the total training load over a period spanning 3-6 weeks. The acute load depicts the "fatigue" state of the athlete, and the chronic load depicts the "fitness" state of the athlete[170,173]. Work in this area showed that athletes exposed to high training loads at different phases of training were at increased risk of injury. For example, athletes exposed to an acute load of 3000-5000 arbitrary units (AU) per week during the preseason were 50-80% more likely to sustain an injury than athletes exposed to <3000 AU[117,170]. The same was shown during the early to late competition phases, even though acute loads were lower than that experienced in the preseason[174]. Further research conducted on cricketers and soccer players showed that spikes in acute load increased the athlete's risk of injuries[175,176]. An extension of this research showed that the ACWR's range of 0.8 – 1.3 can be considered as the training "sweet spot", as the risk of injury is relatively low. An ACWR's of >1.5 was associated with an increase in an athlete's risk of injury[117,177].

This method of injury prediction has been criticised[178–180]. However, the methodology of the studies has been inconsistent making it difficult to have firm conclusions[181]. There have been various discussions about how the acute and chronic loads are calculated. For example, the two most popular methods of calculating the acute load or chronic load are the rolling average method[182,183] and the exponentially weighted moving averages (EWMA) method[182]. Although the rolling average method has shown to be useful in determining injury risk, the EWMA seems to be more sensitive in detecting risk of injury associated with spikes in training load or higher ACWR[182,184]. It must also be noted that not all training spikes may lead to injury and that some spikes may be unavoidable at certain times. Importantly the athletes should be sufficiently robust to handle the stress of these spikes, through a well-planned and structured training schedule[181,185].

More recently, critiques of the ACWR have claimed it is flawed, since the data used to reach the ranges in risk ratios were from various sporting codes with varying training load constructs. Both, published and unpublished work were combined to reach these conclusions[178–180,186–188]. In another study, the authors argue that the ratio rescaling method of attaining the ACWR may exponentially increase the effect of the acute load and that in general the ACWR and the acute load do not provide any useful information regarding injury risk[178]. Furthermore, Buchhiet et al (2017), showed that the acute: chronic workload ratio was questionable when implemented in football players, and that it may be more important to understand individual needs and profiles of players to aid in injury prevention[189].

Regardless of the doubts and questions around the ACWR, it is important to understand the relevance of training load monitoring in sport. Training load monitoring provides real time data on the external load placed on athletes and matches these loads with their internal responses. The relationship between external load and internal physiological responses is critical in making decisions about how the athlete is responding to training and whether the training load should be adjusted to negate unexpected fatigue and enhance performance and reduce the risk of injury. Thus, training load monitoring provides information which assists in making informed decisions about individual athletes within a team setting. In particular, training load monitoring assists in determining the internal-external load ratio or the fitness-fatigue status of an athlete and can improve the design of training and recovery schedules[98].

2.7 Objective monitoring strategies in elite athletes

Various methods have evolved to quantify training loads, with each method having pros and cons. Some of these methods have been discussed previously.

Objective measures can be subdivided into internal and external measures. For example, heart rate, blood lactate, oxygen consumption and TRIMP are considered measures of internal load[46,98]. Whereas, training duration, training mode, power output, accelerometer variables and global positioning system variables (GPS) are considered measures of external load[37,98]. Each environment is unique, and therefore different monitoring strategies should be considered on a case-by-case basis. More importantly, there is no single best method. A preferred method, which is considered best practice, is to apply multiple strategies to get a complete assessment of the athlete’s fitness-fatigue responses[157].

2.7.1 Internal load

Internal load can be defined as the internal physiological and metabolic responses (or disturbance of homeostasis) to an external stimulus an athlete is exposed to during training or competition. These responses may be influenced by chronological age, training age, gender, and fitness levels, but are measured objectively[190].

2.7.2 Physiological measures of internal load

Heart rate (HR) has been one of the most utilised methods of internal load monitoring over the past two decades[191,192]. Monitoring heart rate responses has been predominantly used as an indication of training and competition intensity[191]. For example, the HR and oxygen consumption (VO_2) relationship has been well established and utilised as a reflection of training intensity and energy expenditure[193]. Furthermore, HR monitoring during exercise also allows for the determination of zones, that coincide with specific development of energy systems (e.g., aerobic vs anaerobic)[194]. Moreover, heart rate fluctuations over time may provide insight into an athlete's state of adaptation and fatigue[15,191,195,196].

Heart rate recovery measures autonomic control and by implication is a marker of training status[14,15,197,198]. For example, Borresen et al (2007), showed that heart rate recovery slows with an acute change in training load[15]. Further to this, Lamberts et al (2010), showed that heart rate recovery is a valid measure of endurance performance changes and allows coaches to prescribe training loads more accurately in elite cyclists[14,199]. Similarly, in team sport athletes, specifically in field hockey, researchers have shown that players with a faster heart rate recovery are able to perform a greater amount of high intensity running in matches[198]. A review of studies on heart rate recovery and training status showed that changes in heart rate recovery has the potential to be a valuable tool to monitor changes in training status in athletes[102].

Resting heart rate has been used as an indicator of autonomic nervous system status[191,196], the premise being that increases in resting heart rate indicates an athlete is experiencing acute fatigue or symptoms of overreaching[200,201]. However, it has been shown that resting heart rate has a poor sensitivity (<20 %) to change, irrespective of the use of various markers of training status or performance, especially when measured infrequently[202]. This reduces the practical application of using resting heart rate as a marker of training status.

Heart rate variability (HRV), particularly resting HRV has also been used as a marker of the autonomic nervous system[203]. HRV has been suggested to be more sensitive to training status than heart rate recovery, however there are confounding opinions on this. Changes in HRV have been shown to occur with an increased training load and during periods associated with tapering[204,205]. For example, increases in vagal-related indices (i.e., increase in HRV) of resting as well as post-exercise HRV have been shown to accompany improvements in performance[206,207]. However, various studies conducted with the aim of identifying reductions in performance using HRV as a measure have disagreed on the direction of change. Some showing a decrease and others showing an increase in HRV associated with performance decrements. Thus, it suggests that overreaching may have little effect on HRV[197,208]. These differences may be due to various methodological approaches associated with HRV as a measure[205,209]. For example, the signal or noise associated with the measurement as well as the timing of the measurement (Morning resting HRV vs Post Exercise resting HRV), all play a significant role in the interpretation of the data[202]. Furthermore, data obtained from short-term measures (e.g., 24 h) of HRV should not be used interchangeably with ultra-short-term measures (e.g., 2 min). Additionally, published norms are not accurate across all populations, thus practitioners are encouraged to produce their own population specific norms. This adds to the complexity of the measurement[210].

2.7.3 External load

Subjective external load monitoring was covered in the previous section. These methods included sRPE, which is the product of duration (minutes) and rating of perceived exertion (RPE). It follows that training duration has an important contribution to accumulated training load per session. Through direct observation and recoding of training time, teams can quantify their time "on feet" as well as their training impulse (load) for that session or day[46,211]. However, training duration has its limitations as it only provides insight into the actual volume of training performed, not the content of that volume. Information about the content can be provided by GPS variables, in particular variables related to load and intensity of training[212,213].

There have been various studies on the validity and reliability of GPS devices. For example, distance covered was measured more accurately with higher sampling rates (5 Hz and 10 Hz). With sampling rates of 5 Hz and 10 Hz the standard error of estimate was 6-10 %. However, as the velocity of the task performed increases, the accuracy of measurement decreased. With the advances of technology, Scott et al (2015), showed that 10 Hz devices were the most valid and reliable devices, with 15 Hz not adding any significant value over the former[214]. The CV of 10 Hz devices for low-speed distance was 1.90 %, for high-speed distance was 4.70 % and for very high velocities was between 2.50-5.30 %. This makes them practical and relevant for measuring external load during sporting activities. The 10 Hz units are preferred over other units as they have better intra-unit and inter-unit validity and reliability compared to all other sampling rates.

Most GPS units now have integrated triaxial accelerometers capabilities with sampling rates up to 100 Hz. Accelerometers allow for the quantification of movements in 3 axes (X, Y and Z planes) to measure the composite magnitude vector in G-force. Furthermore, they can quantify collisions, accelerations, and decelerations, change of direction and bodyload, which is a summation of total external load or mechanical stress an athlete is exposed to in a session[214,215]. The CV of accelerometers ranges between 1.20 % and 6.50 % for acceleration and deceleration variables respectively[216]. Similar to the recommendation for GPS variables, 10 Hz seems to be the minimum sampling rate for accelerometers for acceptable reliability[216,217]. Lastly, when using GPS devices to track players' external load, it is advisable that the same unit gets used by a player each time data are collected. This reduces the error arising from inter-device measurement differences[213,218].

In summary, the use of GPS units are a valid and reliable method of quantifying external load during training sessions and match play. In particular, they can measure the following variables: total distance (m), high speed distance (m), velocities across various zones, accelerations and decelerations, and change of direction[219], all of which add value to external mechanical load data when monitoring training loads.

2.8 Objective measures of fitness and fatigue

Earlier we had looked at the effects of fatigue on the central and peripheral nervous system. More specifically, the effects of fatigue on neuromuscular function. With the understanding that with accumulated fatigue, both acute and chronic, there is a transient decrease in various markers of neuromuscular performance[69]. One important marker being the decrease in the muscle force generating capacity. Considering the importance of force generation in sports performance, it is plausible to suggest that monitoring a decrease in force through simple tests, such as the countermovement jump, may prove consequential in identifying an athletes neuromuscular training status[75,82].

2.8.1 Countermovement Jump

An athlete’s ability to produce maximal force and power in the shortest time has long been a desired attribute at the elite level, as these properties of muscle correlate well with aerobic and anaerobic sports performance[220]. These characteristics of muscle can be measured using many different protocols[221]. The vertical jump test, in particular the countermovement jump, is often a preferred test because it is reliable, non-fatiguing and relatively easy to administer[222]. The countermovement jump test can be used to assess several variables of neuromuscular performance including the stretch shortening cycle (i.e., neuromuscular signalling pathways capabilities)[223]. This is an important characteristic of muscle function because athletes who are able to utilise both the stretch reflex as well as muscular contractile force optimally, have superior lower body force producing capacities[224]. Furthermore, the optimal usage of the stretch shortening cycles reduces the metabolic cost of all movements. It is plausible to suggest that a reduced “signalling pathway” within the stretch shortening cycle my lead to higher degree of peripheral muscle fatigue[224].

There are different mechanisms associated with the stretch shortening cycle. These differences have been described in two models, for example;

1) **Mechanical Model**: Hill (1938) proposed that force should be analysed as a summation of 3 components, a) contractile (actin and myosin), b) the parallel elastic component (sarcolemma and muscle fascia), and c) as the series elastic component (cross bridges, structural proteins, and tendons)[225]. Each component has a fundamental role in force production[224,226].

2) **Neurophysiological model**: This model consists of the muscle spindles and Golgi tendon organs within the muscle. Force produced by the muscle is moderated by these two mechanisms. The first mechanism incorporates the muscle spindle which potentiates the force after a pre-stretch. This occurs because additional motor units are recruited, enabling muscle to produce higher forces. The second mechanism incorporates the Golgi tendon organ which regulates muscle tension to avoid harm[224,226].

2.8.2 The force-time curve of the countermovement jump

Force plates have become readily available outside the laboratory setting and have been used with the countermovement jump to measure various outputs associated with the test. Force, displacement, and velocity can be measured continuously during the different phases of the countermovement jump (FIGURE 2.3). The countermovement

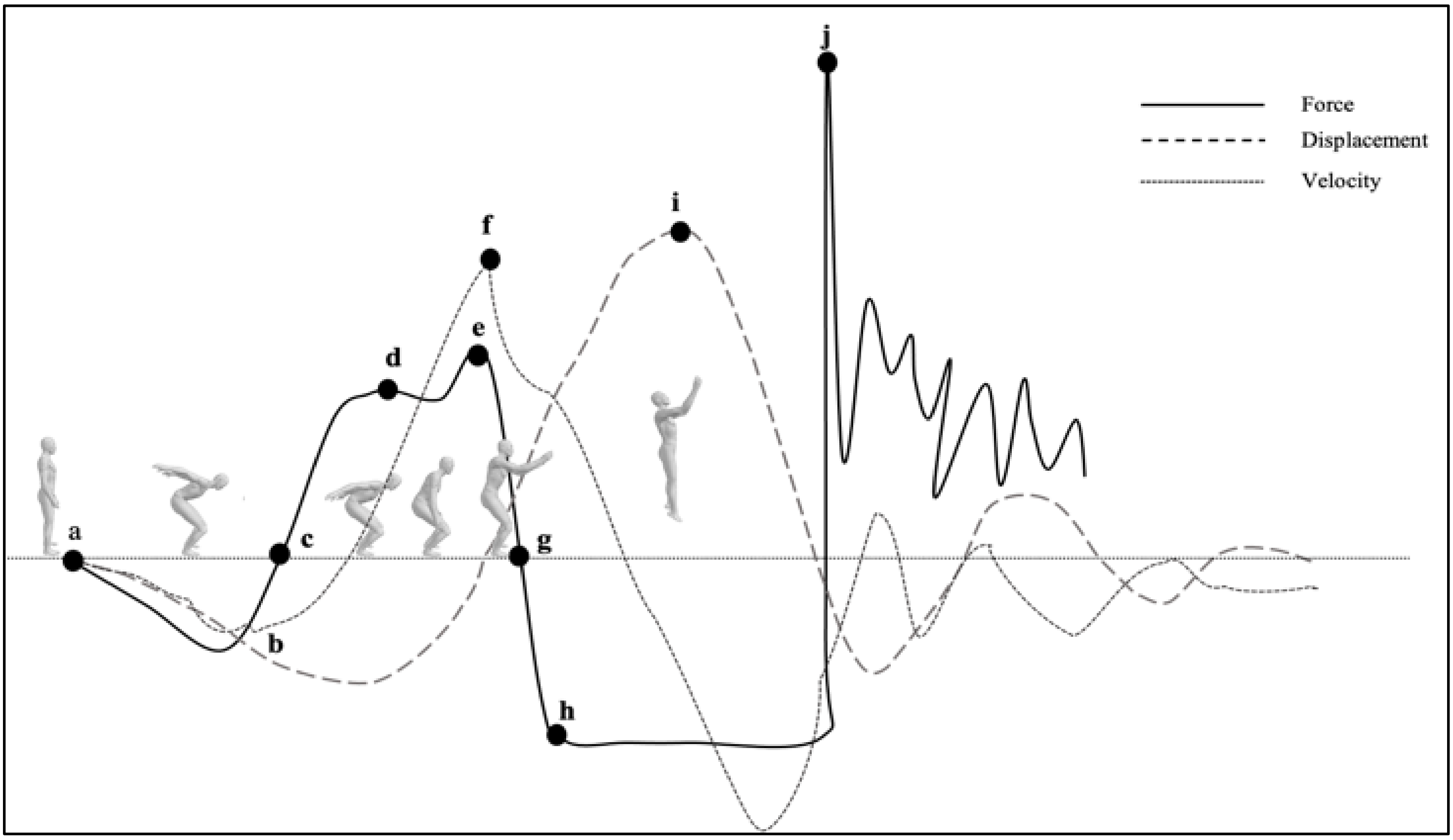


FIGURE 2.3: Graphical representation of the force-time curve during the countermovement jump (adapted from Sole et al (2017) [216] & Chavda (2018) et al) [218]

jump comprises different phases from which various variables are derived (FIGURE 2.3). Through a better understanding of the force-time curve kinetics of the countermovement jump, practitioners can better understand the neuromuscular characteristics of the movement[227].

FIGURE 2.3 above shows each phase of the CMJ represented alphabetically according to the sequence of events captured on the force plate throughout the movement. At Point **(a)** the athlete initiates the downward movement, known as the unweighting phase. At this point the athlete starts to flex their knees and hips with downward acceleration achieving the lowest velocity at point **(b)**. Point **(c)** represents the phase at which the vertical ground reaction forces return to the system's weight (i.e., body weight). To overcome the initial downward acceleration, the athlete activates their lower body musculature. Once zero velocity is reach at point **(d)** the athlete has reached their lowest point (greatest downward displacement) within the countermovement jump. This is known as the "breaking or eccentric phase". This is followed directly by the "propulsive or concentric phase", shown by the increase in force from points **(d)** to **(e)**. The time taken from point **(d)** to **(e)** is also used to calculate the rate of force development[228]. A decrease in force at point **(f)** is due to the athlete's centre of mass reaching zero acceleration, and height of the athlete's centre of mass being greater than that at the start of the movement, as their feet leaves the surface. Peak velocity occurs just before the flight phase**.** Points **(g)** to **(h)** are the propulsive deceleration phase. With point **(h)** also being the point at which there is zero force. At point **(i)** the athlete is in flight, and their centre of mass decelerates moving neither up nor down, at which point the athlete reaches their point of maximum displacement (Jump Height). The final phase is achieved upon landing where the greatest force is achieved at point **(j)**[223,227,229]**.**

To further improve data analysis and interpretation of the countermovement jump data it is important to consider the instructions provided for the jump, including whether an arm swing is permitted and whether the participants have a self-selected countermovement depth or predetermined countermovement[230]. From a practical perspective a self-determined countermovement depth is perhaps a preferred instruction to ensure natural characteristics are not affected. Moreover, instructing participants to jump as “fast and as high” as possible reduces the amortization / breaking phase at the bottom of the countermovement, allowing for better use of the stretch shortening cycle[227].

As mentioned, the inclusion or exclusion of the arm swing needs to be considered to standardise the protocol. The inclusion of an arm-swing in the protocol increases the measurement reliability in skilled jumpers[227,231,232]. The inclusion of an arm swing also increases jump height (~37 %), acceleration impulse (~15 %) and average force (~3 %)[233]. The inclusion of an arm-swing also increases the vertical ground reaction forces and peak positive power[234]. Previous research has shown that the countermovement jump performed with or without arm swing has acceptable levels of inter-session and intra-session reliability (ICC >0.70; CV <10%), with high capacity to detect inter-session change (i.e., the smallest worthwhile change is greater than the typical error of measurement)[231].

Gender and sports participation differences in countermovement jump metrics should also be considered when analysing data. For example, it has been shown that males jump up to 26% higher than females. Furthermore, all variables associated with force (e.g., eccentric rate of force development, concentric force) are higher in male jumpers compared to female jumpers[235]. Another consideration should be the type of sport that the jumper participates in, with participants in certain sports showing greater ability in all countermovement jump variables than others[235]. Various devices are available for the measurement of countermovement jump data[236–238]. Amongst these force plates are regarded as the gold standard for data collection[239–241].

2.8.3 Using the countermovement jump to assess athlete neuromuscular status

The countermovement jump can be used to assess athlete fatigue or super compensatory status, collectively known as training status[242]. The countermovement jump variables have been used to monitor neuromuscular performance in players from various sporting codes such as rugby union[243], soccer[135], rugby league[244], Volleyball[245], Australian rules football[80], Snowboarding[243] and basketball[108].

The variables from the countermovement jump respond differently to different training stimuli. For example, CMJ variables such as flight time, time to peak force and peak force decreased over a 6-week training block in female rugby league players. These changes may be associated with neuromuscular fatigue[246].

Before researchers or practitioners make certain “assumptions” when using the CMJ, and the multiple variables associated with it, they should follow the rigorous procedures in accordance with the principles laid out within the field of clinimetrics[247]. For example, Impellizzeri et al (2009) propose that all physiological and performance tests in sport science, are thoroughly analysed according to 3 main criteria[248].

1) **Reliability:** is the measure of the degree to which repeated measures vary for individual athletes (Absolute reliability) or the degree to which individual’s position remains unchanged within a sample with repeated measures (Relative reliability).
2) **Validity:** is the degree to which a test measures what is it supposed to measure. A valid test should also be sensitive enough to discriminate individuals of different competition levels.
3) **Responsiveness:** is the sensitivity of a measuring instrument (e.g., Force Plate) to depict change over time.

Examples of clinimetric procedures on the CMJ are shown in studies on the two codes of rugby football, where researchers reported that CMJ peak or mean force are reliable (Coefficient of variation (CV) >5 %) and sensitive (responsive) to change (CV< smallest worthwhile change (SWC)) in accessing neuromuscular function[115]. In further studies in rugby the reliability of the CMJ on a force plate was reported as a CV of 1 % to 6 %. The same studies also showed that CMJ peak force and peak power decreased with progressive increases in training and or competition load without sufficient rest periods. However, returned to baseline post 24-72 hours rest[103,249–251]. In a study on Australian rules football players, Cormack et al, (2019) suggest that flight time to contraction time (FT:CT) ratios are sensitive to changes in neuromuscular fatigue with the magnitude of change ranging from *unclear* to a *substantial* decrease[80]. Similar findings have been shown in female basketball players, where FT:CT decreased following a single training session but jump height remained unchanged[108]. Interestingly, in a study on basketball players, Freitas et al, (2014) showed that despite an intensified block of training, CMJ variables did not change[136], which is dissimilar to studies reported earlier.

The recommendations following a meta-analysis of countermovement jump and neuromuscular status were[242];

1) Certain variables are more sensitive to fatigue changes (e.g., jump height and peak power) and other variables more sensitive to super compensatory patterns (e.g., peak velocity, PPO equation)
2) The mean value of each variable is more sensitive to change than the single maximum value.
3) Variables used to monitor neuromuscular status should have a *small* to *moderate* coefficient of variation and a *moderate* to *large* effect size.

4) Some of the variables with the greatest responsiveness include average jump height, average peak power, average peak force, average peak velocity and average peak power (calculated by equation).

It is evident that a valid and reliable objective marker of neuromuscular status can contribute to a more holistic approach to monitoring systems within team sport environment. An objective measure like the countermovement jump can guide practitioners in decision-making in terms of individual and team responses to training exposure. Thus, the identification of a valid and reliable measurement system (e.g., force plate) and performance test (e.g., CMJ), in a controlled laboratory environment my prove useful in determining the measurement of choice. However, in a "real-world" elite sport environment, controlled laboratory conditions are rarely possible. Thus, the use of "proxy" laboratory measurement system such as portable force plates are increasing in popularity. However, for these "real-world" research studies to be sufficiently robust, it is important that the same clinimetric principles are followed when conducting studies on elite athletes. In this manner we can more confidently take research "out of the lab" and into the "real-world" of elite sport.

Lastly, FIGURE 2.4 encapsulates a conceptual model of the basic principles of an effective monitoring strategy. By incorporating both subjective and objective data of fitness and fatigue, coaches can react accordingly and make informed decisions about the athlete's training.

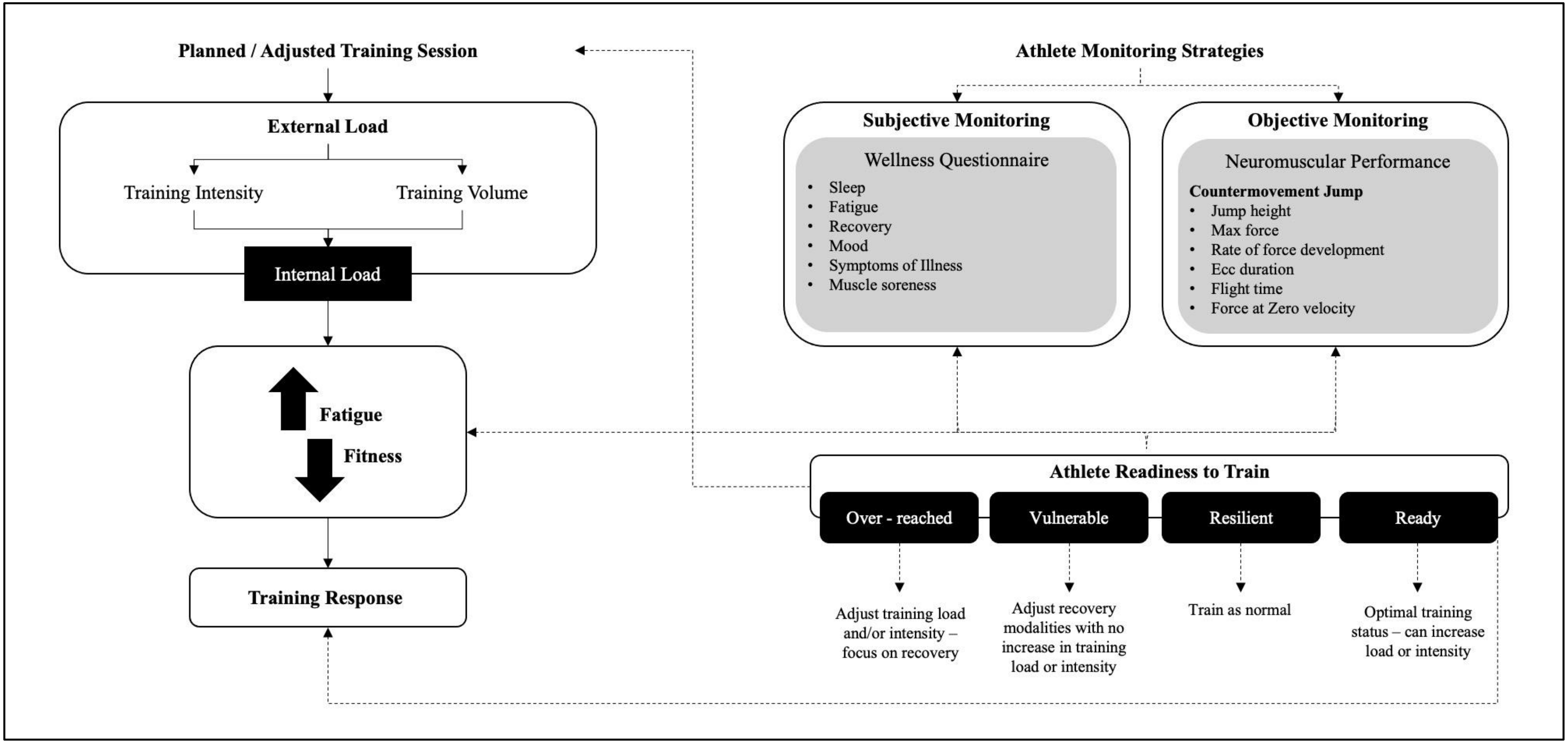
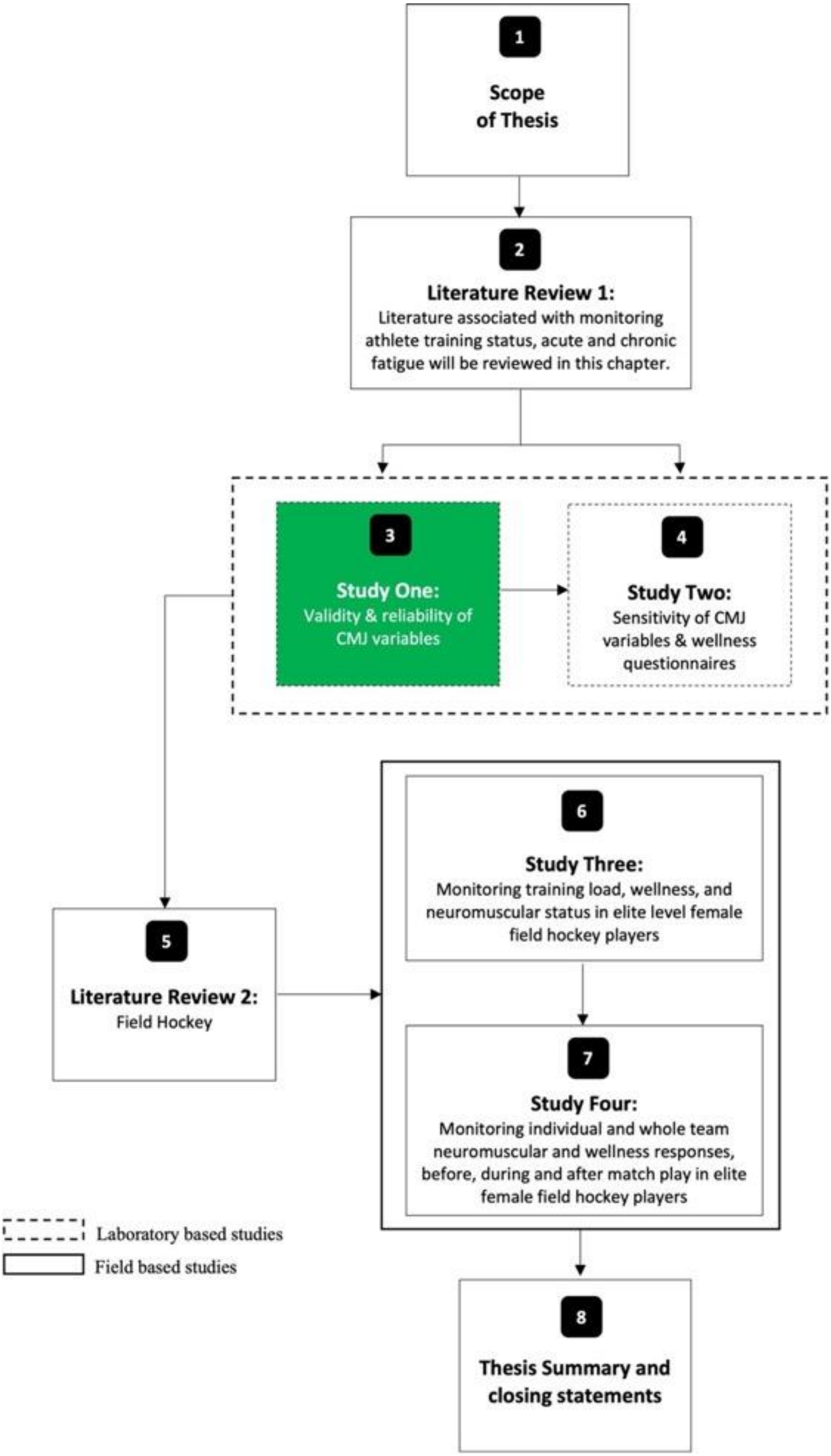


FIGURE 2.4: Conceptual model of the monitoring process, depicting the dose response relationship decision making model.

2.9 Chapter Two – Summary points

1. Monitoring systems enable support staff to determine the training status of individual athletes more accurately.
2. An important consideration with monitoring athletes is how to best translate the science in a simple and meaningful way to improve engagement of the coaching staff and athletes.
3. As with periodisation an integrated approach is needed for monitoring, with the incorporation of measurements of internal and external load, athlete wellness and neuromuscular status to better understand individual adaptations to training programs.
4. A key concept of monitoring is to act as an early warning signal of non-functional overreaching. It follows that markers of training status need to be sufficiently sensitive to detect meaningful changes.
5. Neuromuscular fatigue can manifest as a decrease maximum voluntary muscular contraction, that is either due to a reduced activation signalling (central fatigue) or reduced contractile function (peripheral fatigue).
6. Wellness questionnaires that are tailored to the environment in which the data are being collected, are beneficial and should be considered an important tool for effective monitoring.
7. External load has an effect on wellness responses and wellness responses have an effect on subsequent training sessions outputs.
8. RPE is a valid and reliable method of assessing the intensity of several sports and physical activities in both genders, in all age groups and across various levels of sporting expertise providing the scales are kept consistent and implemented correctly.

9. sRPE is a useful way to quantify training load in a variety of sports or modes of training. Due to its ease of use and low cost many practitioners use sRPE in a high-level sport setting.
10. GPS units are a valid and reliable method of quantifying external load during training sessions and match play.
11. The countermovement jump is a valid and reliable performance measurement that can be used to assess an athlete’s neuromuscular status.
12. Some of the countermovement jump variables with the greatest responsiveness, include average jump height, average peak power, average peak force, average peak velocity, and average peak power (calculated by equation).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Literature associated with monitoring athlete training status, acute and chronic fatigue will be reviewed in this chapter.
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3. Chapter Three

Study One: Validity and reliability of countermovement jump variables as measured on a force plate

3.1 Introduction:

The CMJ test is one of the most popular tests to measure an athlete's maximal lower body power output[242,252]. Performance in the CMJ test is a consequence of maximal force, the rate at which force can be developed and neuromuscular co-ordination[252]. The rate of force development (RFD) is the rate at which muscle develops force from the onset of a contraction until it reaches peak power output and is generally used as an index of explosive strength[253,254]. Neuromuscular function, coordination as well as RFD are important concepts in sport as they have been shown to be associated with both performance as well as injury occurrences[254,255]. An increase in RFD decreases the time required to reach maximal power output and therefore is associated with improved muscle performance and joint integrity during dynamic movements[256]. However, as with many CMJ variables, RFD may decrease with an accumulation of neuromuscular fatigue[257], making it a potentially sensitive marker of exercise-induced neuromuscular fatigue[258]. However, it is erroneous to use only one variable within the CMJ to measure an athlete's neuromuscular performance and or training status. Thus, an important consideration when using the CMJ as an acute or chronic marker of neuromuscular performance or training status is to incorporate multiple variables as each may provide unique information[246,259]. For example, only looking at mean force or flight time may not indicate neuromuscular fatigue as variables incorporating time-based analysis such as RFD, time to maximum force and flight time seem to be more indicative of neuromuscular performance[115,246,260].

Although several studies have measured these variables during a countermovement jump on a force plate[242] the validity, reliability and smallest detectable differences have not been clearly established in populations of varying athletic ability[253]. This is an important consideration before the measurement can be interpreted with confidence in a practical and applied setting. Therefore, the aim of this study was to assess the clinimetric properties of the CMJ variables as performed on a force plate, to determine whether the measurement can be used to monitor training status or adaptations. The objective was to measure the validity, reliability, and the smallest detectable difference of the variables, in participants with varying athletic ability.

3.2 Methods

3.2.1 Subject recruitment

Thirty male participants, of varying training age, were recruited for the study. Inclusion criteria were males, aged between 18 – 35 years with no previous injuries within the 6 months before the start of the study. Participants were assigned to one of three groups according to their strength training age – untrained (< 2 months strength training), semi-trained (2-6 months strength training) and trained (>12 months strength training)[261]. All participants provided written informed consent (Appendix 3) and the protocol was approved by the Human Research Ethics Committee of the Faculty of Health Science (HREC REF 563/2014; Appendix 4).

3.2.2 Familiarisation

Participants completed an American College of Sports Medicine Health and Fitness questionnaire (Appendix 1) and were cleared to participate in the study before any measurements were recorded. The first visit included a familiarisation session, which consisted of an introduction to the standardised warm up and the countermovement jump protocol that was going to be used in the study.

3.2.3 Assessment of body composition

Body mass was recorded on an electronic scale (MVW Industrial Floor scale; 200 kg capacity) in kilograms (kg) to the nearest 100th gram (0.1kg), while the participant was barefoot. Stature was recorded to the nearest millimetre (mm) with the participant barefoot using a stadiometer (SECA Leceister 214 stadiometer). Skinfold measurements of the triceps brachii, biceps brachii, subscapularis, suprailliac, abdominal, mid-thigh and calf were measured using Harpenden skinfold callipers. The average of three measures were recorded for each site by the same assessor. Body fat was expressed body fat percentage was calculated using the 4-site skinfold equation by Durnin and Womersley together with the Siri equation[262]. Fat mass and lean muscle mass were calculated from the percentage body fat and body mass. Lean thigh volume was calculated by the truncated cone formula[263].

3.2.4 Performance measures

CMJ height and a 3-repetition maximum (3 RM) squat test were used as lower body performance measures. CMJ height was measured using a Vertec vertical jump measuring apparatus (Perform Better, USA), with the best of three attempts recorded to the nearest centimetre (cm). The 3 RM squat test was conducted with a loaded bar attached to a Smith machine. Participants were instructed to squat down until their thighs were parallel to the ground, with the aim of completing 3 full repetitions with the maximum amount of weight achievable in as few attempts as possible. 3RM results were converted to a 1 RM score using the Epley conversion formula[264] and were recorded to the nearest kilogram (kg) **(**TABLE 3.1**)**. Both performance measures were included to classify the participants into their relative training groups. The groupings were defined as follows;

- **Untrained:** 1 RM <95 kg and Vertical Jump of <50 cm
- **Semi Trained:** 1 RM range of 96-120 kg and Vertical Jump range of 51-63 cm
- **Trained:** 1 RM range of 121-175 kg and Vertical Jump range of 64-74 cm

3.2.5 Standardised warm up

The standardised warm up of 3 minutes light aerobic work consisted of various movements (carioca, high knees, butt kicks, side shuffles etc) over 20m and lower body specific dynamic stretches (focusing on hamstrings, calves, quadriceps, and gluteal muscles) through a full range of motion.

3.2.6 Countermovement jump (CMJ) protocol

Participants performed five maximal effort CMJs with their weight distributed evenly between their feet while standing on the force plate. Each jump was separated by 1-minute rest. The force plate was custom made and fitted with five RSS-type II loads cells (Route Industrial Automation, JHB RSA), each with a 2-tonne maximum load capacity. The force plate was embedded into and flush with the floor surface. The force plate had a cable feed which connected to a summation box and strain amplifier[265]. Force-time data were filtered using a 2nd order Butterworth low-pass filter with a cut-off frequency of 5 Hz. The force plate was previously tested and presented with a high degree of reliability (intraclass coefficient (ICC); 0.88 to 1.00) with a low typical error of measurement (TEM) (1.3 to 1.6 %) for mean and peak force[266]. The participants were instructed to squat as deep as they felt comfortable and to jump as high as they could each time, with the aim of keeping each jump as consistent as possible. Arm swings were allowed for each jump; however, the participants were instructed to avoid any knee tuck or bend after take-off[234].

Throughout each jump, ground reaction force was recorded at a sampling frequency of 2000 Hz, and a digital-to-analogue converter card converted the raw voltage signal into a standard measure that could be imported into Excel (Microsoft Office Excel 2007). The force-time curve produced for each jump was then analysed using Excel, and the various CMJ variables were extracted through a custom code and then calculated.

Time to maximal force was calculated as the difference in time at the start of the concentric phase and the end of the concentric phase. The determination of these two points was done in accordance with previous research by Sole et al (2018), McMahon et al (2018) and Chavad et al (2018), in that the concentric phase was deemed to start at the point when positive centre of mass velocity was achieved and ended just before take-off (or at peak centre of mass velocity)[223,227,229]. Jump height was calculated by using time in the air which was identified as the period between take-off and ground contact after flight, with the equation[267];

- *Jump height (meters) = (0.5 x 9.81) * (FT/2)*^{2}
- *Where FT = flight time (s)*

Rate of force development was calculated as the difference in force in Newtons (N) divided by the time in seconds (s) measured between the points at the bottom (minimum force) and the top (maximum force) of the concentric phase and expressed as N.s^{-1}[253]. Force was measured in Newton's (N) and time was measured in seconds (s), giving an RFD unit of N.s^{-1}.

$$\mathbf{RFD} = \frac{Maximum\ force\ of\ Concentric\ phase\ (B) - Minimum\ force\ of\ Concentric\ Phase\ (A)}{Time\ from\ A\ to\ B}$$

3.2.7 Testing days

All three-force plate CMJ testing sessions were conducted within one week, 48 hours apart and at similar time (within 2 hours) each day. This controlled for potential changes in strength characteristics that may occur due to training adaptations or circadian rhythms. The specific rest period of 48 hours allowed for adequate recovery between testing sessions.

3.2.8 Data Capture

Throughout each jump, the ground reaction force was recorded at a sampling frequency of 2000 Hz and a digital to analogue converter card converted the raw voltage signal into a standard measure that could be imported into Excel (Microsoft Office Excel 2007). The force-time curve produced for each jump was then analysed using Excel. The force achieved at the bottom of the concentric phase and the top of the concentric phase (peak force) was recorded. RFD was calculated as the difference in force (N) divided by the time (s) between these two points and expressed as $N.s^{-1}$ (FIGURE 2.4, Ch 2 p 46). Flight time was also recorded for each jump as an added measure to assess consistency.

3.3 Statistical analysis

All statistics were performed using Statistica version 12 (StatsSoft Inc. USA). The participant characteristics of the three groups were assessed for homogeneity and equal variance using a Levene's test. All variables displayed equal variance except for 1 repetition maximum (1RM). However, non-parametric analysis of this variable yielded similar results to the parametric analysis. Therefore, we decided to report all the data using analyses derived from parametric statistics. In accordance, a one-way analysis of variance was used to determine whether there were significant differences in participant characteristics between the three groups. If necessary, a Tukey *post hoc* test was used to identify specific differences. A two-way analysis of variance for repeated measures was used to determine whether there were significant differences in the CMJ data for either main effect of 'time' or 'groups' or for the interaction between 'time x group'. The five CMJ variables analysed included, maximum force, time to maximum force (TTMF), RFD, Jump height and flight time. The values from the 5 CMJs were combined and expressed as an average ± standard deviation for each day. Statistical significance was accepted when $p < 0.05$.

Reliability of the countermovement jump data was assessed using the spreadsheet “Reliability from consecutive pairs of trials”, downloaded from www.sportsci.org (Hopkins, 2000). Typical Error of Measurement (TEM), as a % of the mean (CVTEM) and the Intra-class Correlation Coefficient (ICC) were calculated for each jump variable for the group as a whole and also individually per training status group.

The TEM estimates how repeated measures of a person on the same measurement tool tend to be distributed around his or her “true” score. In the case of this study the TEM is directly related to the reliability of the force plate; that is, the larger the TEM, the lower the reliability of the force plate with less precision of the measurement[115]. An important form of typical error is the coefficient of variation: the typical error expressed as a percent of the mean (CVTEM). The CVTEM is particularly useful for representing the reliability of athletic events or performance tests and since it is unitless enables a comparison between variables with different units[116].

The ICC was used to assess the consistency or reproducibility of maximum force, TTMF, RFD, jump height and flight time over the three testing sessions.

Counter movement jump data representing the smallest meaningful differences in the four CMJ variables that would be a *trivial, small* or *medium* change were calculated according to Cohen’s effect size (< 0.2 = *trivial,* < 0.5 = *small,* < 0.8 = *medium,* >0.8 = *large*). The typical error for each variable was then compared to the relevant meaningful difference to assess the magnitude of difference the force plate could detect.

3.4 Results

Participant characteristics are shown in TABLE 3.1. The anthropometric characteristics of the three training groups were similar. The 1RM squat scores were significantly different (p<0.006) between the untrained vs. trained groups (trained 58 % higher than untrained) and between the semi-trained vs. trained group (trained 30 % higher than semi-trained). FIGURE 3:1 shows the relationship between the CMJ variables and relative strength for each of the training status groups. CMJ jump height was statistically different (p<0.001) between the untrained vs. trained group (trained 31 % higher than untrained). TABLE 3.2 displays the CMJ data for maximum force, TTMF, RFD and flight time for the whole group; as well as divided into the separate training status groups.

TABLE 3.1: Participant characteristics divided into subgroups; untrained; semi-trained and trained according to self-reported strength training age.

Participant characteristic	Untrained (n=10)	Semi-trained (n=9)	Trained (n=10)	Total (n=29)
Age (years)	26 ± 4	26 ± 3	25 ± 2	25 ± 3
Body mass (kg)	80.4 ± 12.6	80.7 ± 10.0	84.7 ± 9.4	82.0 ± 10.6
Stature (m)	178.1 ± 8.7	179.4 ± 10.5	180.1 ± 5.6	179.2 ± 8.2
BMI (kg.m^2)	25.5 ± 4.7	25.1 ± 2.9	26.1 ± 2.5	25.6 ± 3.4
Body fat (%) (Means)	20.3 ± 4.8	17.0 ± 4.4	15.8 ± 3.2	17.7 ± 4.5
Fat mass (kg)	16.8 ± 6.3	13.9 ± 4.4	13.4 ± 3.3	14.7 ± 4.9
Lean body mass (kg)	63.6 ± 7.5	66.9 ± 7.9	71.3 ± 7.9	67.3 ± 8.2
Lean thigh volume (l)	5.6 ± 0.6	7.0 ± 2.2	7.1 ± 1.2	6.5 ± 1.6
1 Repetition maximum Squat (kg)	78.8 ± 15.4	105.9 ± 16.8	143.1 ± 32.5	109.4 ± 35.2*
CMJ height (cm)	47.1 ± 5.1	54.7 ± 10.3	64.1 ± 10.0	55.3 ± 11.1#

*Untrained vs. trained, semi-trained vs. trained – p < 0.006.

#Untrained vs. trained – p < 0.001

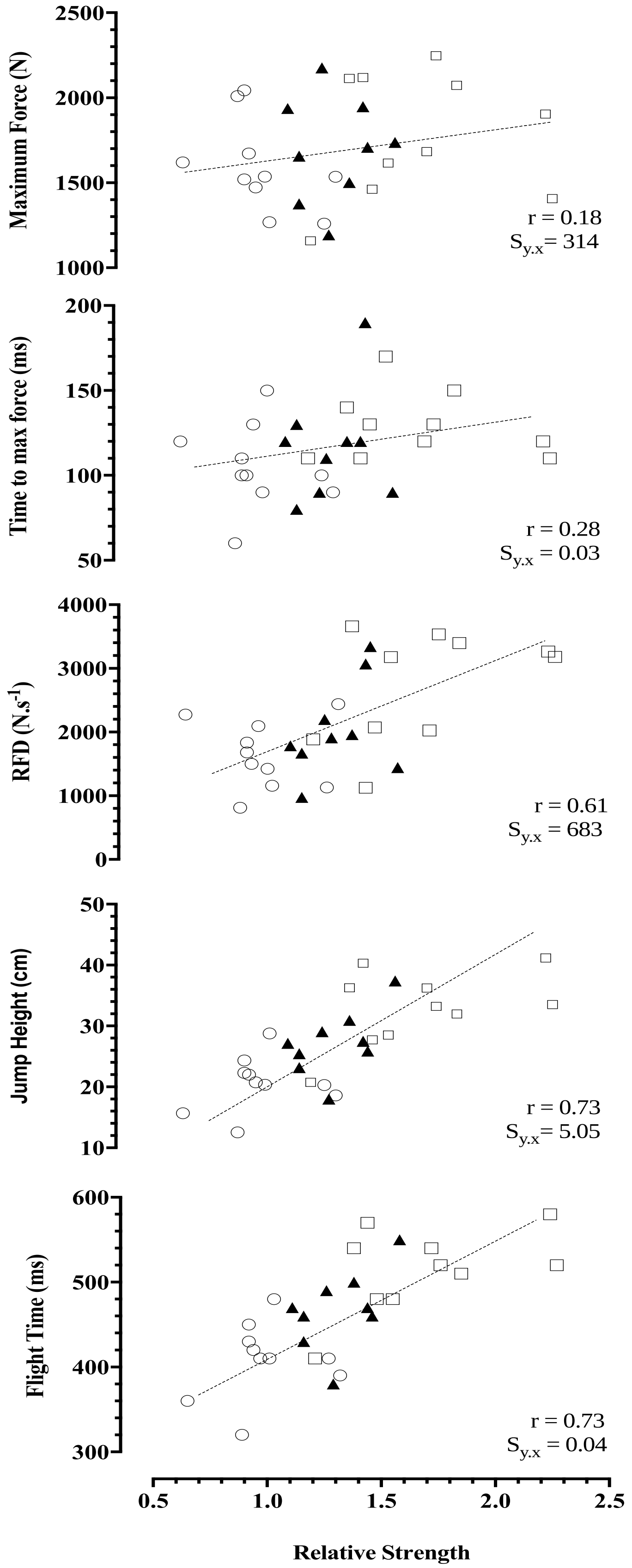


FIGURE 3.1: Relationship of variables RFD, maximum force, time to maximum force and flight time to relative strength of participants. Symbols indicate training status; ◦ untrained, Δ semi-trained and □ trained. Correlation indicated by r values and standard error of estimate by Sy.x.

TABLE 3.2: Countermovement jump data for the individual training groups and the entire group. Data are expressed as the mean ± standard deviation of the 5 countermovement jumps completed for each day. Whole group (n=29); untrained (n=10), semi-trained (n=9), trained (n=10).

Variable	Day 1	Day 2	Day 3	Mean
Maximum force (N)				
- Untrained	1614 ± 301	1592 ± 269	1584 ± 267	1597 ± 279
- Semi-trained	1715 ± 394	1648 ± 327	1690 ± 249	1684 ± 323
- Trained	1702 ± 360	1712 ± 368	1827 ± 367	1747 ± 365
- Whole group	**1675 ± 341**	**1649 ± 314**	**1701 ± 307**	**1675 ± 321**
Time to maximum force (m.s^{-1})				
- Untrained	120 ± 70	100 ± 30	100 ± 20	110 ± 40
- Semi-trained	120 ± 60	110 ± 30	110 ± 20	110 ± 40
- Trained	140 ± 60	120 ± 110	120 ± 10	130 ± 30
- Whole group	**120 ± 60**	**110 ± 30**	**110 ± 20**	**120 ± 40**
Rate of force development (N.s^{-1})				
- Untrained	1441 ± 482	1782 ± 737	1655 ± 630	1626 ± 616
- Semi-trained	2225 ± 1175	1930 ± 734	2011 ± 737	2055 ± 882
- Trained	2510 ± 824	2690 ± 975	2797 ± 870	2666 ± 889
- Whole group	**2052 ± 947**	**2122 ± 886**	**2159 ± 877**	**2111 ± 903**
Jump height (cm)				
- Untrained	20.1 ± 4.4	20.4 ± 5.2	20.8 ± 4.3	20.4 ± 4.5
- Semi-trained	27.8 ± 6.6	26.9 ± 4.9	26.9 ± 5.2	27.2 ± 5.4
- Trained	32.7 ± 6.0	31.6 ± 6.4	34.1 ± 6.8	32.8 ± 6.3
- Whole group	**26.86 ± 7.71**	**26.07 ± 7.09**	**27.25 ± 7.76**	**26.73 ± 7.45**
Flight time (m.s^{-1})				
- Untrained	400 ± 40	400 ± 50	410 ± 50	400 ± 50
- Semi-trained	470 ± 60	470 ± 40	470 ± 50	470 ± 50
- Trained	510 ± 50	510 ± 50	520 ± 50	510 ± 50
- Whole group	**460 ± 70**	**460 ± 60**	**470 ± 70**	**460 ± 70**

3.4.1 Maximum force

There was no difference in maximum force for the whole group over the 3 testing sessions ($F_{2,44} = 1.22$, $p = 0.30$) or between the training status groups ($F_{2,22} = 0.15$, $p = 0.87$). There was also no statistically significant interaction effect between group and time ($F_{4,44} = 1.27$, $p = 0.29$). TABLE 3.3 displays the reliability results for maximum force. As a whole group, the typical error was 84 N, which translates to a 0.3 % variation in maximum force when measured by the force plate. This variation was less in the trained group alone, with only a 0.2 % variation detected in maximum force. The ICC was high for the entire group (ICC = 0.93) with the trained group displaying the highest consistency (ICC = 0.96). TABLE 3.4 displays the smallest differences necessary to represent *trivial*, *small*, and *medium* changes for the four CMJ variables. With the level of error observed for the whole group, the force plate was able to detect *small* changes in maximum force. This was the same for the individual training status groups.

3.4.2 Time to maximum force

There was no difference in TTMF for the whole group over the 3 testing sessions ($F_{2,44} = 1.92$, $p = 0.16$) or between the training status groups ($F_{2,22} = 0.92$, $p = 0.41$). There was also no statistically significant interaction effect between group and time ($F_{4,44} = 0.18$, $p = 0.95$). TABLE 3.3 displays the reliability results for TTMF. As a whole group, the typical error was 0.03 seconds, which translates to a 0.74 % variation in time when measured by the force plate. The semi-trained group displayed the lowest variation (0.55 %). The ICC for TTMF was poor for the whole group (ICC = 0.47) with the semi-trained group displaying the highest consistency (ICC = 0.72). Based on the effect sizes (TABLE 3.4), the force plate was able to detect only *medium* changes in TTMF, with the semi-trained group faring better than the trained and untrained groups by detecting *small* changes.

3.4.3 Rate of force development (RFD)

There was no difference in RFD for the whole group over the 3 testing sessions ($F_{2,44} = 0.57$, $p = 0.57$) or between the training status groups ($F_{2,22} = 3.07$, $p = 0.07$). There was also no statistically significant interaction effect between group and time ($F_{4,44} = 1.42$, $p = 0.24$). TABLE 3.3 displays the reliability results for RFD. As a whole group, the typical error was 385 $N.s^{-1}$, which translates to a 0.4 % variation in RFD when measured by the force plate. Like maximum force, the trained group displayed the lowest variation (0.3 %). The ICC was high for the whole group (ICC = 0.83) with the trained group displaying the highest consistency (ICC = 0.94). It is clear from this analysis that all groups displayed adequate consistency with the trained group displaying the least variation. With the level of error observed for the whole group and the trained group, the force plate was able to detect *small* changes in RFD (TABLE 3.4), however only *medium* changes for the semi-trained and untrained group.

3.4.4 Jump height

There was a significant difference in jump height for the whole group over the 3 testing sessions ($F_{2,4} = 6.5$, $p = 0.003$). Furthermore, there was a difference between the three different training status groups ($F_{2,22} = 9.63$, $p = 0.001$), as well as a statistically significant interaction effect between group and time ($F_{4,44} = 4.1$, $p = 0.006$). As a whole group the typical error was 1.06 cm which translates to a 0.18 % variation in jump height when measured by the force plate. Again, the trained group displayed the lowest variation (0.19 %). The ICC was the highest compared to all other variables (ICC = 0.97) with the trained group displaying the highest consistency (ICC = 0.97). Jump height also achieved the highest level of precision, with the force plate being able to detect *trivial* changes in the trained group (TABLE 3.4).

3.4.5 Flight time

Similar, to that of jump height, there was no difference in flight time for the whole group over the 3 testing sessions ($F_{2,44} = 2.43$, $p = 0.09$), however there was a difference between the three different training status groups ($F_{2,22} = 10.18$, $p < 0.05$). There was no statistically significant interaction effect between group and time ($F_{4,44} = 1.64$, $p = 0.18$). TABLE 3.3 displays the reliability results for flight time. As a whole group the typical error was 0.01 seconds which translates to a 0.18 % variation in flight time when measured by the force plate. Again, the trained group displayed the lowest variation (0.18 %). The ICC was the highest compared to all other variables (ICC = 0.97) with the trained group displaying the highest consistency (ICC = 0.97). Flight time also achieved the highest level of precision, with the force plate being able to detect *trivial* changes in this variable (TABLE 3.4).

FIGURE 3.2 provides a summary of the CV_{TEM} for all groups for all CMJ variables. The trained group had the lowest typical error (highest reliability) for all variables except TTMF, which was high for all groups. The TTMF also had much more variability as shown by the 90 % CI error bars.

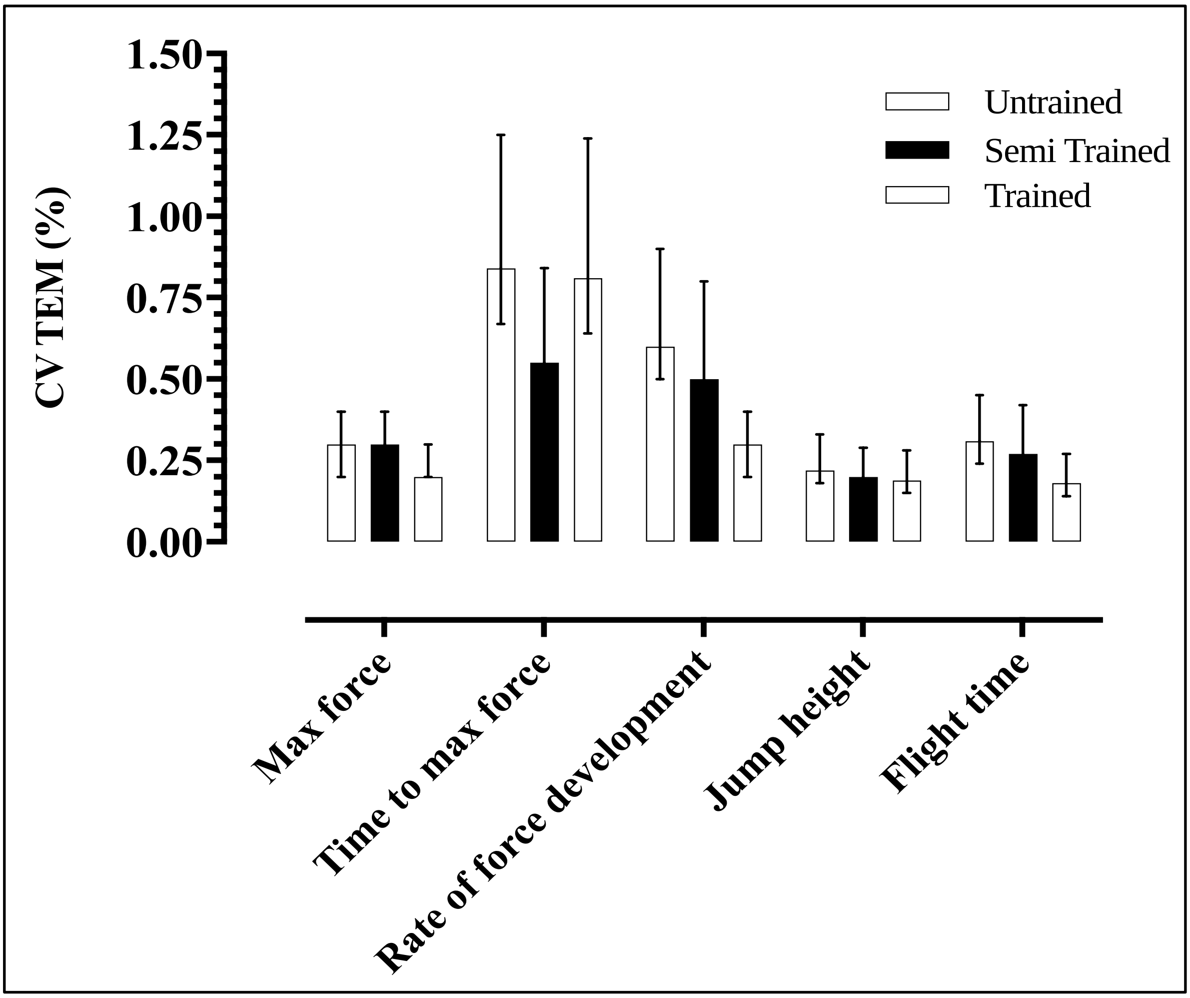


FIGURE 3.2: Typical error as a coefficient of variation (CVTEM) for maximum force (MF), time to maximum force (TTMF), rate of force development (RFD) and flight time (FT) for each of the training status groups. Untrained (n=10), semi-trained (n=9), trained (n=10). Error bars represent the ± 90 % CI.

TABLE 3.3: Reliability data for all CMJ variables recorded for the whole group as well as each individual training group over the 3 testing days. Whole group (n=29), untrained (n=10), semi-trained (n=9), trained (n=10). TEM= Typical Error of Measurement, CVTEM= TEM as a % of the mean, ICC= Intra-class Correlation Coefficient. Results are expressed with 90 % confidence limits.

Variables		Untrained	Semi- Trained	Trained	Whole Group
Maximum force (N)					
TEM (N)	Day 1 vs. 2	75 (54 - 129)	90 (63 - 161)	61 (43 - 109)	**79 (64 - 103)**
	Day 2 vs. 3	73 (54 - 121)	105 (76 - 180)	87 (63 - 149)	**89 (73 - 115)**
	Mean	**74 (59 - 110)**	**98 (76 - 144)**	**76 (59 - 111)**	**84 (72 - 104)**
CV TEM (%)	Day 1 vs. 2	0.3 (0.2 - 0.5)	0.3 (0.2 - 0.4)	0.2 (0. 1 - 0.3)	**0.3 (0.2 - 0.3)**
	Day 2 vs. 3	0.3 (0.2 - 0.5)	0.4 (0.3 - 0.7)	0.2 (0.2 - 0.4)	**0.3 (0.3 - 0.4)**
	Mean	**0.3 (0.2 - 0.4)**	**0.3 (0.2 - 0.4)**	**0.2 (0.2 - 0.3)**	**0.3 (0.2 - 0.3)**
ICC	Day 1 vs. 2	0.95 (0.83 - 0.98)	0.96 (0.85 - 0.99)	0.98 (0.93 - 0.99)	**0.95 (0.90 - 0.97)**
	Day 2 vs. 3	0.94 (0.83 - 0.98)	0.90 (0.70 - 0.97)	0.96 (0.87 - 0.99)	**0.92 (0.86 - 0.96)**
	Mean	**0.93 (0.85 - 0.97)**	**0.91 (0.81 - 0.96)**	**0.96 (0.91 - 0.98)**	**0.93 (0.89 - 0.96)**
Time to maximum force (ms)					
	Day 1 vs. 2	50 (40 - 90)	30 (20 - 50)	40 (30 - 70)	**40 (30 - 50)**
TEM (ms)	Day 2 vs. 3	10 (10 - 20)	20 (10 - 30)	10 (10 - 10)	**10 (10 - 10)**
	Mean	**40 (30 - 50)**	**20 (20 - 30)**	**30 (20 - 40)**	**30 (20 - 40)**
	Day 1 vs. 2	6.05 (4.34 - 10.35)	0.73 (0.52 - 1.32)	3.38 (2.38 - 6.07)	**1.82 (1.48 - 2.39)**
CV TEM (%)	Day 2 vs. 3	0.48 (0.35 - 0.79)	0.67 (0.48 - 1.15)	0.66 (0.47 - 1.13)	**0.54 (0.44 - 0.69)**
	Mean	**0.84 (0.67 - 1.25)**	**0.55 (0.43 - 0.84)**	**0.81 (0.64 - 1.24)**	**0.74 (0.63 - 0.91)**
	Day 1 vs. 2	–0.03 (-0.62 - 0.52)	0.71 (0.22 - 0.91)	0.09 (-0.62 - 0.62)	**0.24 (-0.11 - 0.52)**
ICC	Day 2 vs. 3	0.85 (0.60 - 0.95)	0.75 (0.34 - 0.92)	0.75 (0.34 - 0.92)	**0.79 (0.63 - 0.88)**
	Mean	**0.30 (-0.17 - 0.62)**	**0.72 (0.41 - 0.86)**	**0.35 (-0.16 - 0.66)**	**0.47 (0.25 - 0.65)**
Rate of force development ($N.s^{-1}$)					
	Day 1 vs. 2	478 (350 - 834)	584 (412 - 1050)	232 (163 - 416)	**471 (382 - 620)**
TEM ($N.s^{-1}$)	Day 2 vs. 3	275 (200 - 452)	369 (265 - 631)	209 (150 - 357)	**287 (236 - 372)**
	Mean	**389 (311 - 576)**	**482 (372 - 706)**	**220 (169 - 321)**	**385 (329 - 475)**
	Day 1 vs. 2	1.2 (0.9 - 2.1)	0.8 (0.5 - 1.37)	0.3 (0.2 - 0.5)	**0.6 (0.5 - 0.8)**
CV TEM (%)	Day 2 vs. 3	0.4 (0.3 - 0.7)	0.6 (0.4 - 0.9)	0.2 (0.2 - 0.4)	**0.4 (0.3 - 0.5)**
	Mean	**0.6 (0.5 - 0.9)**	**0.5 (0.4 - 0.8)**	**0.3 (0.2 - 0.4)**	**0.4 (0.4 - 0.5)**
ICC	Day 1 vs. 2	0.45 (-0.15 - 0.79)	0.70 (0.18 - 0.90)	0.90 (0.80 - 0.90)	**0.75 (0.56 - 0.86)**
	Day 2 vs. 3	0.87 (0.65 - 0.96)	0.80 (0.46 - 0.94)	0.90 (0.88 - 0.99)	**0.90 (0.82 - 0.95)**
	Mean	**0.63 (0.28 - 0.80)**	**0.72 (0.42 - 0.86)**	**0.94 (0.87 - 0.97)**	**0.83 (0.72 -0.90)**
Jump Height (cm)					
	Day 1 vs. 2	1.37 (0.398 - 2.35)	1.46 (1.03 - 2.62)	1.08 (0.76 - 1.93)	**1.38 (1.13 - 1.81)**
TEM (cm)	Day 2 vs. 3	0.65 (0.47 - 1.06)	0.69 (0.50 - 1.18)	1.32 (0.95 - 2.26)	**0.66 (0.54 - 0.84)**
	Mean	**1.05 (0.84 - 1.56)**	**1.12 (0.86 - 1.64)**	**1.21 (0.93 - 1.77)**	**1.06 (0.91 - 1.30)**
	Day 1 vs. 2	0.30 (0.21 - 0.51)	0.26 (0.18 - 0.47)	0.18 (0.12 - 0.32)	**0.24 (0.19 - 0.31)**
CV TEM (%)	Day 2 vs. 3	0.13 (0.10 - 0.22)	0.13 (0.10 - 0.23)	0.20 (0.15 - 0.35)	**0.11 (0.09 - 0.15)**
	Mean	**0.22 (0.18 - 0.33)**	**0.20 (0.15 - 0.29)**	**0.19 (0.15 - 0.28)**	**0.18 (0.15 - 0.22)**
ICC	Day 1 vs. 2	0.94 (0.81 - 0.98)	0.96 (0.84 - 0.99)	0.98 (0.92 - 0.99)	**0.95 (0.91 - 0.97)**
	Day 2 vs. 3	0.99 (0.96 - 1.00)	0.99 (0.96 - 1.00)	0.97 (0.90 - 0.990	**0.99 (0.98 - 0.99)**
	Mean	**0.95 (0.90 - 0.98)**	**0.96 (0.92 - 0.98)**	**0.97 (0.92 - 0.98)**	**0.97 (0.95 - 0.98)**
Flight time (ms)					
	Day 1 vs. 2	20 (10 - 30)	10 (10 - 20)	10 (10 - 20)	**10 (10 - 20)**
TEM (ms)	Day 2 vs. 3	10 (10 - 20)	10 (10 - 20)	10 (10 - 20)	**10 (10 - 20)**
	Mean	**10 (10 - 20)**	**10 (10 - 20)**	**10 (10 - 10)**	**10 (10 - 20)**
	Day 1 vs. 2	0.33 (0.24 - 0.l56)	0.27 (0.19 - 0.l48)	0.18 (0.12 - 0.31)	**0.16 (0.13 - 0.24)**
CV TEM (%)	Day 2 vs. 3	0.30 (0.22 - 0.49)	0.32 (0;.23 - 0.55)	0.19 (0.13 - 0.32)	**0.20 (0.16 - 0.28)**
	Mean	**0.31 (0.24 - 0.45)**	**0.27 (0.21 - 0.42)**	**0.18 (0.14 - 0.27)**	**0.18 (0.15 - 0.24)**
ICC	Day 1 vs. 2	0.93 (0.77 - 0.98)	0.95 (0.84 - 0.99)	0.98 (0.92 - 0.99)	**0.97 (0.95 - 0.99)**
	Day 2 vs. 3	0.94 (0.82 - 0.98)	0.93 (0.79 - 0.98)	0.98 (0.92 - 0.99)	**0.96 (0.92 - 0.98)**
	Mean	**0.91 (0.81 - 0.96)**	**0.93 (0.84 - 0.97)**	**0.97 (0.93 - 0.99)**	**0.97 (0.94 - 0.99)**

TABLE 3.4: The magnitude of the differences that would equate to effect sizes corresponding to *trivial*, *small*, and *medium* changes for the three groups (untrained n=10, semi-trained n=9 and trained n=10) and the whole group (n=29). The values that are bolded and underlined are greater than the typical error and represent the smallest detectable change for that variable.

Variables	**<0.2 (trivial)**	**<0.5 (small)**	**<0.8 (medium)**
Maximum force (N)			
- Untrained	56	**140**	**223**
- Semi trained	65	**162**	**258**
- Trained	73	**183**	**292**
- Whole group	**64**	**161**	**257**
Time to maximum force (ms)			
- Untrained	8	20	**32**
- Semi trained	8	20	**32**
- Trained	6	15	**24**
- Whole group	**8**	**20**	**34**
Rate of force development (N.s^{-1})			
- Untrained	123	308	**493**
- Semi trained	176	441	**705**
- Trained	178	**445**	**711**
- *Whole group*	181	**452**	**722**
Jump height (cm)			
- Untrained	0.90	**2.26**	**3.60**
- Semi trained	1.10	**2.70**	**4.30**
- Trained	**1.25**	**3.13**	**5.00**
- Whole group	**1.50**	**3.73**	**5.96**
Flight time (ms)			
- Untrained	**10**	**25**	**49**
- Semi trained	**10**	**25**	**40**
- Trained	**10**	**25**	**40**
- Whole group	**14**	**35**	**56**

3.5 Discussion

The aim of this study was to assess the validity and reliability of a force plate to measure various CMJ variables. A further aim was to assess whether the strength training age of participants would influence the validity and reliability of these variables. The main finding of this study was that there were no significant differences in any of the CMJ variables over the three testing sessions. This consistency was the same for each of the training ages. The variation around each measurement was attributed to the typical error of the measurement (FIGURE 3.2).

The three groups, defined by strength training age, differed only in terms of their performance characteristics. This was expected because the groups were divided according to months participating in strength training. This was confirmed with the performance test when using the notion that a higher training age would lead to a better performance in the 3RM and CMJ tests[96]. In accordance with this, the trained group also had the highest average maximum force, RFD and flight time compared to the other groups. However, the trained group also had the highest TTMF, which is possibly due to their ability to produce a greater amount of force during the jump. However, the type of resistance training the participants used was not assessed. Therefore, the high TTMF can be explained by the possibility that the ‘trained’ athletes possibly lacked exposure to explosive power training, which would decrease the TTMF[268].

Typical error indicates the variation in a measurement around its true value when measured on repeated occasions[269]. Although this variation is referred to as error, it is important to note that only part of the variation is due to technological error from the measurement tool. Variation may also be caused by the participant’s biological variation and the inconsistencies in the instruction from the researcher[270].

All participants in this study were tested within one week to minimise the effect of biological changes in any of the CMJ variables. Therefore, a large portion of the variation can be attributed to the technological error of the force plate. CV_{TEM} expresses typical error as a percentage making it easier to compare and relate to other variables with different units of measurement. Furthermore, it appears subjects who have greater technical competence and experience in CMJ execution display a smaller CV_{TEM} for all variables measured.

Intraclass correlation coefficients have various categories ranging from "questionable" (0.7–0.8) to "high" (>0.9)[271]. Previous research focuses mainly on the variables of maximum force or time to maximum force using force plates with ICC values ranging from 0.92 to 0.99[239,267,272]. The present study achieved similar results for maximum force, jump height and flight time (0.93 and 0.97) but the ICC for RFD and time to maximum force (0.83 and 0.47) for the whole group were lower.

The added value of the present study was to include three groups of participants (untrained, semi-trained and trained) to determine whether there were differences in reliability of the force plate to measure CMJ variables in people of varying strength. The trained group had lower typical error and higher ICC values for maximum force, RFD, jump height and flight time than the semi-trained and untrained groups. Similarly, the semi-trained group had lower typical error and higher ICC values for RFD, jump height and flight time than the untrained group. This indicated a trend of decreasing reliability for CMJ variables with decreasing strength-training experience. This may be explained by the fact that the untrained participants were unfamiliar with the CMJ and struggled to maintain consistency with their jumping technique. This also manifested itself with the low ICC value for time to maximum force (ICC = 0.30) seen in the untrained group, which reduced the whole group average. It is also important to note that jump height and flight time when tested on the force plate were able to detect trivial changes in the trained group, suggesting that these variables may be the preferred measurement to indicate any change due to negative (fatigue) or positive (increase in performance) adaptations to training. Consequently, its plausible to say that the measurement of CMJ variables such as Force$_{max,}$ (small changes detectable), RFD (small changes detectable), jump height and flight time (trivial changes detectable) show a greater reliability in well trained individuals. This is similar to what has been found in previous research, when considering the complexity of measuring metrics like RFD especially outside of the laboratory setting. For example, Maffiuletti et al, suggest that RFD is a challenging metric to measure, due to the variability in muscle activation at the onset of contractions, decreasing the reliability of the measurement[253]. Further research is required to establish the relationship between acute and/or chronic training adaptations and/or fatigue and the associated of these CMJ variables.

3.5.1 Conclusions

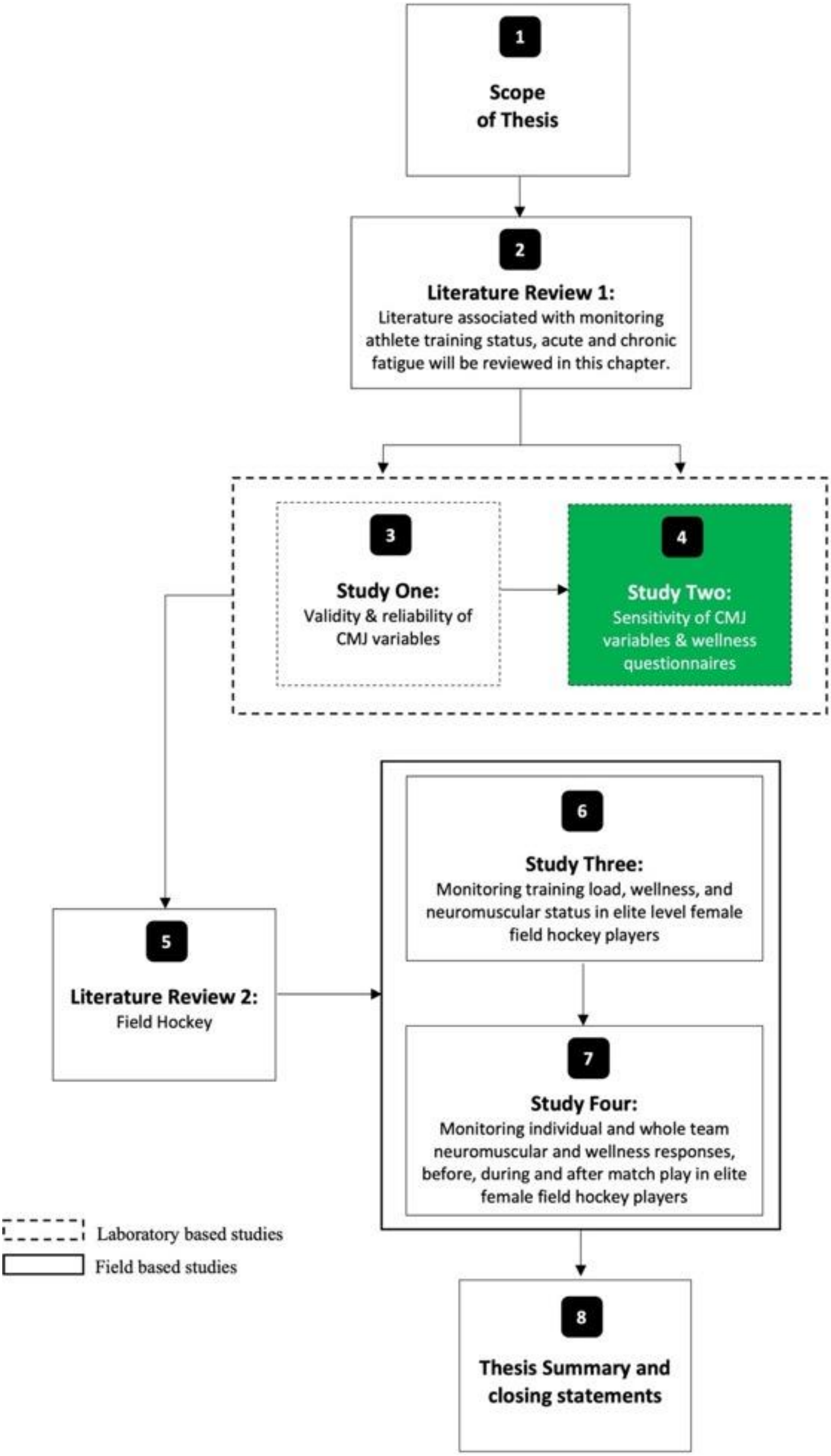
Coaches wanting to utilise various CMJ variables as a means of monitoring training adaptability are more likely to be working with well-trained athletes. The results from this study provide evidence that all CMJ variables in this study can be measured reliably during a countermovement jump on a force plate. The results can be further used to provide quantitative information for a practical setting. The TEM for RFD was 220 N.s^{-1} for the trained group. This means that a change in RFD of more than 220 N.s^{-1}, can be measured on the force plate. When expressed as a percentage, the present study showed an RFD variation of 0.30% between testing sessions when measured by the force plate. When looking at responsiveness to change, jump height and flight time proved to be able to detect the smallest changes, with the difference between trials showing an effect size of <0.2 for all groups and CV TEM of 0.30 % in trained individuals. Max force when measured on a force plate can detect small changes (ES

<0.5) with a CV TEM of 0.30 %. From this evidence, it seems that by performing a CMJ on a force plate it may be possible to detect small changes in RFD, maximum force, jump height and flight time in athletes of various training ages. However, further research is required on elite level athletes to monitor their training status throughout a training and/or competition cycle.

In closing, maximum force, rate of force development, jump height and flight time and time to maximum force, associated with neuromuscular function, measured on a force plate during a countermovement jump were valid and reliable. The validity and reliability were best in participants who had a higher strength training age. Lastly, there was sufficient precision to detect *trivial* to *medium* changes in neuromuscular function or status. Further investigation is required to establish the relationship between the CMJ variables and exercise-induced fatigue.

3.6 Chapter Three - Summary points

1. Trained participants' jump height was on average 31% higher than untrained individuals.
2. Flight time also differentiated between participant's training statuses with trained participants TEM being the lowest (0.18 %).
3. Maximum force did not differentiate between training statuses, however trained participants showed the lowest TEM (0.2 %) compared to untrained or semi-trained.
4. Time to maximum force may not differentiate between training statuses, but the semi-trained participants had the lowest TEM (0.74 %).
5. Rate of force development in trained participants showed the lowest TEM (0.3 %), however was not able to differentiate between training statuses.
6. *Trivial* changes can be detected in both jump height and flight time (ES <0.2)
7. *Small* changes can be detected in maximum force (ES <0.5)
8. The validity and reliability of the CMJ metrics were generally best in participants who had a higher strength training age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Literature associated with monitoring athlete training status, acute and chronic fatigue will be reviewed in this chapter.
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4. Chapter Four

Study Two: The relationship between countermovement jump variables, subjective wellness and exercise-induced fatigue

4.1 Introduction

There is a complex relationship between training loads, adaptations to training as well as injury[117,171]. While systematic exposure to high training loads protects against injury and improves the players' fitness, each player adapts and responds differently to training and competition[7]. This variation impacts on each player's fitness and risk of injury[190]. As a result, various monitoring variables are used in sport to identify individual responses to the demands of training and matches[92]. Further to this, post-match recovery is an important consideration because in modern sport the turnaround time from match-to-match can be as short as one day[152]. Thus, identifying markers of post-match fatigue and their "half-life", may allow practitioners to effectively develop post-match recovery strategies and training schedules that are based on principles of best practice[273]. One of the biggest challenges facing the modern-day athlete, therefore, is balancing his/her training load with recovery[38]. Training is a process of overload that disturbs body homeostasis, inducing an acute fatigue response, with the aim of increasing performance at a later stage. With increased load the athlete may experience an initial decrease in performance but with adequate recovery, we know that fatigue "dissipates" at a faster rate than performance, thus allowing for supercompensation to occur, where fitness may surpass the initial baseline levels[10].

Monitoring an athlete's responses to training and competition has the potential to inform coaches and trainers on the need for training load modifications to avoid unexpected responses which may occur with overreaching[257]. Symptoms of fatigue associated with overreaching may manifest as both psychological (subjective) and physiological (objective) disturbances. As a consequence, there is no single marker which consistently identifies fatigue or an athlete's training status[2], making it difficult to measure[67]. This being the case, a combination of subjective and objective measures could offer a more complete description of the training status and well-being of the athlete[132].

Psychological symptoms have been monitored through subjective wellness questionnaires, perceived training load (session rating of perceived exertion)[274] and the Profile of Mood States (POMS), all of which have been used to characterise the training status of athletes through possible psychological disturbances[121,130]. Furthermore, psychomotor speed tests such as cognitive reaction time tests, have also been used, however they are relatively new[275]. A reduced concentration and memory ability, leading to a reduced psychomotor ability (i.e., a slower reaction time), has been shown in patients with chronic fatigue and depression[275].

Another component that should be considered is the somatic nervous system because in intermittent high intensity sports, neuromuscular processes are pivotal to performance. Measures of neuromuscular function such as the jump tests (countermovement/squat jump), sprint performance, agility tests, isokinetic and isoinertial dynamometry are often utilized in professional sport environments[92].

Muscular strength and power are important for most sports[276], therefore it stands to reason that neuromuscular function is a good objective measure of the athlete's training status[242]. As described earlier (Section 2.5.3) neuromuscular fatigue is, "The decrease in muscles' force generating capacity"[69]. A negative consequence is a decrease in maximum force and velocity of muscle contraction and a slowing of muscle contraction-relaxation coupling, which all may limit dynamic sports performance[81,190,243]. Moreover, when the muscle becomes fatigued it becomes more resistant to stretch. This is largely due to the protective effect of the Golgi tendon organ, which decreases the activation of the muscle when large forces are generated, and in this way helps protect the muscle's integrity[86]. Thus, reducing the muscle’s ability to evoke the ‘Stretch-Shortening Cycle’ (SSC) which can result in a decrease in mechanical muscle function, including but not limited to, strength, power, and rate of force development[87]. Neuromuscular fatigue in general affects fast twitch fibres more than slow twitch fibres[257]. This has implications for high intensity intermittent sports and training where short bursts of exercise require the recruitment of fast twitch fibres. Traditionally, neuromuscular fatigue has been examined using single plane, non-dynamic movements incorporating, isometric, concentric, or eccentric contractions[277].

The CMJ has grown in popularity as a common measure of neuromuscular status[242]. CMJ performance is dependent on the neuromuscular interaction between the entire kinetic chain during the sequence of events leading to the take-off and landing phase of the jump[223,278]. As a consequence the CMJ is an attractive tool to monitor neuromuscular function, as the test is non-invasive, non-fatiguing and easy to administer. Claudino et al. (2016) showed that CMJ variables such as peak power, mean power, peak velocity, peak force and mean impulse were sensitive in tracking the supercompensation effects of resistance training [242]. Also, average CMJ jump height compared to peak CMJ jump height was more sensitive at tracking fatigue and/or supercompensation[242]. However, an inconsistency still exists about which CMJ variables are most sensitive to fatigue[242,257,279]. For example, variables incorporating time-based analysis such as rate of force development (RFD) and time to maximum force, seem to be more indicative of neuromuscular performance, whereas jump height and mean force may be indicative of peripheral adaptations or altered movement strategies[259]. Thus, as a continuation from Study one, we will investigate maximum force, time to max force, rate of force development, jump height as well as flight time. However, the responsiveness of these variables after a bout of fatiguing exercise has not been determined. This is an important clinimetric principle which will contribute to a better understanding of how to interpret the results in an applied setting[247]. Therefore, we hypothesize there would be changes in CMJ variables and subjective wellness responses following a protocol designed to simulate the physical demands of intermittent high intensity team sports[280,281].

4.2 Methods

4.2.1 Participants

Twenty-one male participants were recruited from members of the High Performance and Fitness Centres in the Sport Science Institute of South Africa, and sport clubs at the University of Cape Town (UCT). Male participants between the ages of 18-35 years, who were actively involved in physical activity three times a week, were recruited for the study. The baseline characteristics of the participants are shown in TABLE 4.1. All participants provided written informed consent (Appendix 3) after been informed of the study protocol and requirements. The protocol was conducted according to the Declaration of Helsinki and approval was obtained from the UCT Human Research Ethics Committee (HREC REF 341/2015 & HREC REF 282/2015; Appendix 5).

4.2.2 Experimental design and procedures

The study was a randomized cross-over repeated measures design. Initially participants were randomly allocated into one of two groups, with group one doing the intervention trial, Loughborough Intermittent Shuttle Test (LIST) first and group two starting with the control trial of 30 min light physical activity.

The testing protocol followed a structured fifteen-day cycle with a familiarization session conducted on day one (see FIGURE 4.1). During this visit participants completed an ACSM pre-participation screening (Appendix 1) and provided informed consent. On day one, participants reported their subjective readiness-to-train (wellness questionnaire; Appendix 2), dynamic warm-up and three CMJ on a custom-made force plate. The multistage shuttle run test (bleep test) was completed to predict the participants' VO_{2max}[282]. This measurement was used to adjust the intensity of the Loughborough Intermittent Shuttle Test (LIST) for each participant[280].

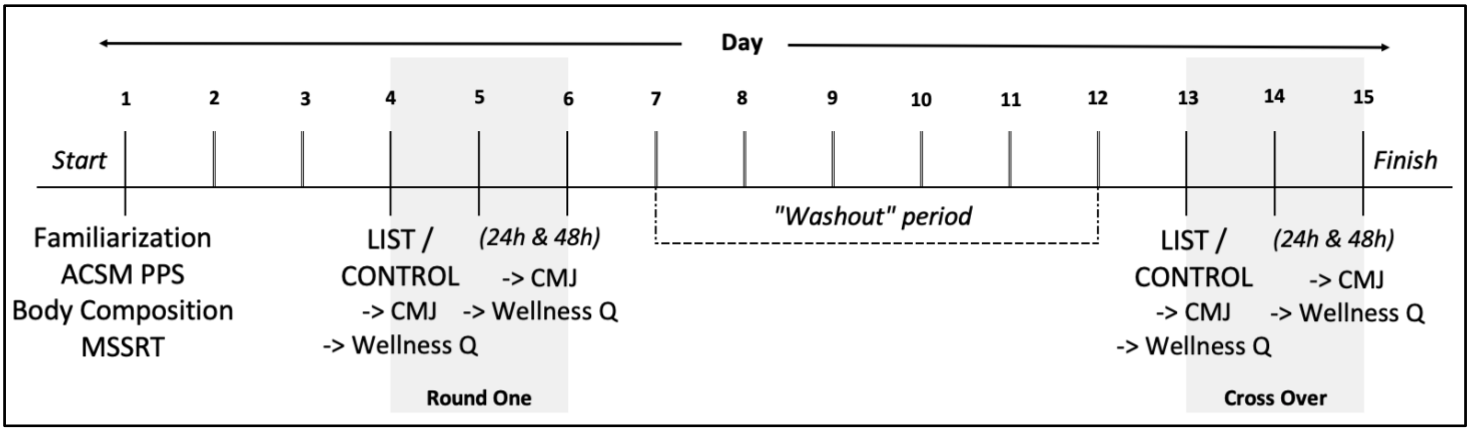


FIGURE 4.1: Study timeline representing the 3 distinct phases (familiarisation, round one and cross over) of the study. The shaded areas show where each of the interventions took place (e.g., round one and the cross over).

Key:

LIST – Loughborough Intermittent Shuttle Test

ACSM PPS – American College of Sports Medicine Pre-participation screening

MSSRT – Multistage Shuttle Run Test

CMJ – Countermovement Jump

Wellness Q – Subjective wellness questionnaire

Participants returned after two days (i.e., day 4) where they completed the wellness questionnaire, dynamic warm-up and three countermovement jumps on the force plate. Participants assigned to the first group completed the LIST intervention and participants in the second group were the CONTROL. The CONTROL intervention equivalent consisted of 30 minutes of light physical activity (Walking or Jogging) where HR was maintained around 65 % or less of age predicted HR_{max}. Heart rates were recorded using Zephyr BioModule and Omnisense software (Zephyr performance systems, Medtronic, Maryland, USA). Participants returned 24 h and 48 h later (i.e., days 5 and 6), where they completed the wellness questionnaire, dynamic warm-up and three CMJ on the force plate on each occasion. Participants refrained from any physical activity after completing the LIST/CONTROL until after their 48 h follow-up session. Participants were also not allowed to use any form of recovery aids during this time. There was a one-week "wash-out" period from day 7-12, where participants returned to their normal training routine. Participants then returned on day 13 where the process was once again repeated, after the crossover. i.e., the first group completed the CONTROL and the second group the LIST on this occasion. To account for diurnal variations, participants visited the laboratory for testing at a similar time of the day on each occasion.

4.2.3 Assessment of body composition

Body composition were assessed according to the protocol described in SECTION 3.2.2**.**

4.2.4 Standardised warm-up

The standardised warm up followed the same protocol as described earlier in SECTION 3.2.5**.**

4.2.5 Countermovement jump (CMJ)

The same CMJ protocol was followed as described earlier in SECTION 3.2.6**.** However, in this study, the mean score of three (as opposed to five) maximal effort CMJ’s for each variable were recoded as the final score.

4.2.6 Subjective wellness and readiness-to-train questionnaire

At the start of each visit the participants completed the wellness and readiness-to-train questionnaire. Since there was no validated questionnaire appropriate for the needs of this study, we developed a seven-item questionnaire that serves as the subjective analysis of the participant’s readiness-to-train. The questionnaire serves as a continuation from study one (Chapter Three), with questions associated with each item being adapted from a survey of coaches[101] and other studies on performance readiness[283]. These questions cover a variety of aspects known to affect wellness and readiness-to-train. We used the data from the 19 participants during the control phase to calculate the typical error of measurement (TEM) using the spreadsheet “Reliability from consecutive pairs of trials”, downloaded from www.sportsci.org (TABLE 4.2). Data were missing on the other two participants for this calculation.

4.2.7 Multi-stage shuttle run test

The multistage shuttle run test was used to predict maximal aerobic capacity of participants. Participants ran back-and-forth between two lines 20 m apart, at a pace set by a recorded sound. The pace increased each minute, and the participant continued to run between the lines until they were unable to maintain the pace for two consecutive laps, or until they decided to voluntarily withdraw. VO_{2max} ($ml.kg^{-1}.min^{-1}$) was predicted from the number of laps they completed[282].

4.2.8 Loughborough Intermittent Shuttle Test (LIST)

The LIST is a 90-minute test designed to mimic the activity pattern, metabolic and physiological responses, and associated fatigue of team-based ball sports such as soccer[280]. The test is composed of two parts. Part A includes 5 x 15-minute exercise periods with 3 minutes of recovery in between. Each 15-minute interval includes the following exercise pattern:

- Stage 1: 3 x 20 m walking
- Stage 2: 1 x 20 m maximal running speed
- Stage 3: 3 x 20 m running speed at 55% predicted VO_{2max}
- Stage 4: 3 x 20 m running speed at 95% predicted VO_{2max}

The speeds for stages 3 and 4 were determined from the predicted VO_{2max} obtained from the multistage shuttle run test completed during familiarization. Part B is an open-ended period of shuttle running, with speeds alternating between 55 % and 95 % VO_{2max}, designed to exhaust the participants. The test was ended when the participants could not maintain the prescribed pace. Fatigue was described as the point where particiapnts could not compete two consecutive shuttles in the required time.

4.3 Statistical analysis

The CMJ data satisfied the criteria for parametric statistics. These data were analysed using a two-way analysis of variance with repeated measures. A Greenhouse-Geisser correction was used when the assumption of sphericity was violated (IBM SPSS Statistics for Mac, version 25 (IBM Corp., Armonk, N.Y., USA). The data for the wellness questionnaire was non-parametric therefore a Wilcoxon match pairs test was used to detect significant differences in answers between pre and 24 h and pre and 48 h for CONTROL and LIST (GraphPad Prism (version 7.00 for Windows, GraphPad Software, San Diego California USA).

The effect size differences (*d*) for the neuromuscular data were calculated between the pre-24 h and pre - 48 h data for CONTROL and LIST according to the Cohen's effect size principle[284,285]. An effect size of < 0.2 was considered *trivial* and an effect size of 0.2 was defined as the smallest worthwhile change. Data are expressed as mean ± standard deviation.

4.4 Results

Participants engaged in physical activity at least three times (5 ± 2 times) per week at a moderate to high intensity (8.3 ± 1.3 RPE). The general characteristics such as body mass, height, lean body mass, and $V0_2$ max of the participants are shown in TABLE 4.1 below.

TABLE 4.1: General descriptive characteristics of participants (n=21)
Data expressed as mean ± SD.

Participant characteristics	**Mean ± SD**	**Range**
Age (years)	24 ± 3	20 – 34
Body mass (kg)	77.3 ± 8.0	59.6 - 93.7
Body fat (%)	12.7 ± 2.3	8.6 – 17.5
Fat mass (kg)	9.8 ± 2.1	5.9 – 14.2
Lean body mass (kg)	67.4 ± 7.1	54.0 – 84.2
Height (cm)	179 ± 5.7	168 - 188
VO_{2max} ($mlO_2.kg^{-1}.min^{-1}$)	49.1 ± 5.3	42.0 – 54.0

Analysis of the subjective wellness questionnaire (TABLE 4.2) revealed significant changes for the LIST group. There was a significant decrease between Pre and 24 h for question 1, **"Do you feel physically strong today?"** ($p = 0.008$). Furthermore, question 2, **"Do you feel mentally strong today?"**, showed a significant decrease between pre and 48 h ($p = 0.02$). Question 6, **"Do you have any muscle soreness today?",** was the only question to show significant increases compared to pre at both 24 h ($p = 0.001$) and 48 h ($p = 0.001$) post intervention. All changes indicated there was fatigue present post LIST intervention.

TABLE 4.2: Answers to the subjective wellness questionnaire for CONTROL and LIST at Pre, 24 h and 48 h (n=19). The Typical error of measurement (TEM) is reported as the mean and 90% limits.

Question	Group	Pre	24	48	TEM
Q1: Do you feel physically strong today? [1-5]	CONTROL	4.1 ± 0.7	3.9 ± 0.7	4.0 ± 0.7	*0.5*
	LIST	**3.9 ± 0.8**	**3.4 ± 1.0****	3.6 ± 0.6	*(0.4 to 0.6)*
Q2: Do you feel mentally strong today? [1-5]	CONTROL	4.1 ± 0.7	4.1 ± 0.7	4.0 ± 0.7	*0.6*
	LIST	**4.2 ± 0.5**	4.0 ± 0.6	**3.7 ± 0.6***	*(0.5 to 0.7)*
Q3: How would you describe your health today? [1-4]	CONTROL	3.6 ± 0.8	3.4 ± 0.6	3.5 ± 0.8	*0.4*
	LIST	3.4 ± 0.5	3.4 ± 0.5	3.5 ± 0.5	*(0.4 to 0.6)*
Q4: How would you describe your appetite over the past 24 h? [1-5]	CONTROL	3.5 ± 0.8	3.3 ±0.8	3.3 ± 0.9	*0.3*
	LIST	3.2 ± 0.7	3.4 ± 0.8	3.4 ± 0.9	*(0.2 to 0.4)*
Q5: How would you describe you sleep quality over the past 24 h? [1-4]	CONTROL	2.9 ± 0.9	2.8 ± 0.9	3.0 ± 0.8	*0.6*
	LIST	2.9 ± 0.6	3.1 ± 0.7	2.9 ± 0.8	*(0.5 to 0.8)*
Q6: Do you have any muscle soreness today? [1-10]	CONTROL	2.0 ± 3.1	1.6 ± 2.6	1.7 ± 2.8	*0.6*
	LIST	**1.3 ± 1.8**	**5.4 ± 1.4*****	**4.3 ± 1.9*****	*(0.5 to 0.9)*
Q7: Rate your motivation-to-train today [1-10]	CONTROL	7.6 ± 1.2	7.2 ± 1.4	7.1 ± 1.7	*0.8*
	LIST	7.3 ± 1.6	7.2 ± 2.0	7.1 ± 1.3	*(0.7 to 1.0)*

* p = 0.02

** p = 0.008

*** p = 0.0001

The range of scores follows each question [....], with the minimum number representing the low anchor and the maximum number the high anchor score for that question. (i.e., for questions 1 – 5, the lower the number the "worse" the score, whereas for question 6 the higher the number the more muscle soreness and for question 7 the higher the number greater their motivation-to-train.).

The maximum force, time to maximum force, RFD, jump height and flight time scores are shown in TABLE 4.3 below. There were no changes either over time (pre vs. 24 h vs. 48 h) or between the trials (CONTROL vs. LIST). The interaction of time X intervention was also not significiant for maximal force, RFD and jump height. The effect size of the differences for CONTROL and LIST data between the pre-to 24 h and pre-to 48 h are shown in FIGURE 4.2. The shaded region represents the effect size of 0.2, upper and lower limits. The mean effect size for maximal force, RFD and jump height and flight time were within the *trivial* zone at pre vs 24 h and pre vs 48 h. Relationships between subjective muscle soreness and neuromuscular data were determined using a Spearman's correlation coefficient. However, no significant relationships were seen between muscle soreness and any CMJ variables.

TABLE 4.3: Maximal force (N), rate of force development (RFD) (N.s^{-1}) and jump height (cm) measured at time points Pre, 24 h and 48 h for both CONTROL and LIST groups (n=21). Data are expressed as mean ± SD. A description of the reliability data for these measurements is described in Chapter three above.

Variable Measured	**Group**	**Pre**	**24 h**	**48 h**	**Group F; p**	**Time F; p**	**Interaction F; p**
Maximal force (N)	CONTROL LIST	2673 ± 225 2681 ± 194	2656 ± 214 2680 ± 233	2666 ± 213 2674 ± 230	0.69; *0.42*	1.33; *0.28*	0.67; *0.51*
Time to max force (ms)	CONTROL LIST	130.6 ± 32.0 131.9 ± 22.9	139.2 ± 31.9 137.7 ± 27.5	133.7 ± 26.3 131.7 ± 25.7	0.01; *0.91*	3.70; *0.03*	0.12; 0.90
Rate of force development (N.s^{-1})	CONTROL LIST	2912 ± 1069 3177 ± 1117	3125 ± 1107 3042 ± 1008	3105 ± 1179 2974 ± 1080	0.03; *0.87*	0.11; *0.90*	2.55; *0.10*
Jump height (cm)	CONTROL LIST	33.6 ± 5.5 33.6 ± 5.6	33.3 ± 5.6 32.6 ± 5.9	33.5 ± 5.8 33.1 ± 5.7	0.86; 0.36	0.56; 0.56	0.37; 0.63
Flight time (ms)	CONTROL LIST	521 ± 45.5 521 ± 45.9	518 ± 45.3 513 ± 48.8	520 ± 47.2 517 ± 46.5	0.43; 0.83	1.82; 0.16	0.49; 0.61

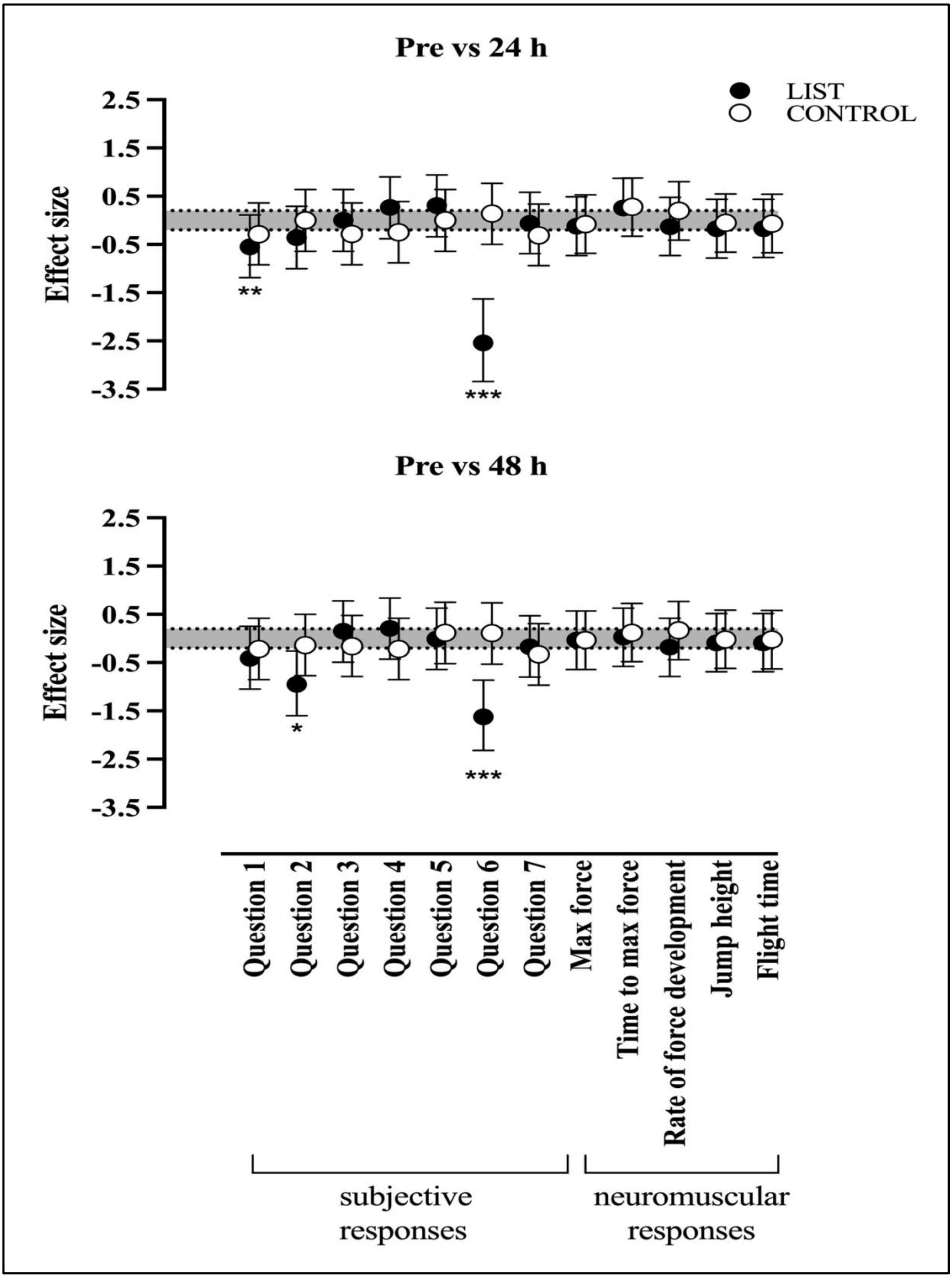


FIGURE 4.2: Effect size of the differences for both LIST and CONTROL between pre and 24 h and pre and 48 h. The upper and lower limits of 0.2 ES are represented by the shaded area.

4.5 Discussion

This study was designed to simulate the demands faced by team ball sport athletes and to determine whether changes in CMJ variables (maximal force, rate of force development and jump height) and subjective responses to a wellness questionnaire, were responsive to match-related fatigue at 24 h and 48 h post exercise-induced fatigue. The practical application of this study was to determine whether these measurements could be useful for monitoring post-match physiological responses of athletes. It must be noted though, that the participants in this study were moderately trained individuals who do not consistently participate in team sports such as soccer, hockey, or rugby. This may have implications on data interpretation, as it cannot be assumed the findings will be the same with participants with a different training status, gender, or age. Furthermore, as the interventions were not specific match-based demands, thus the findings may differ to those of actual match play due to higher mechanical demands and muscle damage[135].

We hypothesized that both subjective and objective variables would be sensitive to changes induced by the low-level fatigue from the Loughborough intermittent shuttle test. However, our results showed that only subjective measurements responded and that the objective measurements did not. In accordance with previous research, the present study found a significant difference in subjective questions, “***Do you feel physically strong today*****?**”, “***Do you feel mentally strong today***” and “***Do you have muscle soreness today****?*”, which showed significant changes for the LIST group[286]. All responsive wellness questions were related to how the participant felt physically or mentally. The responses to questions associated with disturbances in sleep, appetite or health of the participants did not change. This suggests the physical demands of the LIST were not sufficiently high to disturb these aspects. It has been shown that the activity patterns as well as the physical (physiological and metabolic) responses of the

LIST and team sports (such as soccer) are similar[280], therefore these findings have ecological validity.

A surprising finding was that there were no differences between the LIST and CONTROL group at any time points for any of the CMJ variables. This is dissimilar to previous research showing changes in various CMJ variables such as RFD and jump height following exercise-induced fatigue[103,287]. This may be explained by the different types of exercise the participants did in these studies including different intensities and durations. For example, in the study of Thomas et al (2017), the LIST protocol was modified to include a 20 m back pedal at each stage. Further to this it has been shown that backwards running may have an increase in energy expenditure and muscle activity when compared to relative forward running[288]. This suggests the impact of the exercise may manifest fatigue to a greater extent when compared to the original LIST intervention. Furthermore, studies conducted on snowboarders[243] and rugby players[109] showed that participants exposed to various forms of strength and conditioning induced fatigue protocols had a decrease in CMJ variables such as RFD and peak force. This may be due to the type of muscle action affecting acute neuromuscular fatigue and muscle soreness.

The present study did not show any change in CMJ variables in the presence of muscle soreness. This was similar to previous studies where there were only moderate effects for total lower body muscle soreness and a small decrease in CMJ peak force and jump height[103,273]. The changes in the objective and subjective variables in these studies did not occur at the same rate.

It is reasonable to assume that the subjective and objective variables measure a different aspect of fatigue. This has important consequences for monitoring fitness and fatigue, because it shows that a range of subjective and objective variables need to be measured. This is supported by the current literature, showing that collecting a wide spectrum of subjective and objective variables may be better for making informed decisions compared to focusing on either subjective or objective measures only[18,153,289].

For example, researchers have started to investigate CMJ variables such as peak velocity, eccentric and concentric duration, eccentric power, force at 0 velocity and flight time: contraction time ratio (FT:CT)[229,231]. Moreover, Roe et al in showed in two studies, that a 6 second cycle ergometer test (peak power) and plyometric push up test (peak power) can also be used to monitor lower and upper body neuromuscular fatigue in elite level rugby union players[115,251]. However, further research is required to determine which of these objective markers are most sensitive to acute and chronic changes in athlete training statuses. It should also be noted that the present study used moderately trained men as research participants.

This study design did have limitations. Although we requested that participants refrain from any physical activity after completing the LIST/CONTROL until after their 48 h follow up session, we were not able to control for this. Another limitation was not quantifying the state of fatigue prior to starting the LIST. Thus, we cannot assume the findings will be the same for participants with a different training status, gender or age and all factors should be considered when the findings are interpreted.

Lastly, there is ever increasing pressure in elite sport to ensure that athletes are in peak condition on game day. Thus, through the implementation of various monitoring strategies support staff are better able to make informed decisions regarding training leading up to game day. In the present study, we suggest that practitioners should consider using both subjective and objective markers to assess an athlete’s response to match loads or fatigue status. The CMJ is an easy test to administer with minimal additional load imposed on the athletes, making it a useful tool for monitoring neuromuscular status of athlete**[231,290]**. Peak Force, time to peak force, flight time and jump height are a few variables within a CMJ that allow practitioners to gain valuable information regarding an athlete's training status.

Further research is recommended to identify other useful variables that strongly contribute to distinct aspects of jump performance[291]. Self-report questionnaires have a high validity and responsiveness to match and training loads. Thus, they should be considered by practitioners as an effective method in monitoring athlete readiness in conjunction with objective measures.

4.6 Conclusion

It is evident that monitoring strategies such as wellness questionnaires and countermovement jump variables should not be used in isolation. Each mode of monitoring seems to be able to identify different forms of training status and neuromuscular fatigue. It is important that a holistic approach is adapted to fully understand if athletes are responding positively or negatively to a training program. Therefore, in a practical setting it is important that monitoring strategies should include tests that are sufficiently robust in a non-laboratory-based setting. In accordance with this principal TABLE 4.4 shows the most robust variables for the countermovement jump that will be used in the next series of studies which involve monitoring athletes in the field.

TABLE 4.4: Countermovement jump variables evaluation matrix of acceptability in monitoring changes in training status. The “traffic light” rating scale represents an evaluation of “usability” of each countermovement jump variable used in Studies one and two, that would be most valid and reliable in a non-laboratory-based setting.

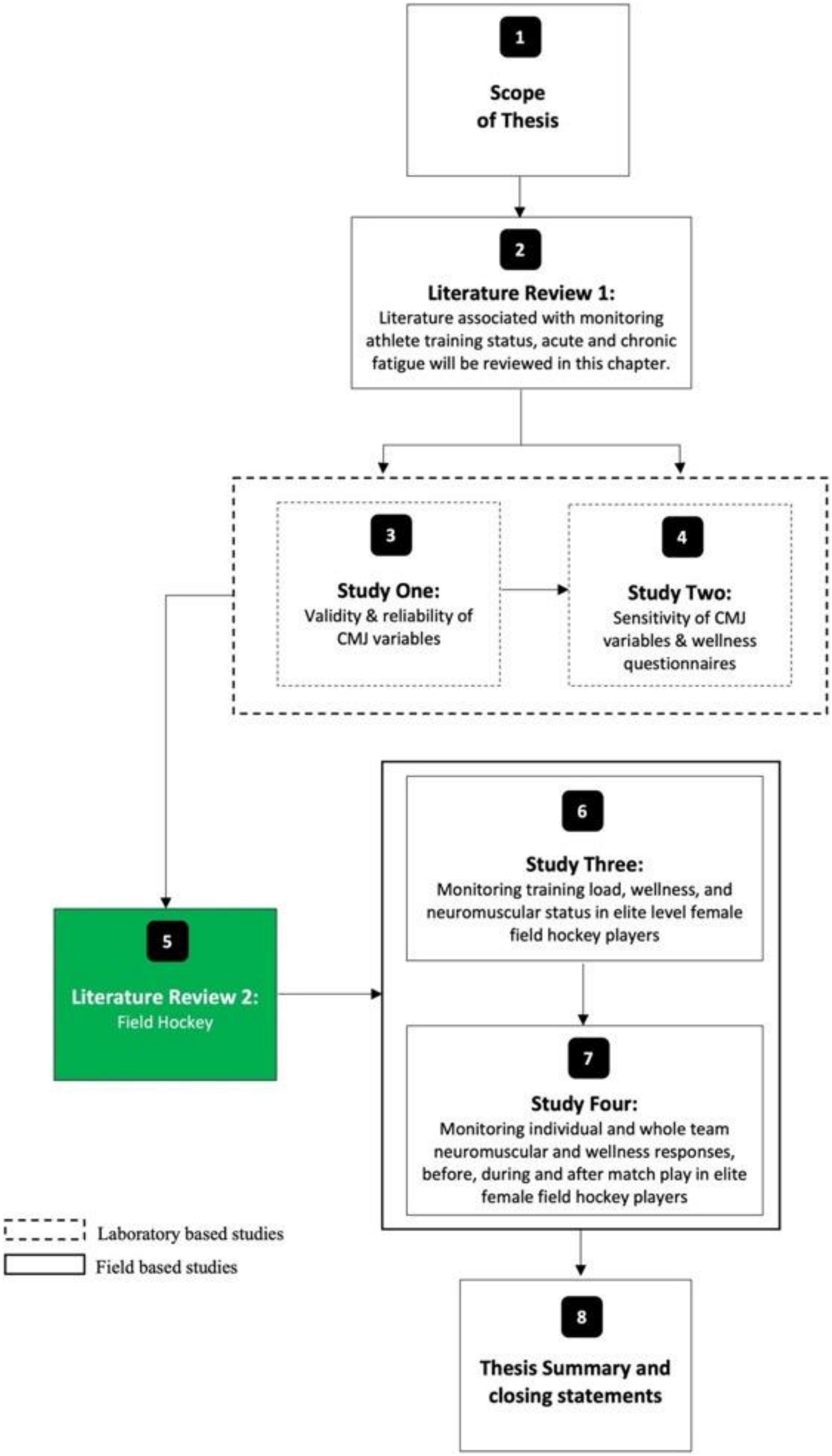
Countermovement jump candidate variable	Ability to detect SMALL changes across various training statuses?	Suitable for identifying the presence of neuromuscular fatigue?	Suitable for identifying super compensatory adaptations to training?	Ability to detect small changes across various training statuses?	Measurement difficulty	Ease of understanding for coaches and athletes
Maximum force (N)	🟢	🟢	🟢	🟢	🟢	🟢
Time to maximum force (ms)	🔴	🟠	🟠	🟠	🟠	🔴
Rate of force development (N.s^{-1})	🟠	🟠	🟢	🔴	🔴	🔴
Jump height (cm)	🟢	🟢	🟢	🟢	🟢	🟢
Flight time (ms)	🟢	🟢	🟢	🟢	🟢	🟢

The traffic light rating system represents an evaluation for the use of specific countermovement jump variables as determined by chapters 3 and 4 for a robust transition from laboratory based to field side research.

🟢	Favourable
🟠	Less than favourable
🔴	Unfavourable

4.7 Chapter Four - Summary points

1. Wellness related questionnaires can detect changes post-acute exercise-induced fatigue.
2. Answers to questions such as “Do you feel physically strong today?” and “Do you feel mentally strong today?”, reflected changes in fatigue status between pre, 24 h and 48 h respectively.
3. Answers to “Do you have any muscle soreness today?” reflected changes in muscle soreness at both pre vs 24 h and pre vs 48 h.
4. No changes in any CMJ variables were induced post exercise intervention.
5. No changes in CMJ variables were observed in the presence of muscle soreness.
6. Subjective and objective markers of training status measure different aspects of fatigue.
7. A holistic approach is required to gain a better understanding of how athletes are adapting to their training. Inclusion of both subjective and objective markers of fitness and fatigue are recommended.
8. Further research with elite level athletes in a practical or real-world environment is required to better understand the role of CMJ variables post exercise.


1
Scope of Thesis
2
Literature Review 1:
Literature associated with monitoring athlete training status, acute and chronic fatigue will be reviewed in this chapter.
3
Study One:
Validity & reliability of CMJ variables
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Study Two:
Sensitivity of CMJ variables & wellness questionnaires
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Literature Review 2:
Field Hockey
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Monitoring training load, wellness, and neuromuscular status in elite level female field hockey players
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Thesis Summary and closing statements
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Field based studies

5. Chapter Five

Field hockey: A review of the literature

5.1 Introduction

The following studies (Study 3 and Study 4) have been conducted in a practical setting using elite level female field hockey players. Therefore, the following brief literature review will set the scene for the reader with regards to field hockey (hereafter referred to as hockey). Field hockey is a stick-and-ball team sport, involving varying movement patterns of high and low intensity efforts. The demands of the game change as the state of play transitions between attack and defence. Hockey is played at amateur to elite levels, with the World Cup and Olympics being the pinnacle of both the men’s and women’s game.

A hockey match is contested between two teams, each consisting of 10 field players and one goalkeeper. A hockey field’s dimensions (91 m x 55 m) are similar to other field-based sports like soccer or rugby. A difference however is that hockey fields have a synthetic playing surface that is water-based. This reduces the ball-to-surface friction, increasing the speed of play[292]. This increase in speed leads to an increased demand on players’ fine motor skills and hand-eye coordination. Further to this there is no offside rule, and no limit for rolling substitutes. Also, the self-pass rule (from free hits) was implemented to increase the flow of game. In 2014 the Federation International de Hockey (FIH)[293] changed the playing time of a match from two halves of 35 minutes each to 4 quarters of 15 minutes each, with a 2-minute rest between quarters and a 10-minute rest between halves. The purpose of these rule changes was to increase the flow, intensity, and spectatorship of the game around the world[293].

5.2 Physical demands of field hockey match play

The International hockey calendar is comprised of various “blocks” of tournaments throughout the year. These tournaments may involve congested match schedules with teams playing between three to four matches in a week. This imposes high demands on players who have limited time to recover, particularly as the tournament progresses from pool to knockout stages. Consequently, high level field hockey players need to train to develop strength, power, speed, cardiovascular fitness, robustness, and resistance to fatigue[294–296].

Research on the demands of hockey players during a match are limited. Most of the research has been conducted on the game played under the old rules[292,297]. A more recent study conducted under the new rules showed that on average female players cover about 6600 m per match, with distances ranging from 3400 m to 9500 m depending on position, duration, and level of play[298]. Players spend most of the time at low to moderate intensities interspersed with bouts of high intensity efforts. A study of elite level female players after the new rules were implemented showed that the percentage of time spent in different types of activities were, standing (11 %) walking (45 %), jogging (35 %), cruising (5 %) sprinting (1.5 %) and lunging (1.3 %)[299]. Some studies have suggested that midfielders spend more time at high intensity running when compared to strikers and defenders[292]. However, this finding is not consistent with other studies showing that forwards spend more time running at high speed compared to defenders and midfielders[298,300,301]. Despite the different findings both midfielders and strikers require a high degree of fitness, specifically with regards to repeat sprint ability and high-speed running capabilities to cope with the demands of their positions. Further to this, Jennings et al (2012) have also suggested that male international level players have a 10% higher multi-stage-fitness-test score (MSFT), perform 42% more high speed running (>4.17 $m.s^{-1}$) and 8% more low speed running

(0.1 - 4.17 m.s^{-1}) than national level players. It is likely similar patterns also occur in the female game. These findings emphasize the importance of superior physical attributes required for playing at international level[302].

A more recent study of match demands played under the new rules showed that elite level female players cover on average between 4847 ± 583 m at 128 ± 16 m.min of which 443 ± 88 m is covered during high-speed running (>4.5 m.s^{-1})[303,304]. Another study on elite level female players showed similar values; average total distance 5147 ± 628 m and an average speed of 113 ± 9 m.min[305]. These data comparisons show that on average it is estimated that 5-10% increase in work rate across playing positions can be expected due to the rule changes. To accommodate the 10-minute reduction in playing time with the new rules, players spent less time on the pitch with more frequent recovery periods, enabling players to play at an increased work rate as shown through m.min and high-speed running data (TABLE 5.1).

TABLE 5.1: Physical characteristics of match play for female hockey players.
Data are expressed as either mean ± SD or range (min – max)

Study	Rules	Level of Play	Total Distance (m)		High Speed Running (m)		m.min	
McMahon et al [306]	New	International	Defenders:	5228 ± 1087	Defenders:	737 ± 196	Defenders:	109 ± 15
			Midfielders:	5431 ± 961	Midfielders:	1089 ± 294	Midfielders:	120 ± 13
			Forwards:	4789 ± 969	Forwards:	955 ± 257	Forwards:	120 ± 10
			All:	5167 ± 1029	All:	959 ± 294	All:	109 ± 13
McGuiness et al [104,303,304]	New	International	Defenders:	5181 ± 607	Defenders:	552 ± 155	Defenders:	115 ± 14
			Midfielders:	4740 ± 530	Midfielders:	545 ± 150	Midfielders:	131 ± 15
			Forwards:	4549 ± 546	Forwards:	657 ± 142	Forwards:	142 ± 17
			All:	4847 ± 383	All:	580 ± 147	All:	127 ± 15
Delves et al[307]	New	National	Defenders:	5301 ± 1120	Defenders:	206 ± 97	Defenders:	98 - 115
			Midfielders:	5266 ± 1074	Midfielders:	421 ± 214	Midfielders:	109 - 132
			Forwards:	5364 ± 894	Forwards:	348 ± 56	Forwards:	110 - 142
Gabbett et al [301]	Old	National	Defenders:	6643 ± 1618	Defenders:	469 ± 252		
			Midfielders:	6931 ± 1882	Midfielders:	648 ± 313		
			Forwards:	6154 ± 271	Forwards:	421 ± 240		
Macutkiewicz et al [308]	Old	International	Defenders:	6170 ± 977				
			Midfielders:	5620 ± 787	All:	620 ± 172		
			Forwards:	4700 ± 918				
Abbott et al [305]	Old	International	Defenders:	5912 ± 1378	Defenders:	931 ± 214	Defenders:	114 ± 9
			Midfielders:	3264 ± 985	Midfielders:	529 ± 224	Midfielders:	120 ± 11
			Forwards:	3091 ± 1094	Forwards:	565 ± 295	Forwards:	117 ± 11
			All:	5921 ± 1675	All:	580 ± 268	All:	117 ± 9
McMahon et al [306]	Old	International	Defenders:	5182 ± 1051	Defenders:	728 ± 214	Defenders:	101 ± 12
			Midfielders:	5195 ± 747	Midfielders:	998 ± 241	Midfielders:	112 ± 9
			Forwards:	4313 ± 783	Forwards:	935 ± 279	Forwards:	111 ± 15
			All:	4879 ± 935	All:	912 ± 270	All:	109 ± 13

5.3 Physiological characteristics of field hockey players

A moderate amount of published research exists on the physiological profiles of elite contemporary hockey players (TABLE 5.2). A review of these studies showed that female hockey players had a similar percentage of oxidative muscle fibres when compared with their male counterparts and significantly more than non-athletic populations[292]. Furthermore, the same review reported that elite female midfielders had the highest $V0_2$ max (60 $ml.kg^{-1}.min^{-1}$), and the highest anaerobic capacity compared with other positions[292]. Some published data exists with the expected normative values required by female players to perform at the elite level such as; 10 m sprint times averaging 1.98 ± 0.04 s, 40 m times averaging 5.98 ± 0.15 s, average 2x20 m repeat sprint ability times of 7.9 – 7.2 s and 30-15 intermittent fitness test (IFT) ranging between level 19 – 21 or multi-stage-shuttle-run scores of between levels 11.1 – 12.8[309,310] When considering strength characteristics, it has been shown that bench press of 0.60 – 1.05 x body weight and squat scores of 1.25 – 2.00 x body weight are expected at international level for female athletes[309,310]. A study conducted on university level female players, showed that players had an average body mass of 61 ± 7 kg, body fat % of 21.2 ± 3.9, $V0_2$max of 2.42 ± 0.26 $l.min^{-1}$, 1RM bench press scores of on average 44 kg and 1RM leg press scores on average of 220 kg[311].

TABLE 5.2: Physiological characteristics of female field hockey players. Data are expressed as either mean ± SD or range (min – max)

Study	Level of Play	Body Composition		Sprint times		Strength & Power		Aerobic & Anaerobic capacity	
Keogh et al[295]	National (old rules)	Body mass (kg) Body fat (%) ∑4 Skinfolds (mm)	58.6 ± 1.2 24.0 ± 0.7 39.3 ± 3.7	10m (s) 40m (s)	2.01 ± 0.02 6.53 ± 0.09	CMJ (cm) Bench Press (kg) Leg press (kg)	35 ± 1 35 ± 1 35 ± 1	MSST (level) VO_2 max (ml.kg^{-1}.min^{-1})	9.1 ± 0.02 43.7 ± 1.2
Astorino et al[311]	College (old rules)	Body mass (kg) Body fat (%)	60.9 ± 6.7 21.2 ± 3.9			Bench Press (kg) Leg press (kg)	44 - 52 220 - 260	VO_2 max (ml.kg^{-1}.min^{-1})	42.9 – 59.3
Boddington et al[312]	National (old rules)	Body mass (kg) Body fat (%)	59.4 ± 5.9 22.9 ± 4.3	40m (s)	6.37 ± 0.27			VO_2 max (ml.kg^{-1}.min^{-1}) 5m RSA	42.1 ± 7.1 650 ± 59
Lemmink et al[313]	Club (old rules)	Body mass (kg) Body fat (%)	67.4 ± 8.0 27.7 ± 5.9					VO_2 max (ml.kg^{-1}.min^{-1})	48.7 ± 4.8
Spencer et al [314]	International (old rules)	Body mass (kg) ∑7 Skinfolds (mm)	57.7 – 70.1 49.5 – 104.3	10m (s) 40m (s)	1.90 – 2.07 5.54 – 6.09			MSST (level)	11.1 – 13.7
Perrotta et al[315]	International (old rules)	Body mass (kg)	61.3 ± 5.7					YoYo Level 1 (m) VO_2 max (ml.kg^{-1}.min^{-1})	2020 ± 325 53.5 ± 7.9
Hamlton[310]	International (old rules)			5m (s) 10m (s) 40m (s)	0.99 – 1.15 1.75 – 1.93 5.40 – 6.00			30-15$_{IFT}$ (Level) RSA mean 6x(2x15m) (s)	19 -21 7.2 – 7.9
Harry et al[198]	Club (new rules)	Body mass (kg)	60.4 ± 6.5					YoYo Level 1 (m) RSA mean 6x(2x15m) (s)	811 - 1048 6.60 – 6.83

Key:

MSST: Multistage Shuttle Run Test

RSA: Repeat Sprint Ability

30-15$_{IFT}$: 30-15 Intermittent Fitness test

CMJ: Countermovement Jump

5.4 Injuries in field hockey

Hockey, as with any team sport involving repeated high intensity efforts interspersed with maximal sprints, carries the risk of players being exposed to various injuries during training and match play. For example, it has been shown that injury rates during training sessions average 4.5 injuries per 1000 athletic exposures and during match play the injuries increase to an average of 7.0 injuries per 1000 athletic exposures respectively[316]. A study of the game played under the old rules questioned 158 hockey players of varying playing levels (High school to national) from around the USA[317]. The participants reported a total of 469 injuries throughout their playing careers (average of 6.8 years of playing experience). The injuries were divided into lower limb (51 %), head and face (34 %), upper limb (14 %) and back or torso (1 %). The most common type of injury was ligament sprains (39 %), followed by contusions (17 %), fractures (16 %), wounds (9 %), muscle strains (8 %), concussions (7 %) and lastly dislocation (1 %)[317]. It must be noted however that the playing surfaces that these players were exposed to were both artificial and grass turf, which could have impacted on the injury trends reported.

More recent studies on international level female players, showed injury rates of 0.7 injuries (95 % CI 0.5 to 1.0) per match. Injuries per 1000 player match hours ranged from 23.4 to 44.2 (average 29.1; 95 % CI 18.6 to 39.7) Another interesting finding in the same study was that many injuries (50 %) occurred in the circle[318]. Further to this they also showed that 54% of all injuries occurred during the second half of the match. Some of the most common injuries reported were head and face (40 %), finger and hand (14 %), thigh and knee (12 %) as well as calf and ankle (16 %)[318,319].

Furthermore, they showed in a follow-up study that there were 190 injuries in 179 matches involving elite level men and women players[316]. Fifty-five injuries occurred in the 73 women's matches analysed. The injury rate was 0.75 injuries per match or 34.2 injuries per 1000 match hours in female players. The injury sites were similar to the earlier study involving the old rules, with head/face (32 %), neck/shoulder (5 %), arm/hand (16 %), hip (1 %), upper leg (3 %), knee (9 %) and lower leg/foot (18 %), with contusions being the most common type of injury reported (51 out of 55)[316]. These data are summarised in FIGURE 5.1.

These studies show the relatively high risk of injury associated with hockey training and matches. It is evident that players should be well prepared physically to meet the demands of the game and build up resilience against injuries.

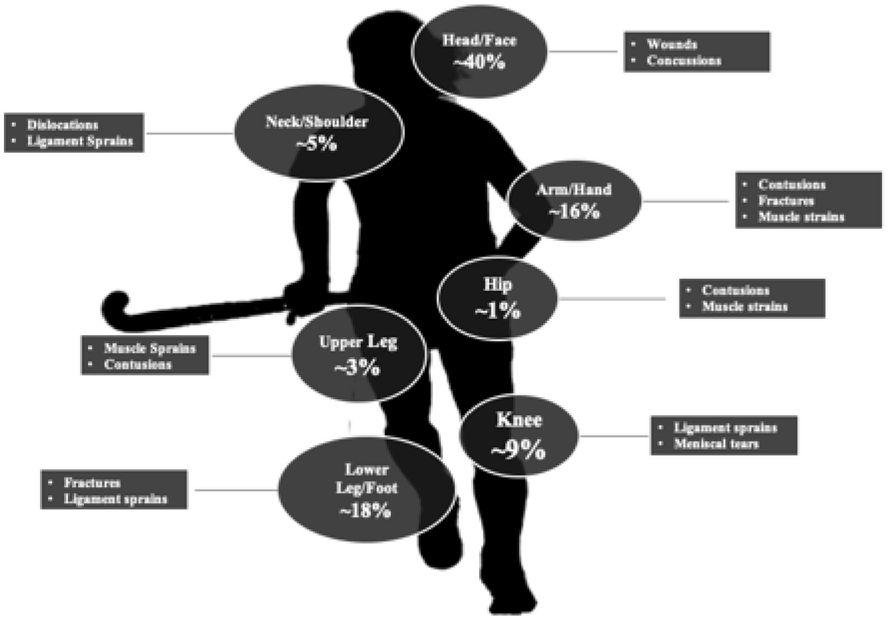
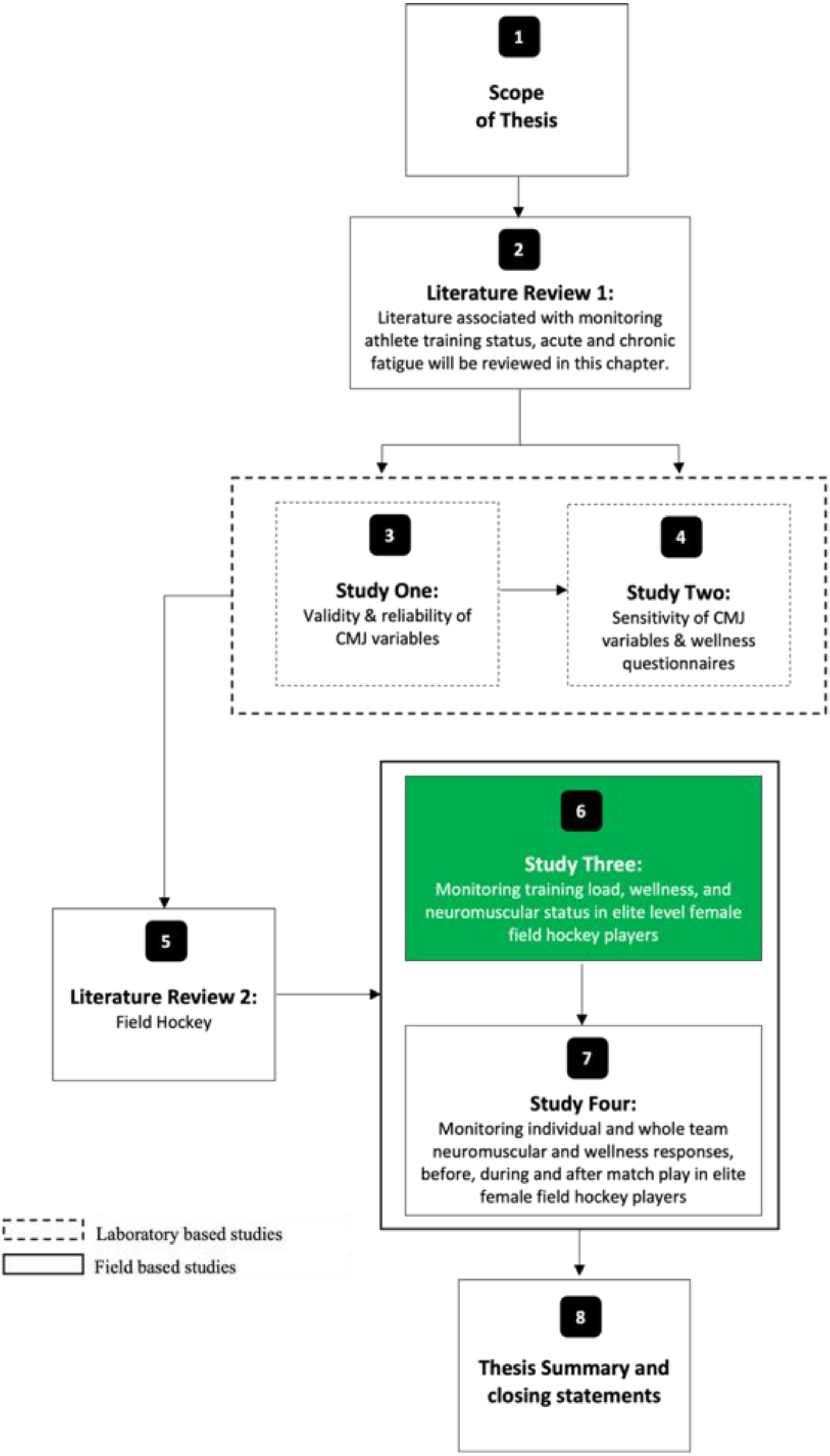


FIGURE 5.1: Schematic of the most common injury sites in field hockey players.

5.5 Chapter Five - Summary points

1. Field hockey is an intermittent high intensity stick-and-ball sport
2. Recent rule changes such as the self-pass, rolling substitutions and 4 x 15min quarters have resulted in the game being played at higher speeds more constantly.
3. Female players can cover between 4847 ± 583 m at 128 ± 16 m.min of which 443 ± 88 m is covered at high-speed running (>4.5 $m.s^{-1}$)
4. 10m sprint times averaging 1.98 ± 0.04s, 40 m times averaging 5.98 ± 0.15s have been reported in female players
5. Average 30-15 Intermittent Fitness Test scores of between 19 – 21 and multistage shuttle run scores of 11.1 – 12.8 have been recorded in female players.
6. Strength values of 0.60 – 1.05 x body weight for bench press and squat scores of 1.25 – 2.00 x body weight.
7. Injury rates during training sessions average 4.5 injuries per 1000 athletic exposures and during match play the injuries increase to an average of 7.0 injuries per 1000 athletic exposures.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6. Chapter Six

Study Three: Monitoring training load, wellness, and neuromuscular status in elite level female field hockey

6.1 Introduction

Hockey players, as with most team sport athletes, are generally exposed to high training and competition demands. For example, players accumulate multiple accelerations, decelerations and high intensity efforts incorporating changes of direction during training, matches and tournament-based competitions. They also undergo strength training which adds to the physical demands[104,303,304,320]. The accumulation in physical demands over time may lead to increased neuromuscular fatigue and a decrease in wellbeing as shown by decreases in subjective wellness scores[100,108,110,111,279]. This reduces the potential for positive adaptations and increases the risk of non-functional overreaching. As a consequence it is imperative to monitor players' internal and external loads and their objective and subjective responses to these loads[92,107] .

As was alluded to in Chapter Four, now that we have identified various possible monitoring variables that showed sufficient validity, reliability, and responsiveness in a controlled laboratory setting, it is important to make the next move into a more practical elite sporting environment. Elite sporting environments are dynamic in nature and can be somewhat chaotic yet organised at the same time. Thus, being able to use robust monitoring tools in these environments bodes well in allowing support staff to provide informed feedback to coaches and athletes alike. It must be noted that there is a vast difference between individual-based sports and team-based sports, and the decisions regarding training can be made in each environment. For example, in team sports, coaches may be reluctant to "pull" a player or players out of training as it may affect their training plan for that day. However, they may be willing to adjust their load and intensity for these players. Thus, interpreting the monitoring data, to identify what may be the "safest" manner to allow a player to train with the team may form the basis of a successful monitoring system. It is erroneous to think of monitoring systems as potential hinderance to athletes' training. In fact, when monitoring systems are used correctly, athletes can train harder but in a smarter manner[117,170]. However, the method of communication of the monitoring data to coaches and athletes should not be understated. Being able to infer meaningful reports that coaches can easily digest and make inferences from should be a priority and will build a better coach-sports science-athlete relationship and trust[99,112].

The overall aim of this study was to determine the intra-individual relationships between various subjective and objective measures of fitness and fatigue (wellness questionnaires and countermovement jump), and subjective and objective measures of training/match demands (RPE and GPS variables). The primary focus was to determine the differences in intra-individual response to internal and external training loads within a team setting in elite level athletes in a "real-world" environment.

6.1 Methods

6.1.1 Participants

Participants in this study were part of the Indian senior women's national hockey team. Participant characteristics (n= 19) are summarised in TABLE 6.1 Ethical approval was obtained through the University of Cape Town (UCT) Human Research Ethics Committee (Ref No.: R024/2017 & 623/2020; Appendix 6 and 7). Players in the squad who were injured (i.e., had musculoskeletal or soft tissue injuries) were excluded from the study and signed an informed consent form (Appendix 3). Goalkeepers were also excluded from the study.

TABLE 6.1: Participant characteristics.
Data are expressed as mean ± SD (n=19).

Characteristic	Mean ± SD	Range
Age (yrs.)	24 ± 3	19 – 31
Height (cm)	162 ± 6	154 - 167
Weight (kg)	55 ± 6	44 - 65

6.1.2 Protocol

The study was conducted in 2018 over a congested training and competition period, spanning a period of 252 days (FIGURE 6.1). The data were recorded during all training sessions as well as during the International Hockey Federations (FIH) sanctioned test series and tournaments comprising a total of 37 matches.

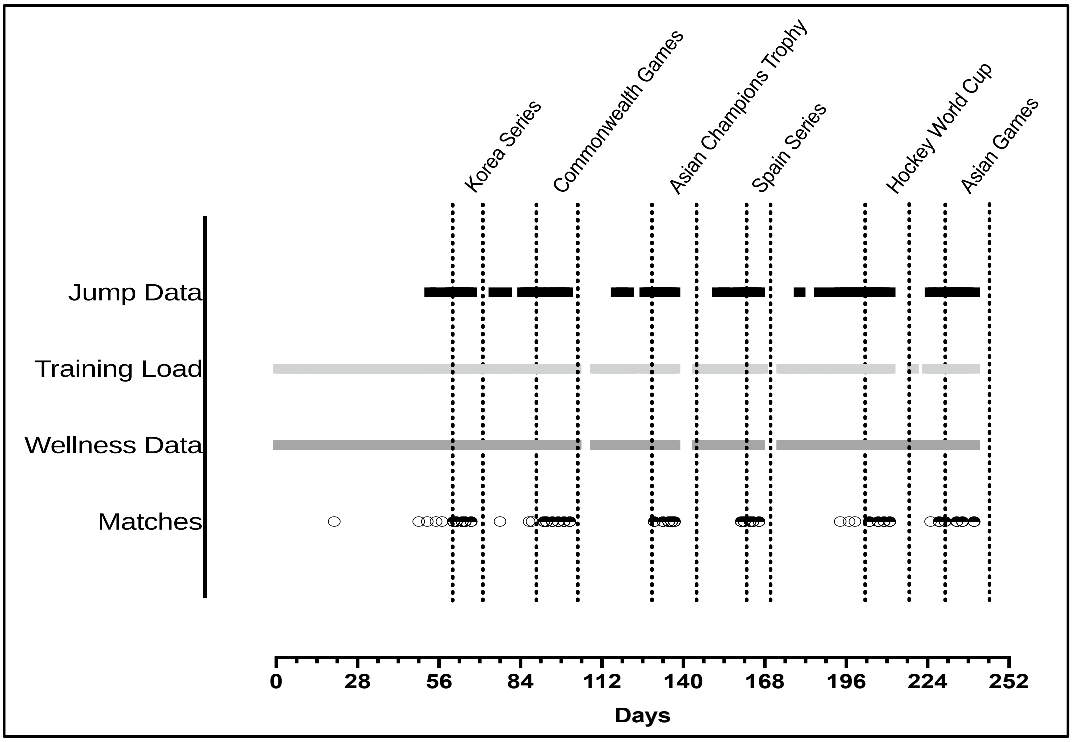


FIGURE 6.1: Graphical representation of the data collection timeline for the duration of the study.

6.1.3 Subjective data collection

The players completed the wellness questionnaire (Appendix 8), via a self-made app and Google Forms on their mobile phones each morning before breakfast. The questionnaire had 11 questions, regarding the players' sleep quality, mood, general health, and general muscle soreness. TABLE 6.2 shows the scoring system used for the subjective wellness questions. Seven of the 11 questions had a numerical value from 1-5 assigned to them, with 1 being a less favourable answer and 5 being the most favourable answer. Players could achieve a maximum score of 35 to derive a subjective readiness score. Muscle soreness scores were also rated on a scale of 0-5, however, 0 being more favourable score (i.e., no muscle soreness) and 5 being less favourable (i.e., extreme muscle soreness). It's important to note that the wording of the questions in the wellness questionnaire differed slightly from the wording in the laboratory study (Chapter Four), to meet the needs of the squad. RPE scores were collected within 30 minutes after each match.

6.1.4 Countermovement jump data collection

Individual neuromuscular performance variables were collected during team gym sessions (while in training camps) or team priming sessions (during competitions). The same CMJ protocol was followed as described earlier in SECTION 3.2.6. However, in this study, the mean score of three (as opposed to five) maximal effort CMJ was recorded as the final score for jump height (cm), maximum force (N) and flight time (ms). Players performed each jump with maximal intent with their weight distributed evenly between their feet while standing on portable force plates (Pasco, 2 axis, 1000 Hz, Roseville, CA, USA). The force plates sampled the ground reaction forces at 1000Hz and have shown to be valid and reliable when measuring countermovement jumps[239–241,289]. The data were recorded via the force decks software (Valdperformance, AUS).

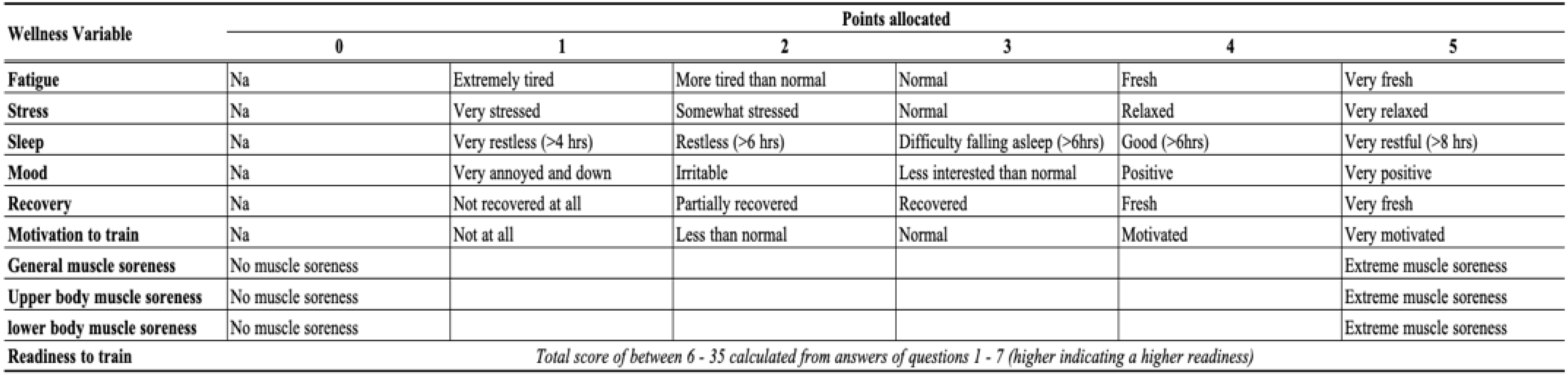
6.1.1 Global positioning system data collection

Each player wore a vest with a GPS unit (GPSport High Performance Unit (HPU), Catapult Sports Pty Ltd, Melbourne, Australia) positioned between their shoulder blades for all training sessions and matches. The GPS measured and recorded players' external demands such as total distance (TD) (m), high speed running (m), sprint counts, bodyload, high intensity efforts (HIE) as well as heart rate >85 % for each match. The data collected during match play were exported to the GPSport analytical software (team AMS) and then further uploaded to the cloud-based system (SPI IQ). These raw data were then transferred into Microsoft Excel for further analysis. Additionally, GPSport HPU, have a high validity and inter-unit reliability, with a sampling rate of 10Hz [321].

6.2 Statistical analysis

A Spearman's correlation analysis was used to establish the intra-individual relationships as parametric characteristics could not be confirmed for all variables. Correlations were presented as r (95 % confidence intervals (CI)). In particular, the relationships between daily measures of player wellness, CMJ variables, subjective training load and objective external and internal training load as determined through GPS data were explored. Group data were presented as r (Lower CI – Upper CI). Statistical significance was defined as $P < 0.05$. Descriptive data were presented as mean ± standard deviation ($x \pm SD$). The D'Agostino-Pearson omnibus normality test was used to test for normality. A Spearman's correlation analysis was used to establish the intra-individual relationships as parametric characteristics could not be confirmed for all variables. The number of comparisons for each participant ranged from 16 to 112.

TABLE 6.2: Numerical scoring system and accompanied nomenclature for the subjective wellness questionnaire.



Wellness Variable	Points allocated					
	0	1	2	3	4	5
Fatigue	Na	Extremely tired	More tired than normal	Normal	Fresh	Very fresh
Stress	Na	Very stressed	Somewhat stressed	Normal	Relaxed	Very relaxed
Sleep	Na	Very restless (>4 hrs)	Restless (>6 hrs)	Difficulty falling asleep (>6hrs)	Good (>6hrs)	Very restful (>8 hrs)
Mood	Na	Very annoyed and down	Irritable	Less interested than normal	Positive	Very positive
Recovery	Na	Not recovered at all	Partially recovered	Recovered	Fresh	Very fresh
Motivation to train	Na	Not at all	Less than normal	Normal	Motivated	Very motivated
General muscle soreness	No muscle soreness					Extreme muscle soreness
Upper body muscle soreness	No muscle soreness					Extreme muscle soreness
lower body muscle soreness	No muscle soreness					Extreme muscle soreness
Readiness to train	*Total score of between 6 - 35 calculated from answers of questions 1 - 7 (higher indicating a higher readiness)*					

6.3 Results

The descriptive characteristics of the participants (n=19) are shown in TABLE 6.1 above.

6.3.1 Intra-individual data analysis

6.3.1.1 Objective (CMJ) vs Subjective (wellness) measures of fitness and fatigue

All intra-individual correlations for max force and subjective measures of fitness and fatigue are displayed in FIGURE 6.2 and FIGURE 6.3. There was a significant negative relationship between maximum force and fatigue for Player 7 (-0.30; -0.50 to -0.07) and Player 16 (-0.32; -0.54 to -0.05). Also, there was a significant negative relationship between maximum force and stress for Player 7 (-0.27; -0.45 to -0.0) and Player 16 (-0.32; -0.54 to -0.05). Player 19 was the only player that had a significant positive relationship with stress (0.25; 0.01 to 0.45).

As for sleep (FIGURE 6.2 *graph c*) and its relationship with maximum force is concerned, Player 3 (-0.35; -0.54 to -0.11) negative relationship and Player 6 (0.35; 0.15 to 0.55) had a positive relationship between sleep and maximum force. Player 18 was the only player with a positive relationship between mood and maximum force (FIGURE 6.2. *graph d*). Player 16 was the only player who had a negative relationship between recovery and maximum force (FIGURE 6.2 *graph e*). Player 4 had a positive relationship between motivation-to-train and maximum force (FIGURE 6.2. *graph f*) In FIGURE 6.3 for graphs “*g*” to “*j*”, only general muscle soreness had more than one significant relationship with maximum force with Player 2 and Player 6 each having a positive relationship, and Player 9 having a negative relationship. Although a few players had a significant relationship between maximum force and subjective measures of fitness and fatigue, it must be considered that some of these relationships are only “by chance”.

For example, Player 7 had a statistically significant relationship between sleep and maximum force. However, if we consider the variance of this relationship, it equates to approximately 12 %, meaning that sleep can only explain 12 % of the variance in maximum force values for Player 7.

The correlation coefficients between jump height and subjective measures of fitness and fatigue are summarised in FIGURES 6.4 and 6.5 below. Two out of the 19 players had a significant positive relationship between fatigue and jump height. With the strongest relationship shown in Player 11 (0.44; 0.24 to 0.61). Stress vs. jump height was significant in Player 8 (0.27; 0.05 to 0.48), while both sleep vs. jump height and mood vs. jump height were not significant in any players (FIGURE 6.4 *graphs c and d*). Player 18 (-0.49; -0.67 to -0.25) had the strongest negative relationship between recovery and jump height.

Players 3, 7, and 8 had a small positive relationship between jump height and motivation-to-train (FIGURE 6.4 *graph f*). Player 16 had the strongest negative relationship between jump height and motivation-to-train. There was a strong significant relationship between readiness-to-train and jump height in Player 7 (0.30; 0.08 to 0.50) and Player 11 (0.36; 0.15 to 0.54). A negative relationship between general muscle soreness and jump height was seen in Players 5, 7, 13 and 14. Additionally, there was a significant negative relationship between upper body muscle soreness and jump height in Players 8, 13 and 18. Player 16 had the only positive relationship between general muscle soreness and jump height. Player 18 had the strongest negative (-0.44; -0.63 to -0.20) and positive (0.44; 0.19 to 0.63) relationship, between upper and lower body muscle soreness and jump height respectively (FIGURE 6.5 *graphs i and j*).

FIGURE 6.6 and FIGURE 6.7 summarise the correlation coefficients between flight time and subjective measures of fitness and fatigue. Player 11 (0.44; 0.24 to 0.61) had the strongest positive relationship between fatigue and flight time. Whereas Player 8 had a low correlation with both fatigue and stress and flight time. Sleep had no significant correlation with flight time for any players. Only Player 1 (0.24; -0.01 to 0.50) had a low but significant relationship between mood and flight time. Three players had a significant relationship between recovery and flight time, but Player 18 (-0.50; -0.67 to -0.30) had the strongest (negative) correlation out of the three (FIGURE 6.6 *graph e*). Players 3, 7 and 8 had a positive correlation between motivation-to-train and flight time, while Player 16 had a negative correlation between motivation-to-train and flight time. Three players had a positive correlation between readiness-to-train and flight time, with the highest correlation only explaining 13 % (Player 11) of the variance. The same was true for general muscle soreness, with three players having a significant correlation, but the highest corelation only explaining 21 % of the variance (Player 13). The relationship between upper body muscle soreness and flight time was significant in 5 players, but the correlation coefficients were low and could be ascribed to chance. Player 18 was the only player with a significant positive relationship between lower body muscle soreness and flight time (0.44; 0.19 to 0.64).

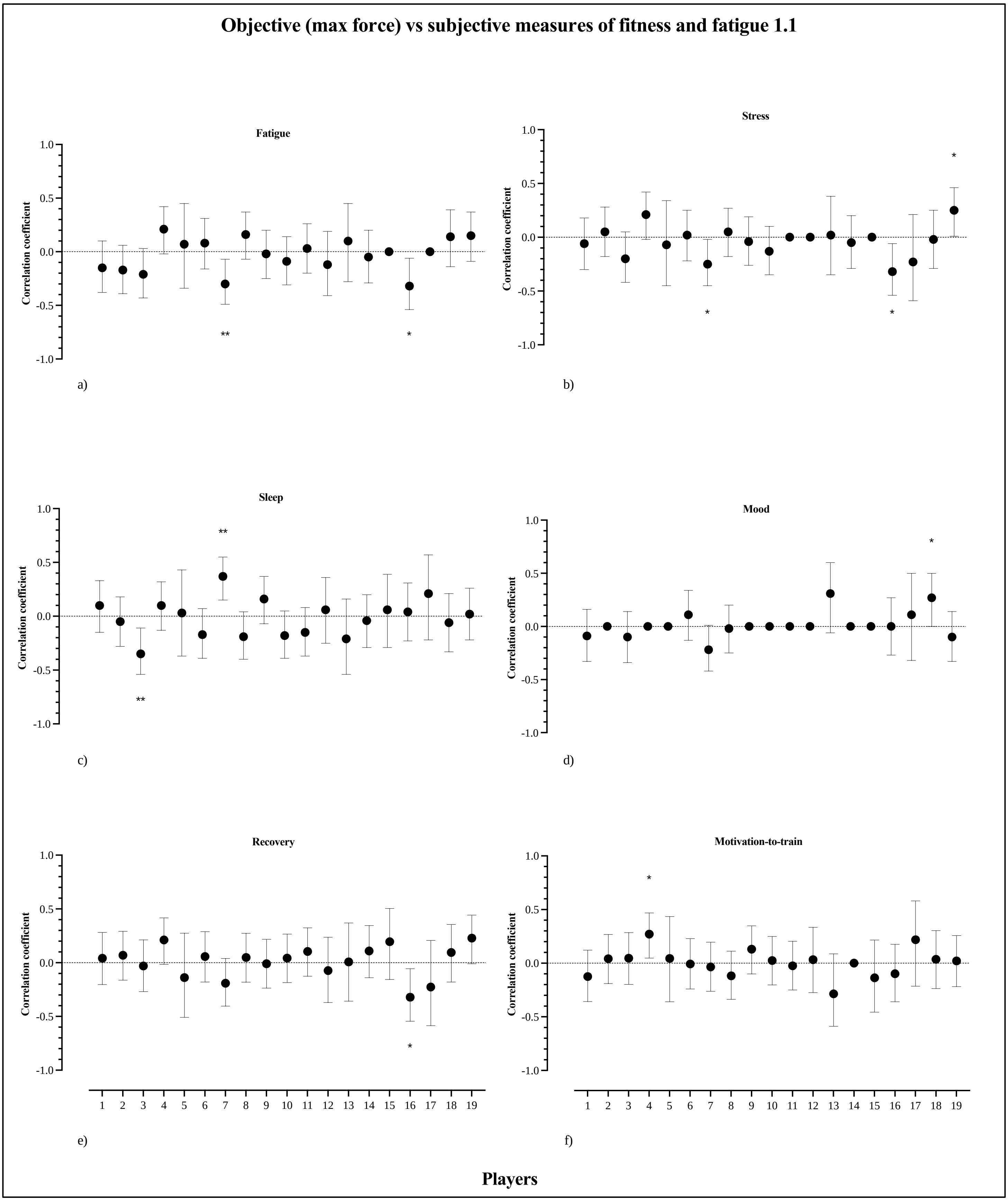


FIGURE 6.2: Intra-individual correlation coefficient for each player for max force vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals

*p = <0.05; **p = <0.01

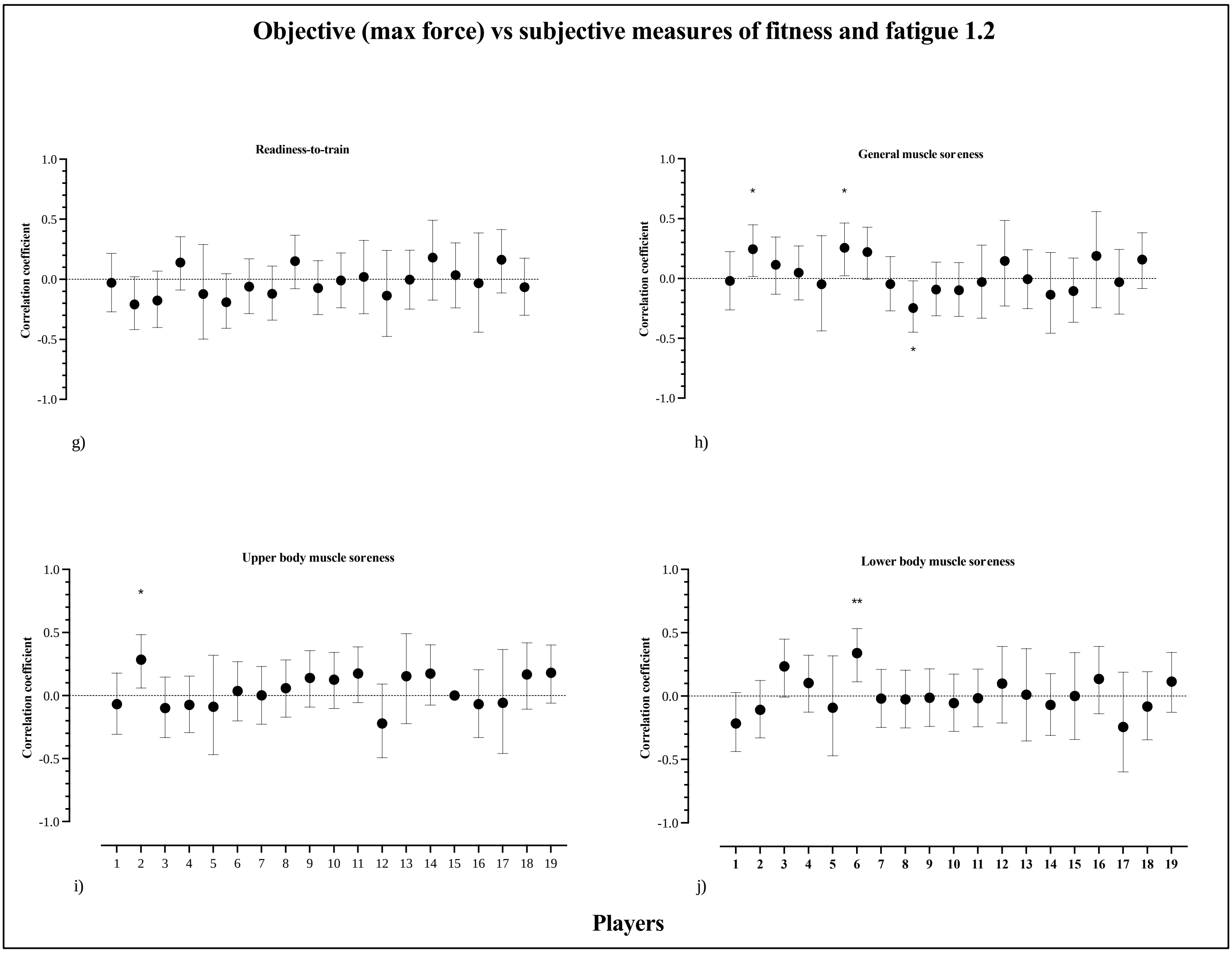


FIGURE 6.3: Intra-individual correlation coefficient for each player for max force vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals

*p = <0.05; **p = <0.01

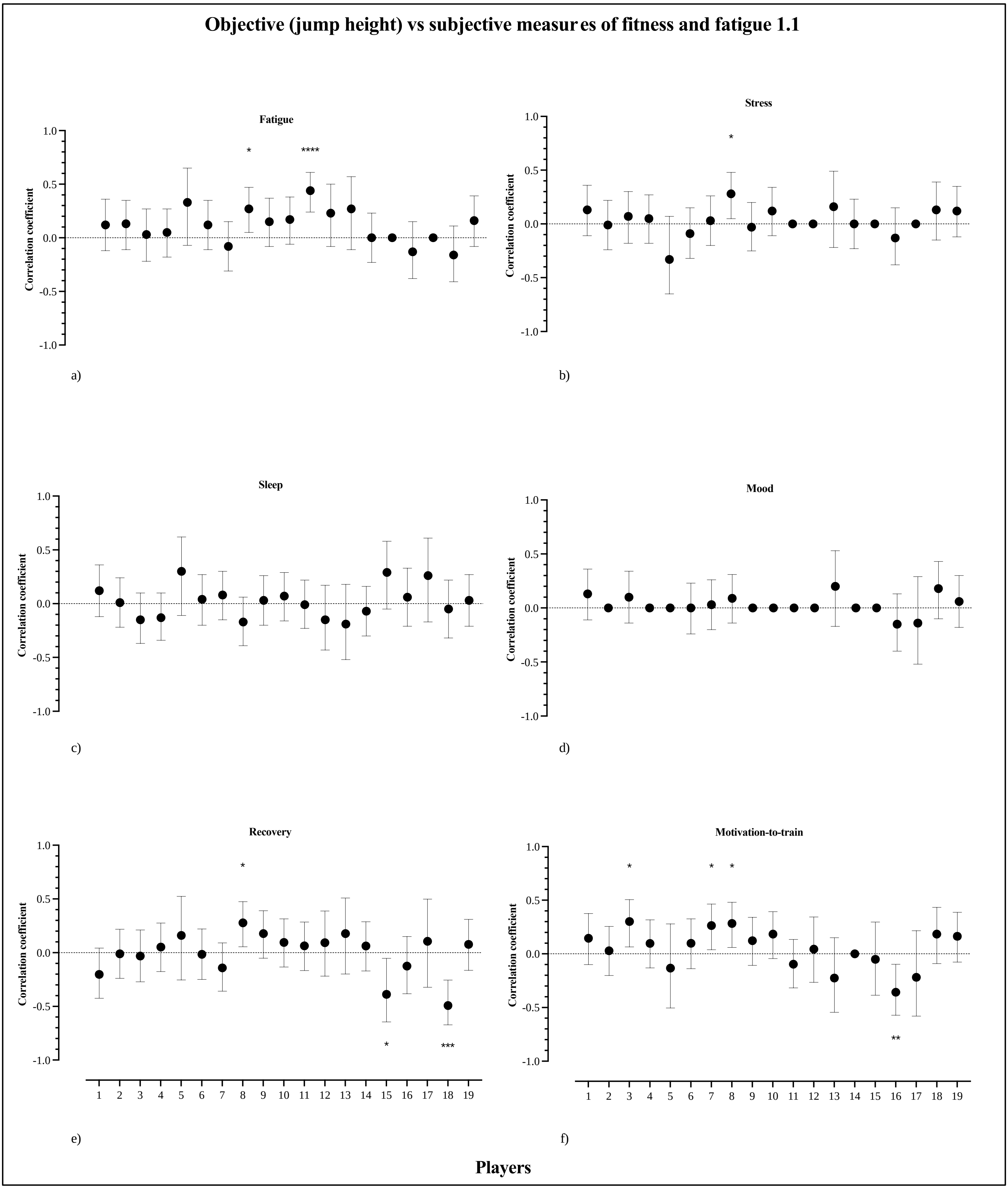


FIGURE 6.4: Intra-individual correlation coefficient for each player for jump height vs subjective measures of fitness and fatigue. Data are represented as r values with 95% upper and lower confidence intervals.

*p = <0.05; **p = <0.01; ***p = <0.0002; ****p = <0.0001

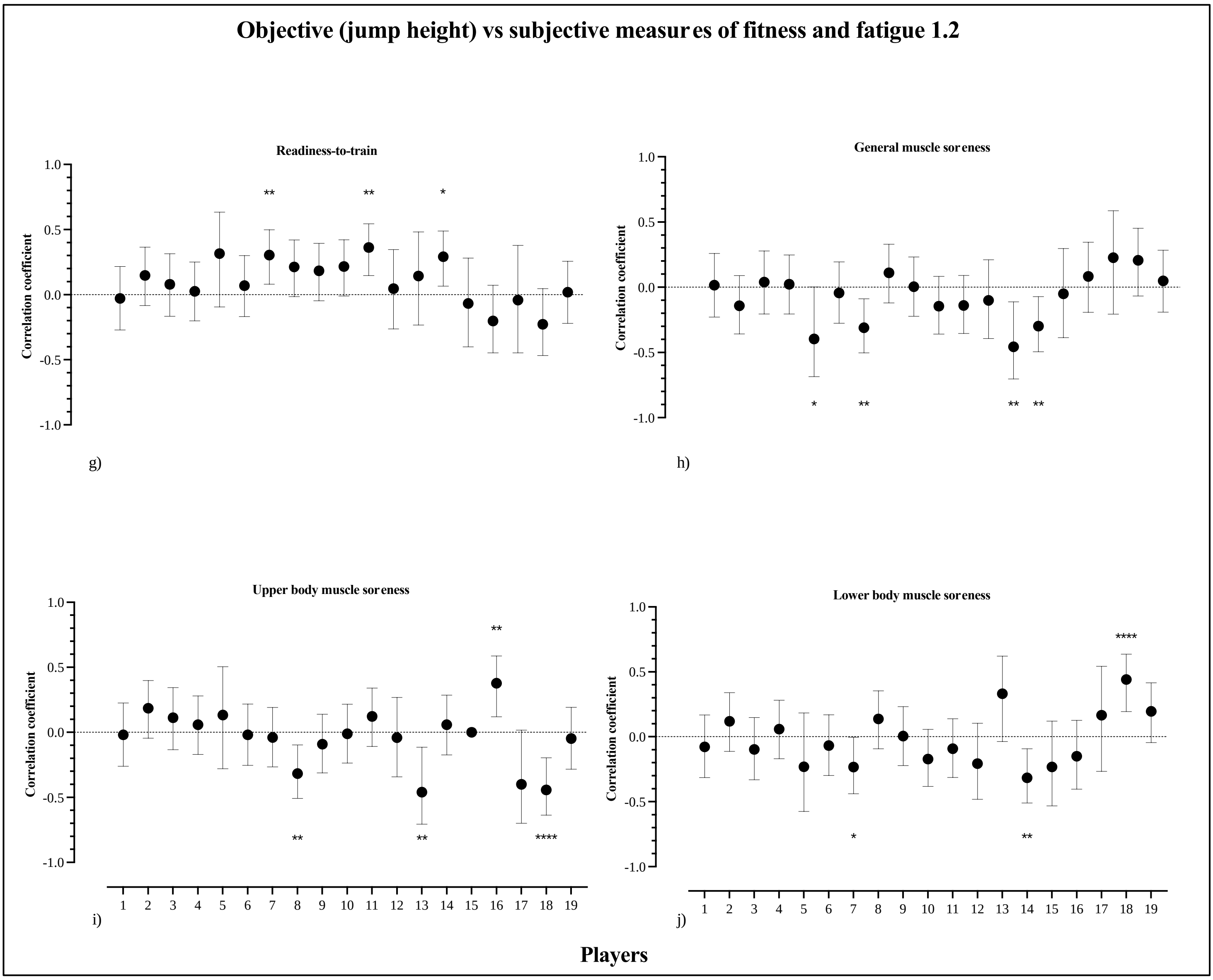


FIGURE 6.5: Intra-individual correlation coefficient for each player for jump height vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01; ***p = <0.0002; ****p = <0.0001

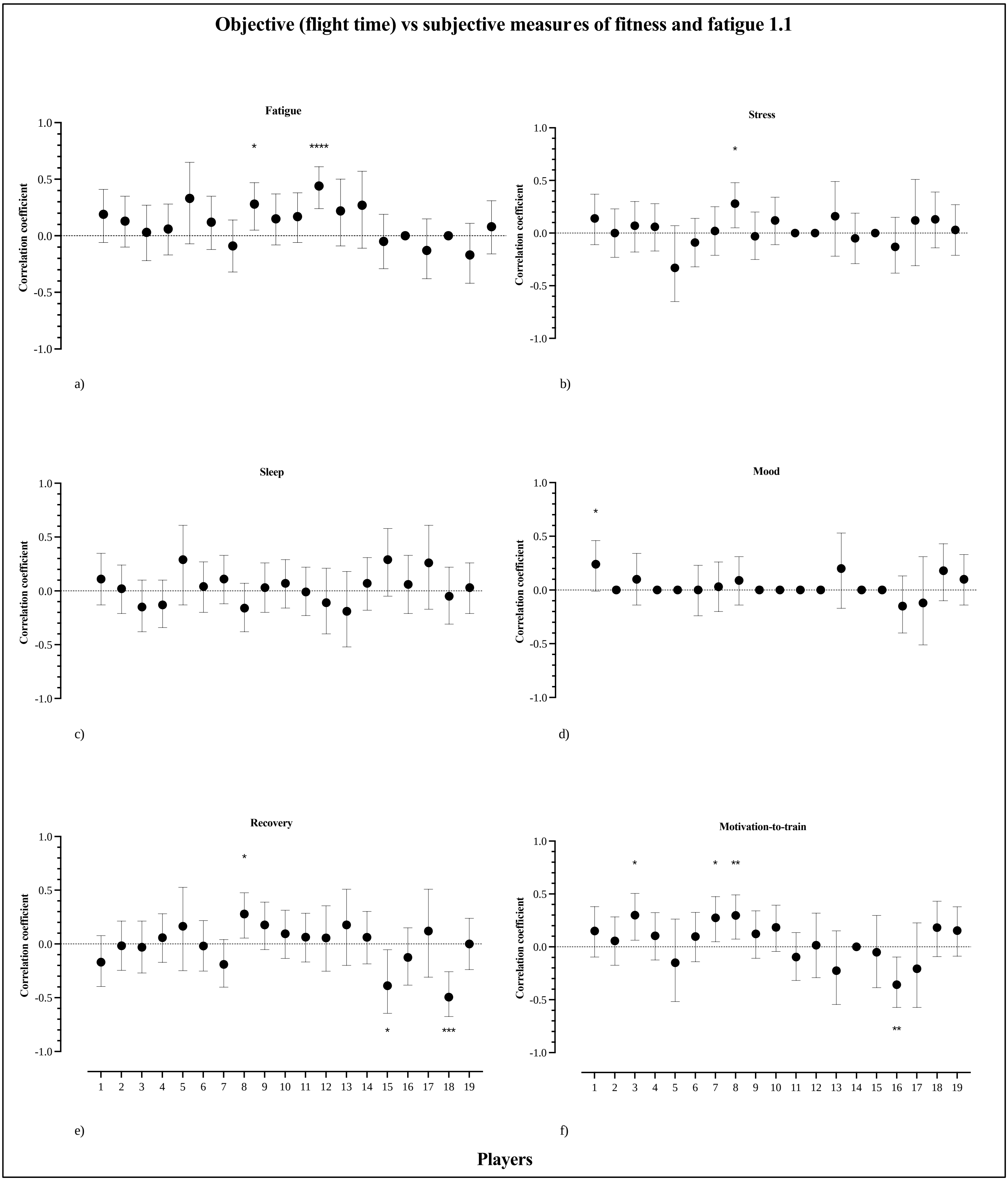


FIGURE 6.6: Intra-individual correlation coefficient for each player for flight time vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01; ***p = <0.0002; ****p = <0.0001

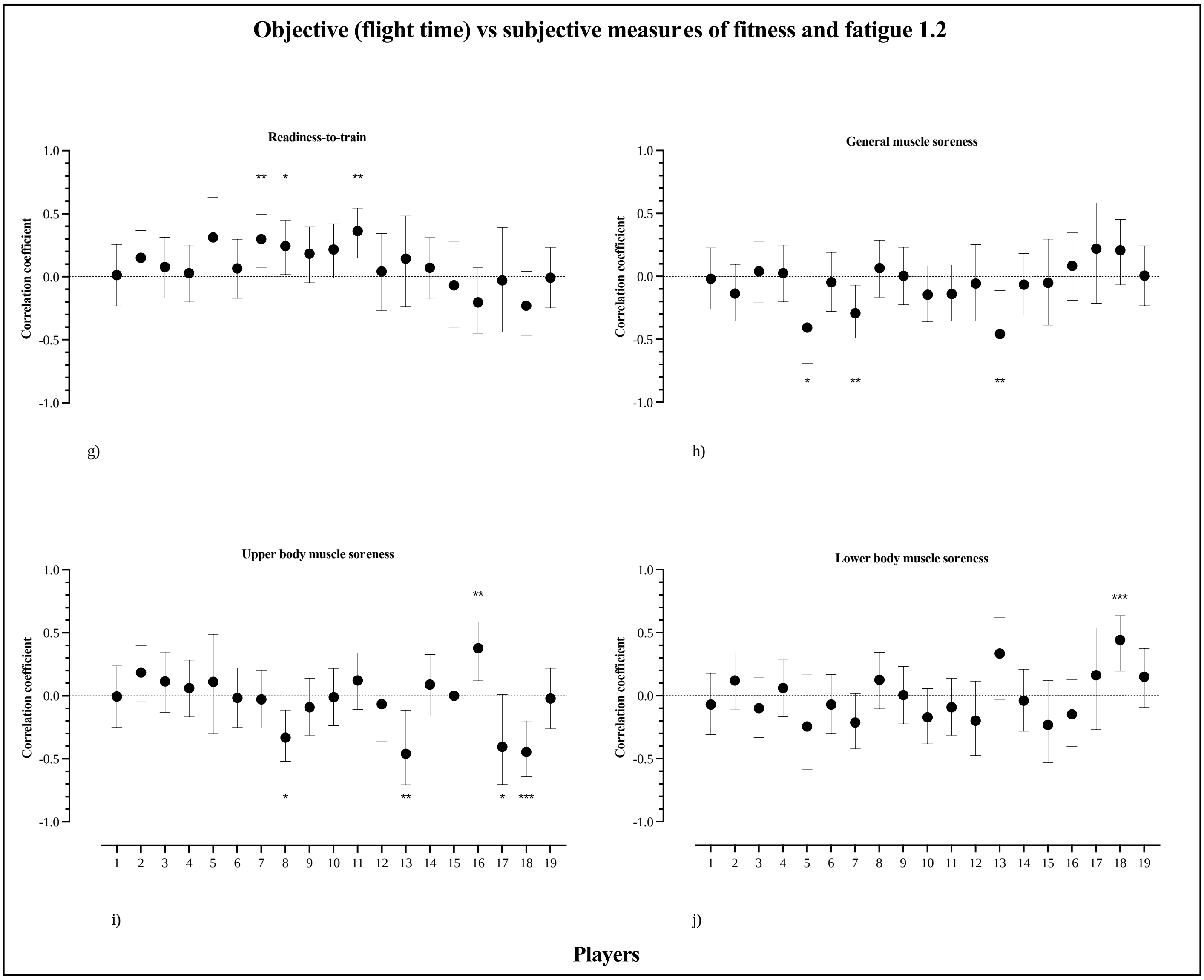


FIGURE 6.7: Intra-individual correlation coefficient for each player for flight time vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01; ***p = 0.0002

6.3.1.2 Objective measures of training and/or match demands vs Subjective (wellness) measures of fitness and fatigue

There were no significant relationships between total distance and fatigue, total distance, and stress, nor between total distance and mood (FIGURE 6.8 *graphs a, b and d).* Only Player 8 (-0.20; -0.42 to -0.05) had a significant negative relationship between total distance and sleep. In two players recovery was correlated with total distance (Player 6 had a positive relationship and Player 7 had a negative relationship) (FIGURE 6.8 *graph e*) The same two players had motivation-to-train significantly correlated with total distance (FIGURE 6.8 *graph f*). Only one player had a significant relationship between total distance and readiness-to-train, general muscle soreness, upper and lower body muscle soreness (FIGURE 6.9 *graphs g – j*).

FIGURE 6.10 and FIGURE 6.11 are a summary of all the correlation coefficients between high-speed running and subjective measures of fitness and fatigue. Only a few significant relationships were observed. For example, only Player 7 and Player 19 had a significant relationship between high-speed running and fatigue, stress, and mood respectively. There were no significant relationships between sleep and high-speed running. While three players had significant relationships between high-speed running and recovery and motivation-to-train. Furthermore, readiness-to-train, general muscle soreness, upper body muscle soreness and lower body muscles soreness only showed a small number of significant correlations.

Sprint efforts correlation coefficient data is summarised in FIGURES 6.12 and 6.13. Player 7 was the only player to show a significant positive relationship between sprint efforts and fatigue and stress. There were no significant relationships between sprint efforts and sleep and recovery. There were four significant relationships between sprint efforts and motivation-to-train with Player 7 having the highest correlation (0.34; 0.17 to 0.51).

While six players had a significant relationship between sprint efforts and general muscle soreness, the strongest relationship only explained for approximately 9 % of the variance between sprint efforts and general muscle soreness.

The correlation coefficient's between bodyload and fatigue, stress, sleep, mood, recovery, and motivation-to-train are summarised in FIGURE 6.14. Players 12 and 13 had a significant positive and negative correlation respectively between fatigue and bodyload (*graph a*). While Player 5 and Player 12 had a positive and negative correlation respectively between stress and bodyload (*graph b*). Three players had a significant correlation between bodyload and sleep (*graph c*) and between bodyload and recovery (*graph e*). However, there were no significant correlations between mood and motivation-to-train compared to bodyload. Furthermore, bodyload was only correlated to one player each for readiness-to-train (Player 13), upper body muscle soreness (Player 1) and lower body muscle soreness (Player 18) (FIGURE 6.15 *graphs g, i and j*). None of the players had a significant relationship between general muscle soreness and bodyload.

When considering high intensity efforts vs subjective measures of fitness and fatigue as summarised in FIGURES 6.16 and 6.17 below, there were no relationships between high intensity efforts and sleep (*graph c*) or upper body muscle soreness (*graph i*). Some of strongest relationships were shown for Player 7 between high intensity efforts and motivation-to-train (0.30; 0.12 to 0.47) and readiness-to-train (0.25; 0.06 to 0.42). Player 12 had the strongest relationship between high intensity efforts and general muscle soreness (0.29; 0.08 to 0.49) (FIGURE 6.17 *graph h*).

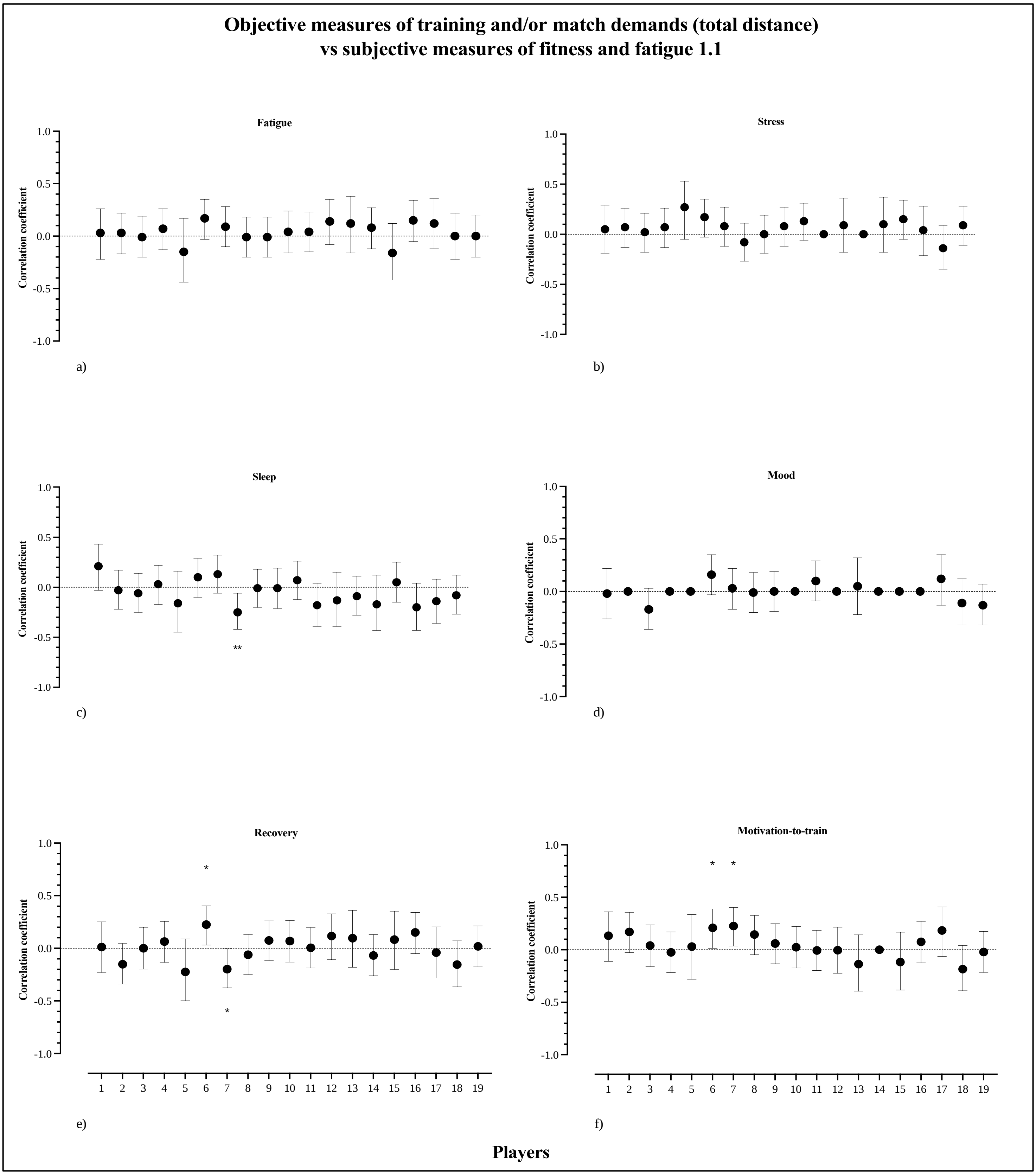


FIGURE 6.8: Intra-individual correlation coefficient for each player for total distance vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01

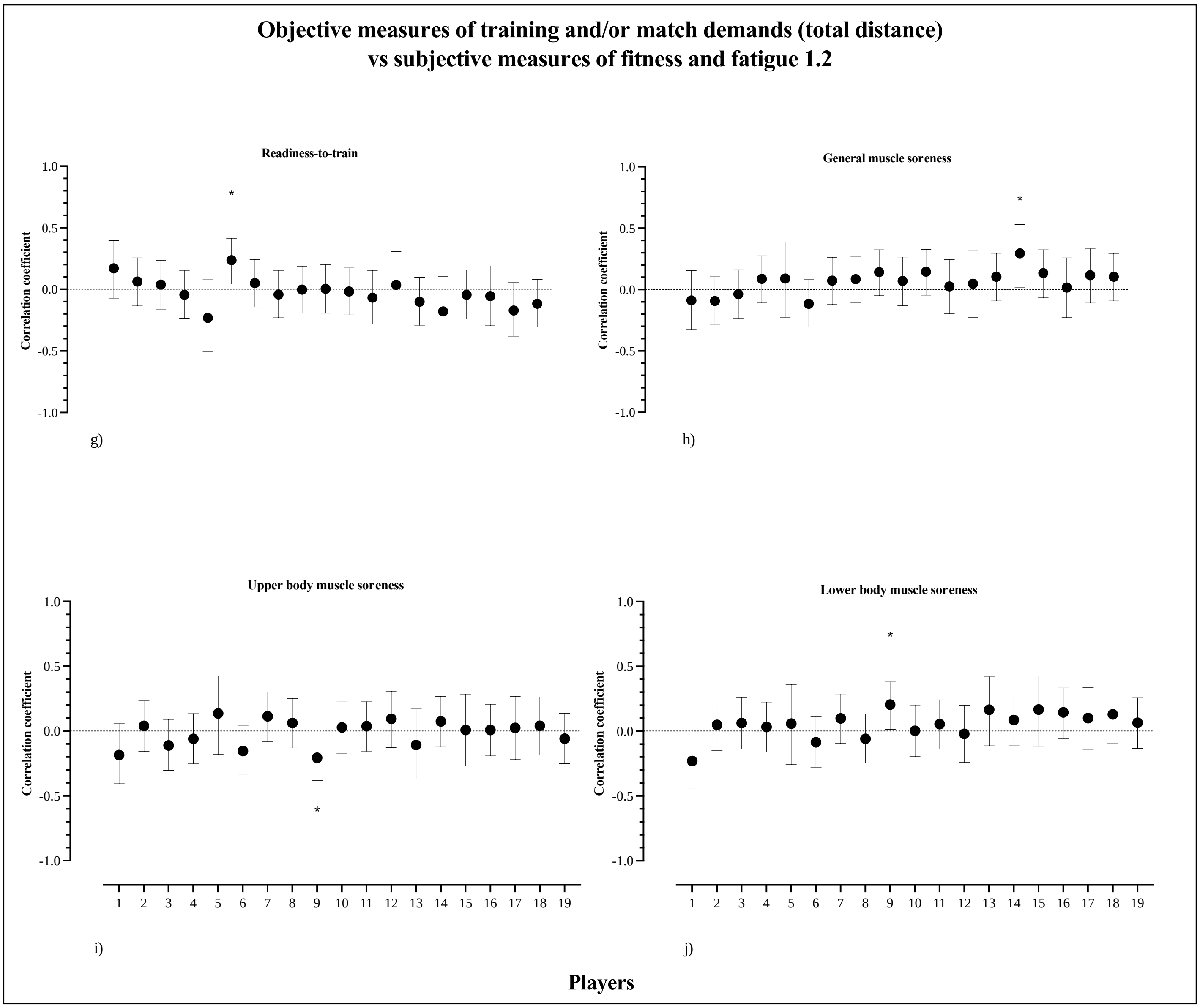


FIGURE 6.9: Intra-individual correlation coefficient for each player for total distance vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05

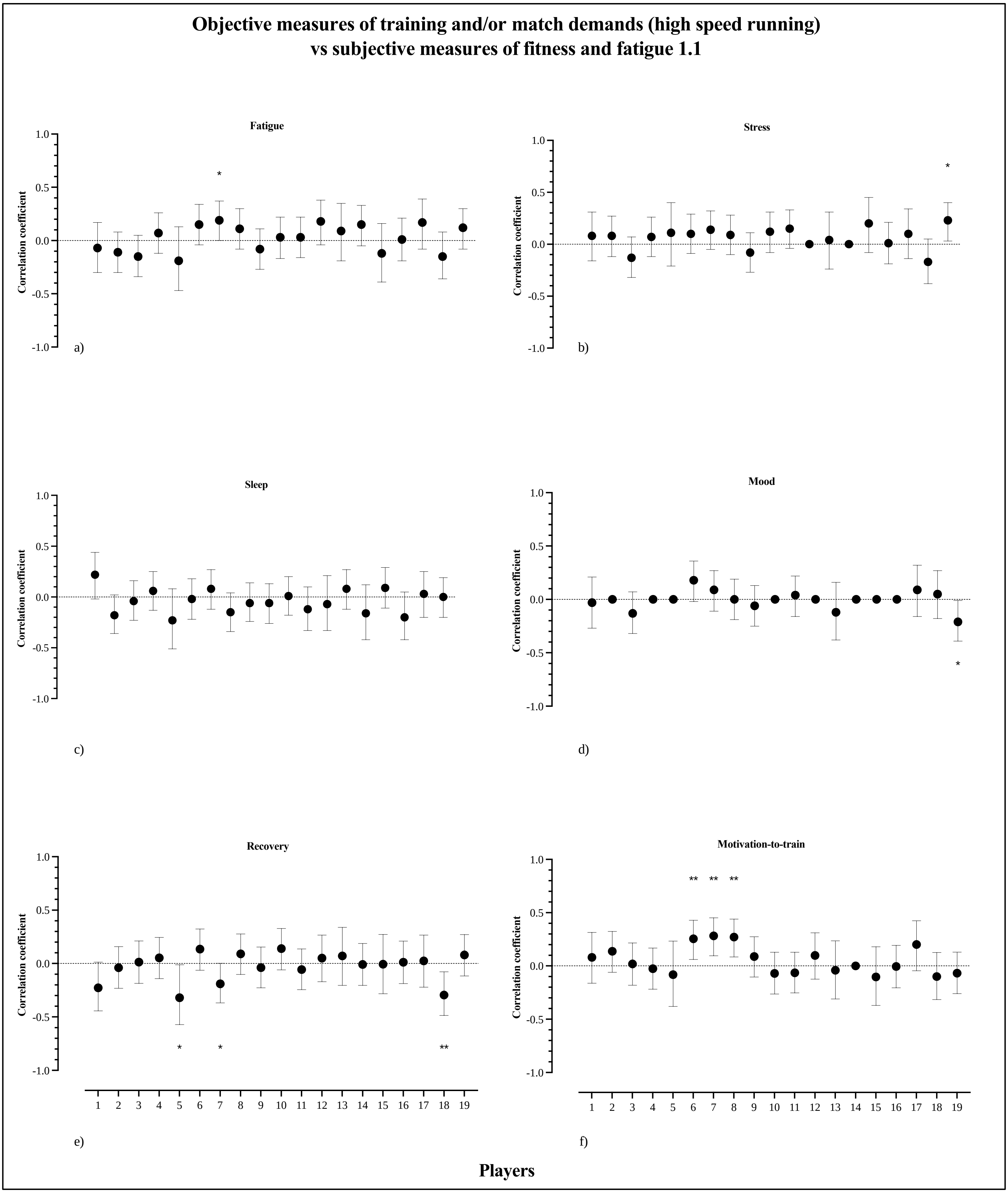


FIGURE 6.10: Intra-individual correlation coefficient for each player for high-speed running vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01

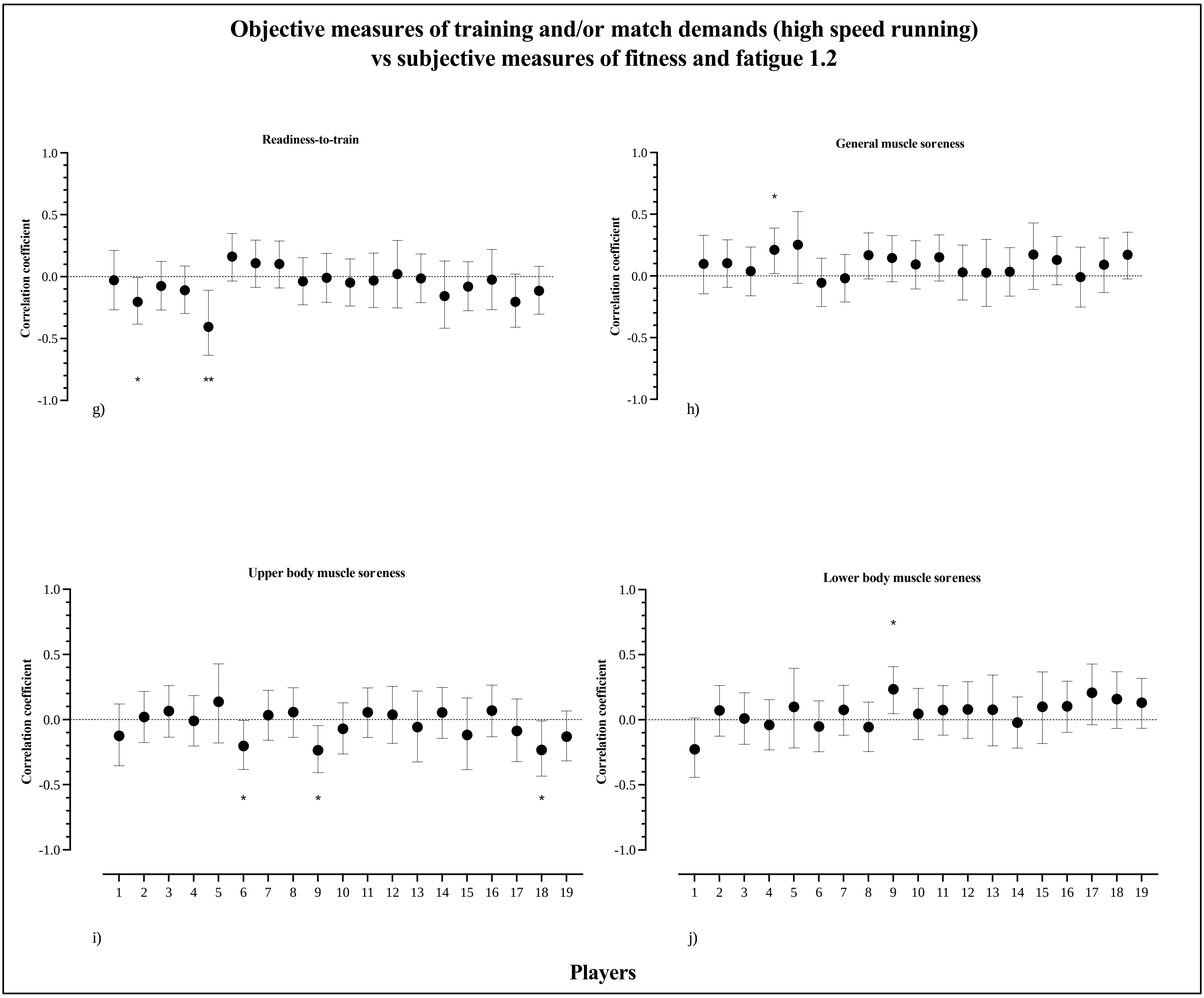
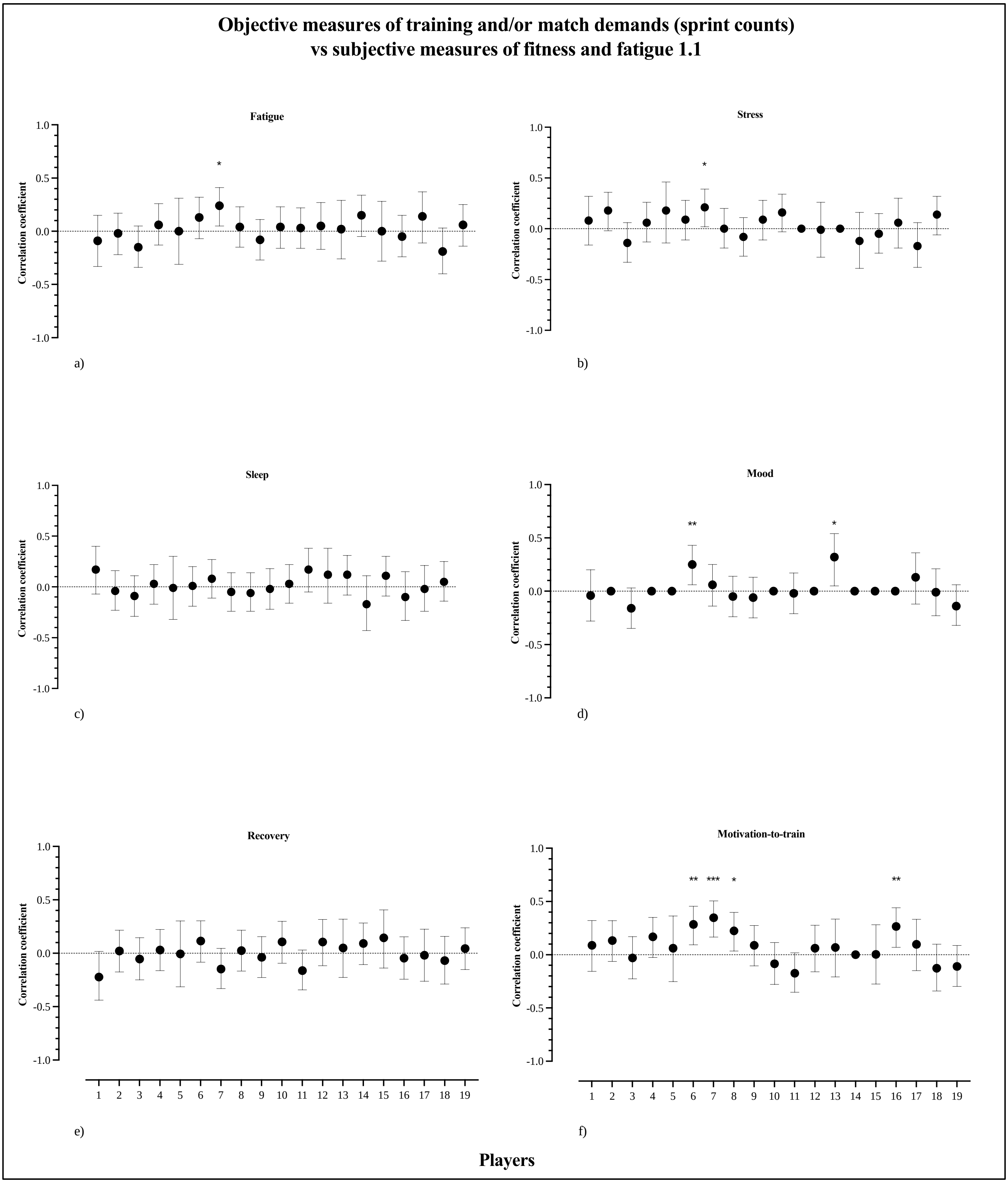


FIGURE 6.11: Intra-individual correlation coefficient for each player for high-speed running vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01



Objective measures of training and/or match demands (sprint counts) vs subjective measures of fitness and fatigue 1.1

Fatigue

Stress

Sleep

Mood

Recovery

Motivation-to-train

FIGURE 6.12: Intra-individual correlation coefficient for each player for sprint efforts vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01; ***p = <0.0002

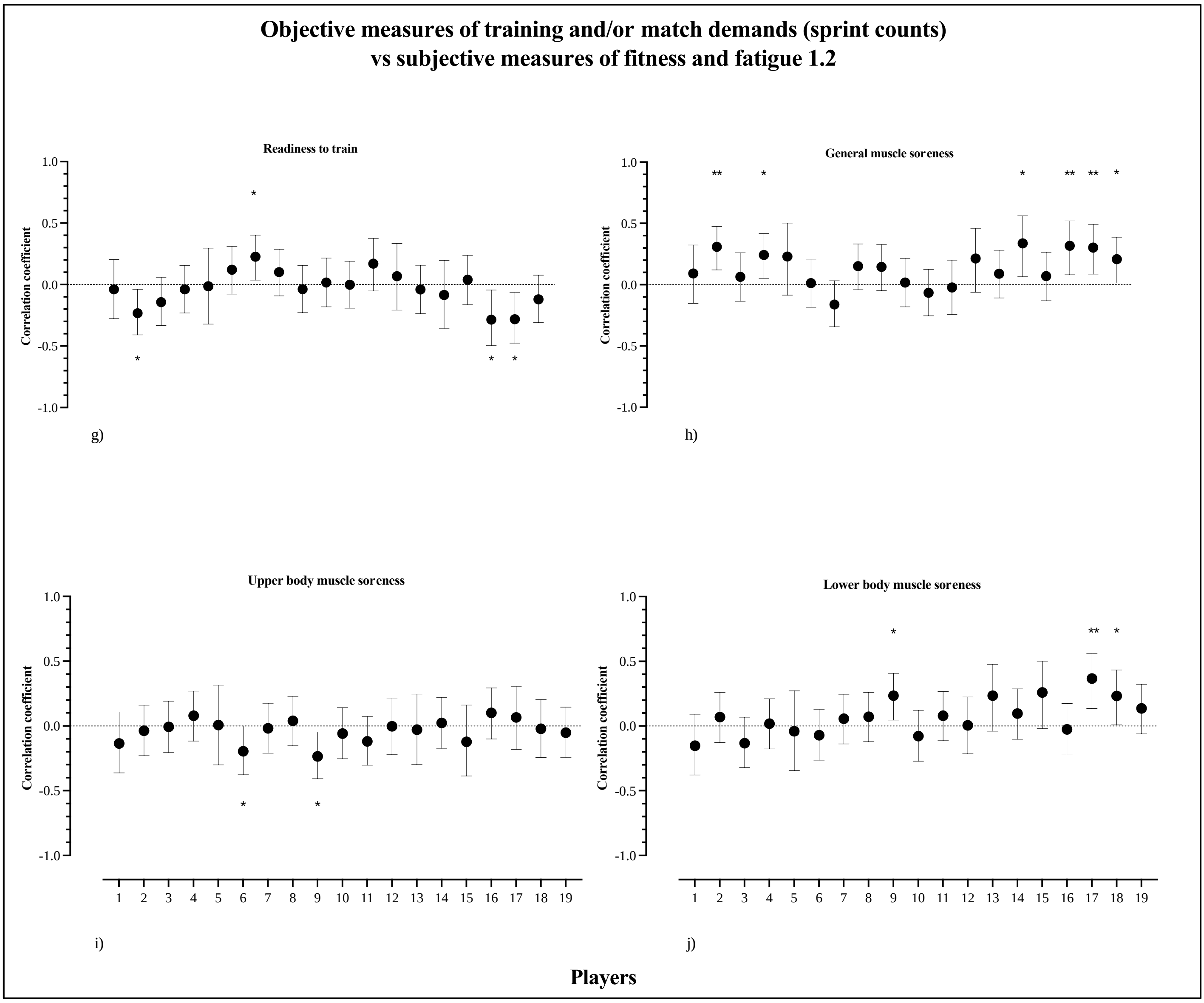


FIGURE 6.13: Intra-individual correlation coefficient for each player for sprint efforts vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = 0.01

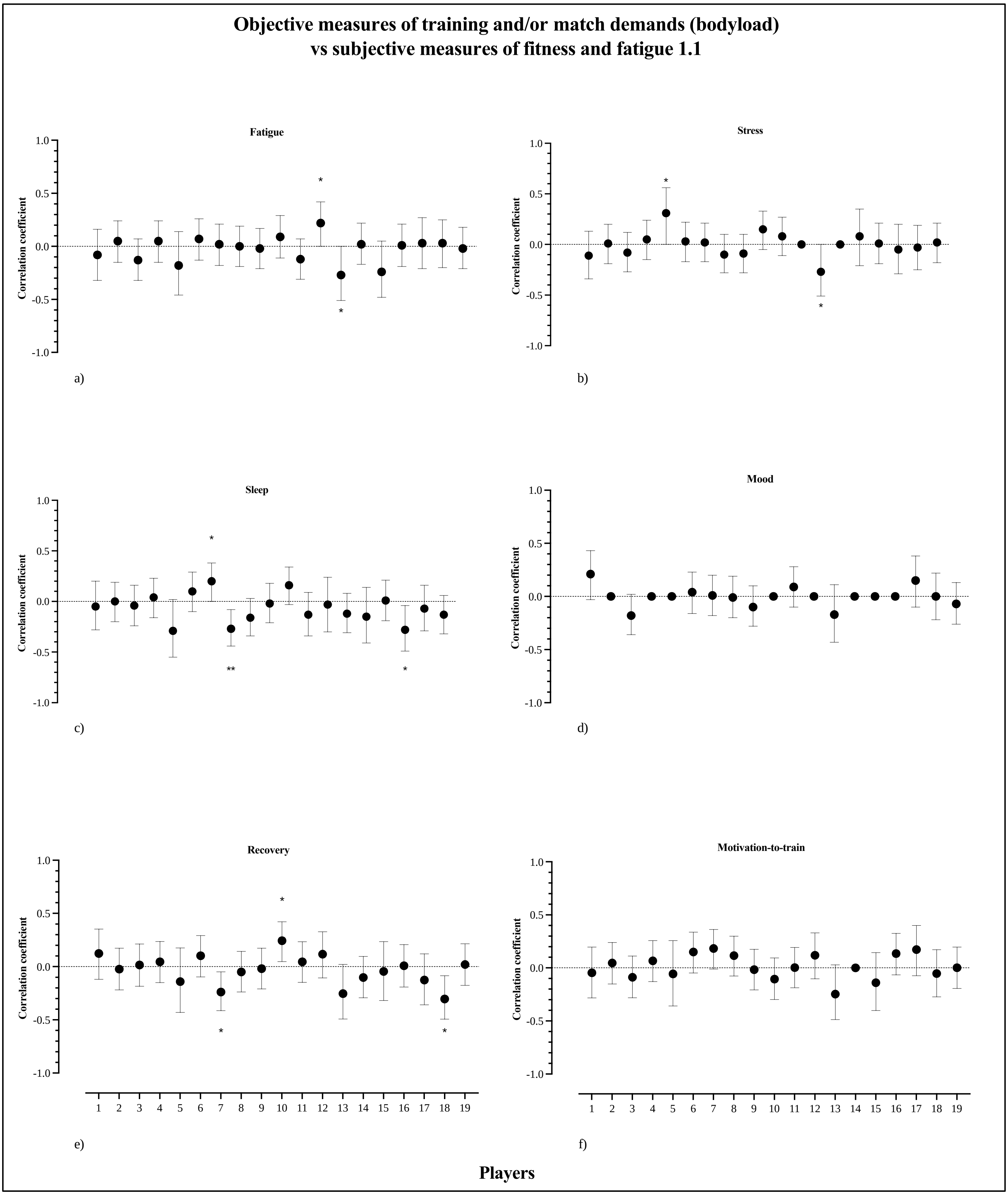


FIGURE 6.14: Intra-individual correlation coefficient for each player for bodyload vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01

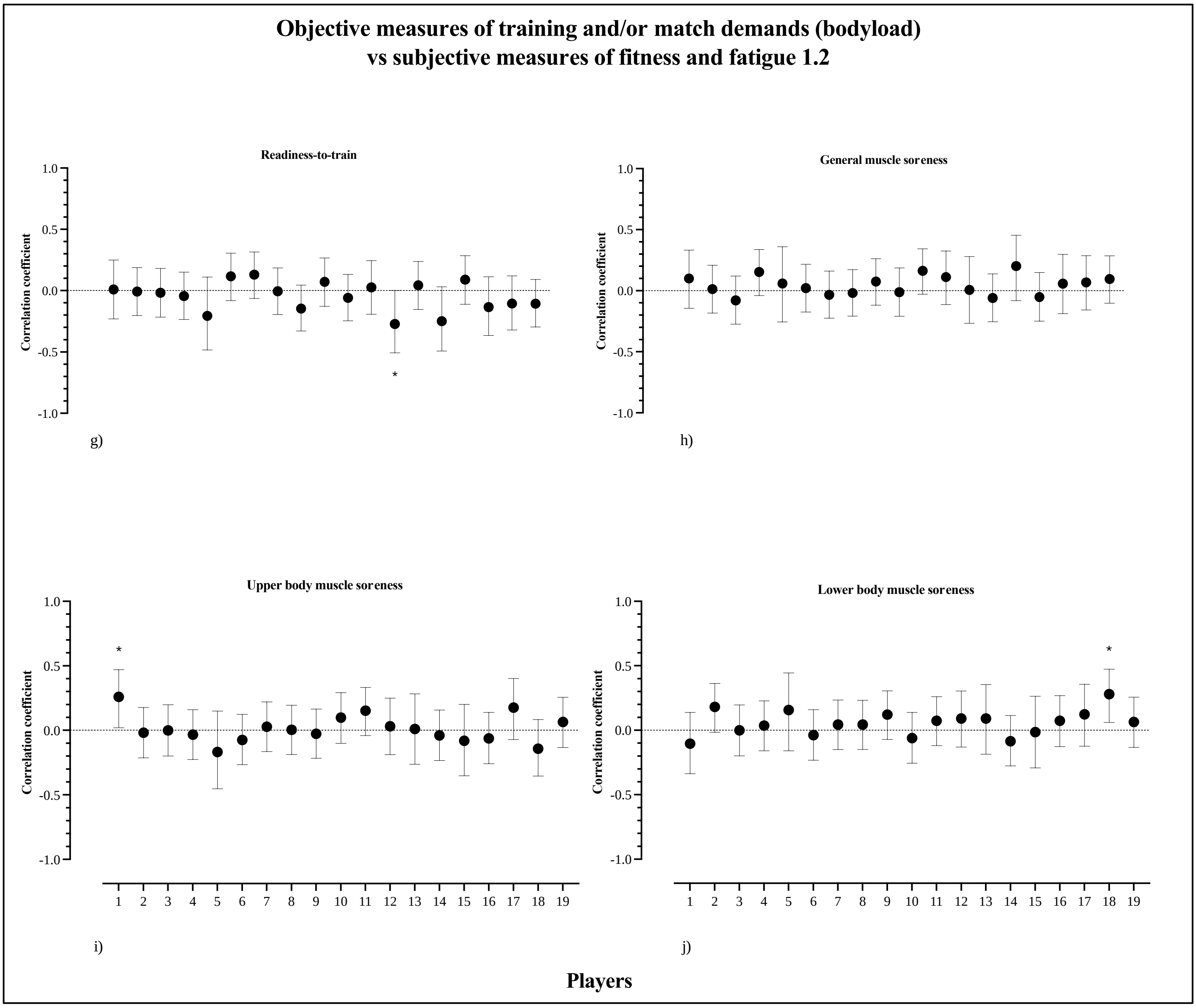


FIGURE 6.15: Intra-individual correlation coefficient for each player for bodyload vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05

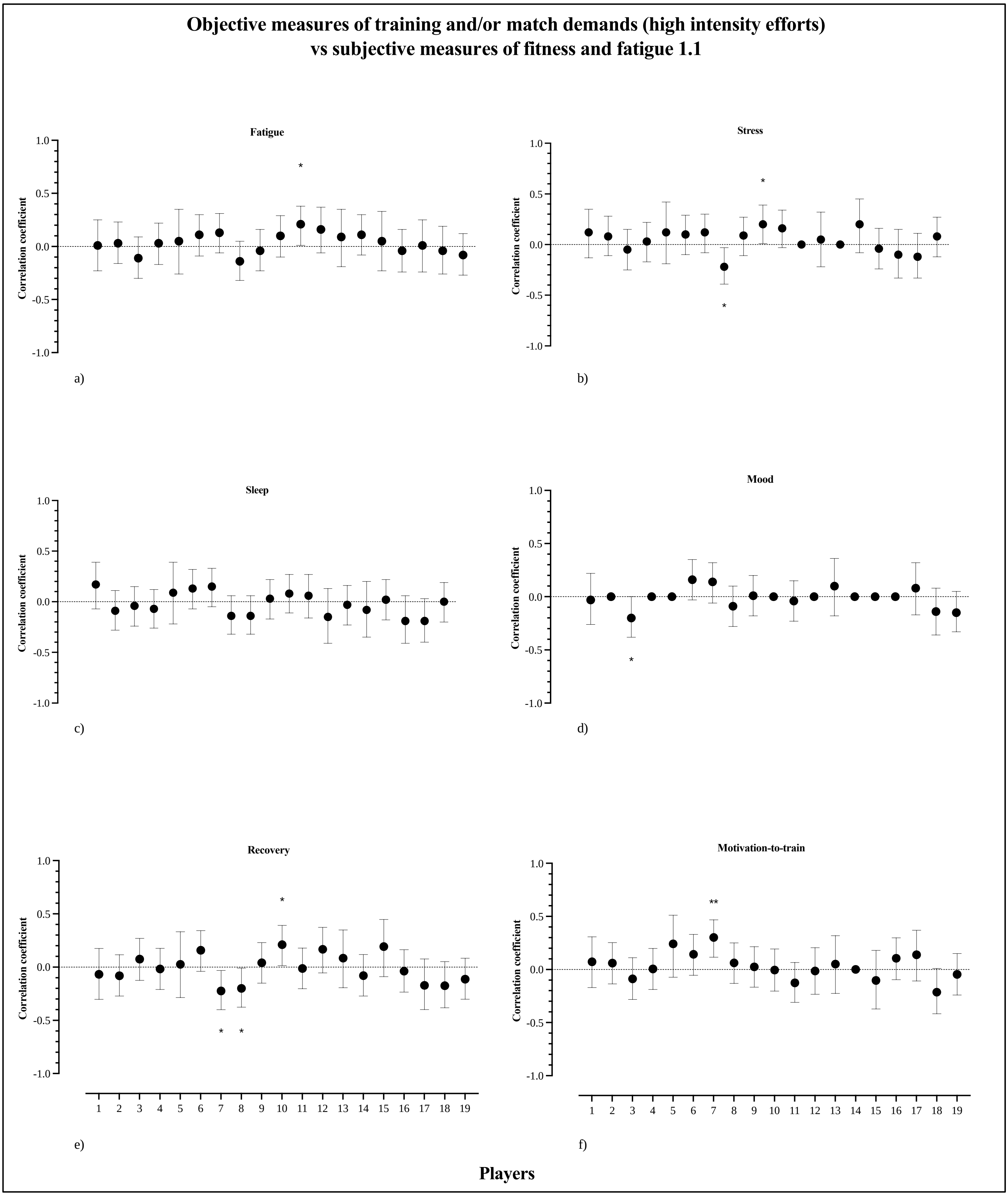


FIGURE 6.16: Intra-individual correlation coefficient for each player for high intensity efforts vs subjective measures of fitness and fatigue. Data are represented as r values with 95% upper and lower confidence intervals.

*p = <0.05; **p =< 0.01

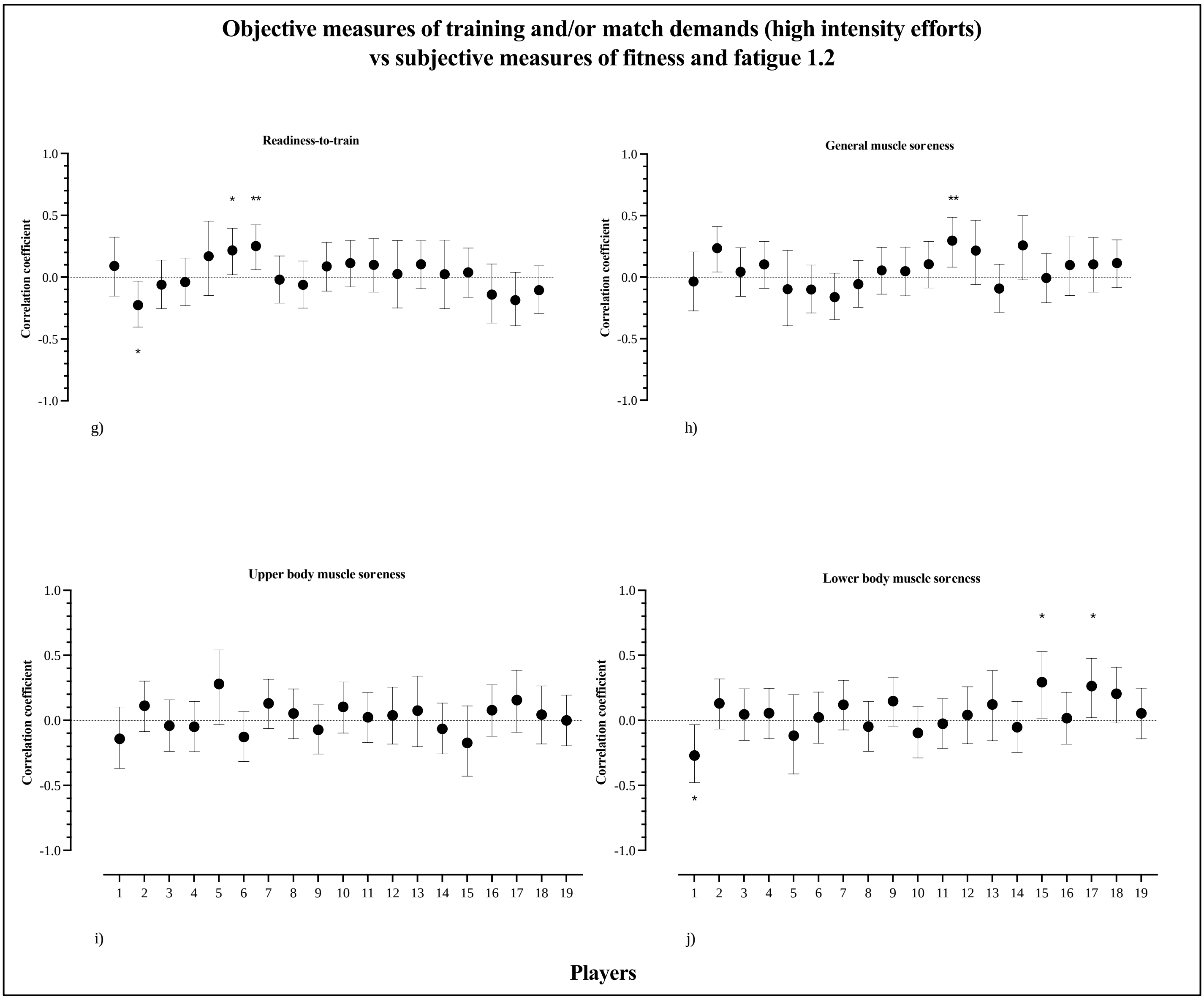


FIGURE 6.17: Intra-individual correlation coefficient for each player for high intensity efforts vs subjective measures of fitness and fatigue. Data are represented as r values with 95% upper and lower confidence intervals.

*p = <0.05; **p = <0.01

FIGURE 6.18 and FIGURE 6.19 summarise the relationships between heart rate >85 % and subjective measures of fitness and fatigue. No players had a significant relationship between heart rate >85 % and mood. Player 15 (-0.39; -0.60 to -0.12) had the strongest significant (negative) relationship between heart rate >85 % and fatigue. Player 10 and Player 17 both had a significant positive relationship between stress and heart rate heart rate >85 % (*graph b*). Four players had a significant relationship between heart rate >85 % and recovery and motivation-to-train. Player 15 (-0.36; -0.58 to -0.09) had the strongest negative relationship for recovery vs. heart rate >85% (*graph e*). While both Player 7 (0.26; 0.07 to 0.42) and Player 8 (0.27; 0.09 to 0.044) had the strongest positive relationship for motivation-to-train vs. heart rate >85 % (*graph f*). Player 17 (0.39; 0.16 to 0.58) had the strongest positive relationship for readiness-to-train vs. heart rate >85 % (*graph g*) and had the strongest relationship between general muscle soreness vs heart rate >85 % (-0.47; -0.64 to -0.24). Furthermore, Player 3 (-0.33; -0.49 to -0.14) had the strongest negative relationship for upper body muscle soreness and heart rate >85% (*graph i*).

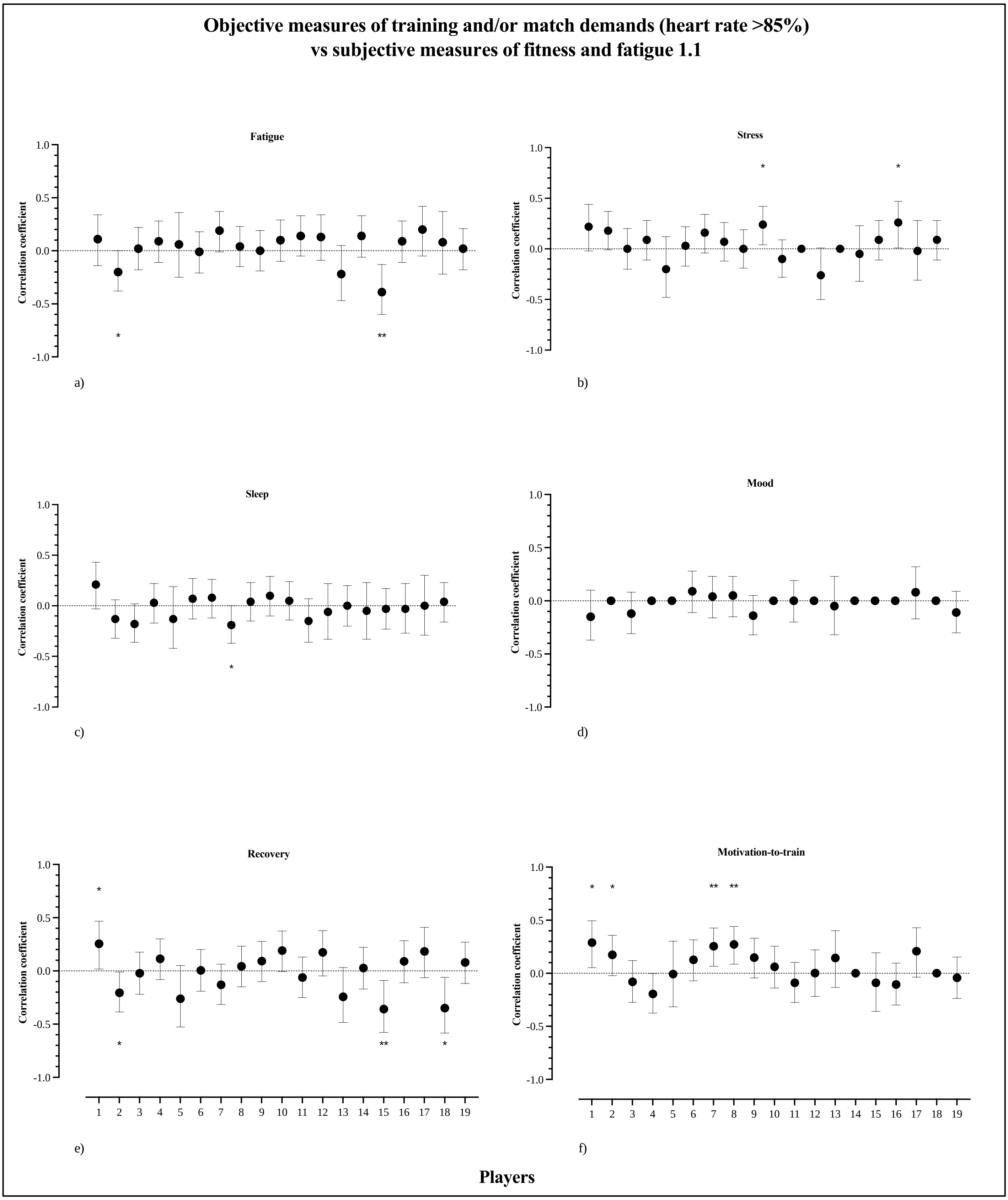


FIGURE 6.18: Intra-individual correlation coefficient for each player for heart rate >85 % vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01

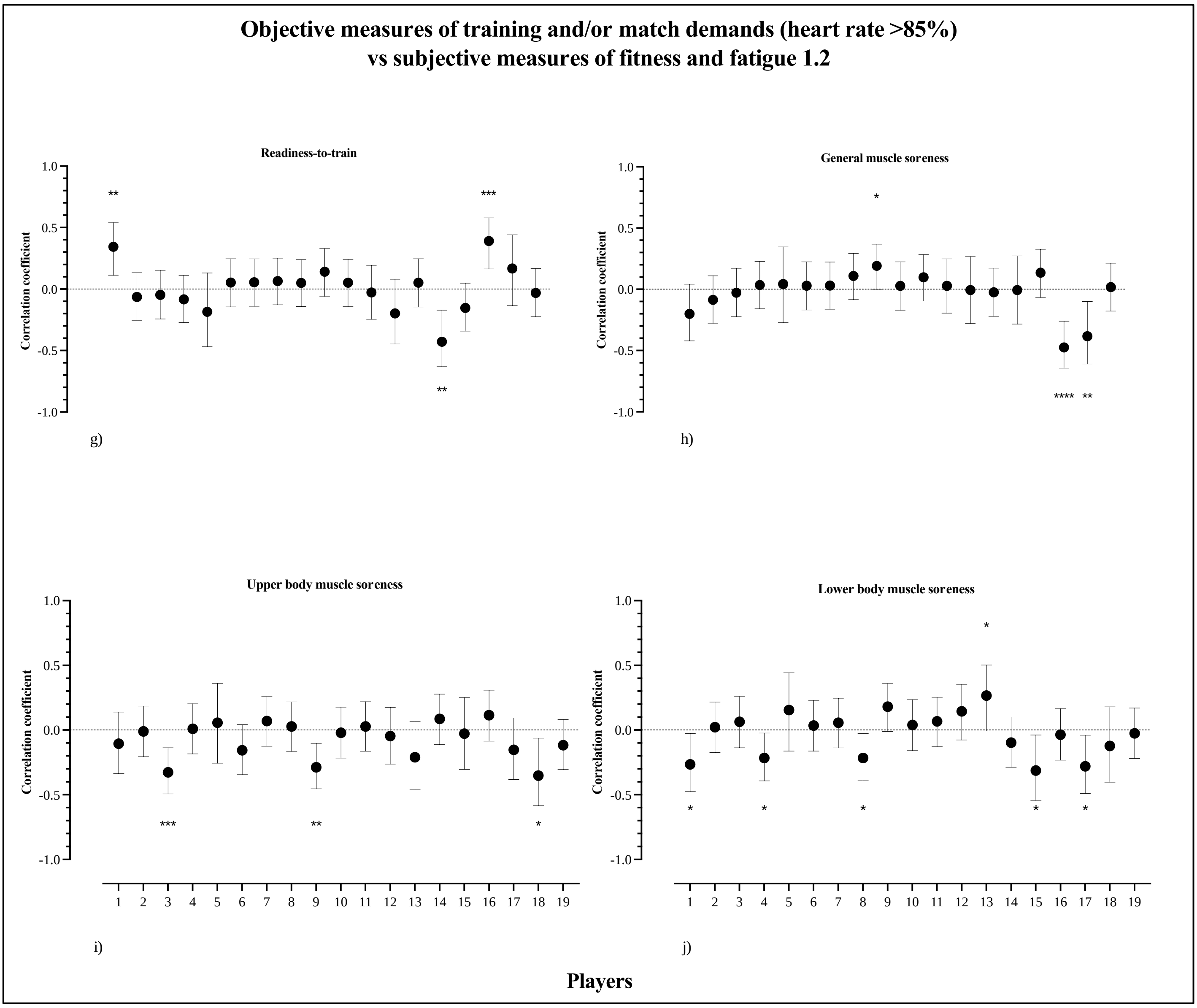


FIGURE 6.19: Intra-individual correlation coefficient for each player for heart rate >85 % vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = 0.01; ***p = 0.0002; ****p = 0.0001

6.3.1.3 Subjective measures of training and/or match demands vs subjective (wellness) measures of fitness and fatigue

The correlations for training load and RPE with subjective measures of fitness and fatigue are summarised in FIGURES 6.20 to 6.23. Player 6 (0.27; 0.11 to 0.41) and Player 9 (0.37; 0.23 to 0.50) both had significant positive relationships between fatigue and training load (FIGURE 6.20 *graph a*). Player 5 had a small significant relationship between stress and training load. Players 11 (positive) and 18 (negative) both had a significant relationship between their sleep and training load. Player 13 and Player 17 had the strongest (positive) correlations between mood and training load (FIGURE 6.20 *graph d*). The highest number of significant correlations (n = 6) occurred between motivation-to-train and training load, with Player 17 (0.40; 0.20 to 0.56) having the strongest relationship out of all players. Five players had significant relationships between training load and readiness-to-train (FIGURE 6.21 *graph g*), with Player 9 (0.34; 0.20 to 0.47) having the highest positive correlation out of all players. There were only small significant correlations between training load and the different muscle soreness values (FIGURE 6.21 *graph h, i and j*).

FIGURES 6.22 and 6.23 summarise the relationships for RPE and subjective measures of fitness and fatigue. Player 6 (0.36; 0.22 to 0.48) and Player 9 (0.37; 0.23 to 0.50) both showed strong positive relationships between fatigue and RPE. Player 17 (0.36; 0.18 to 0.51) had the strongest positive correlation between stress and RPE. Three players had significant relationships with RPE vs. sleep and mood. Several players had significant correlations between RPE and recovery (n = 6) and motivation-to-train (n = 10). Player 6 (0.35; 0.20 to 0.47) and Player 9 (0.40; 0.26 to 0.52) had the strongest relationship between recovery and RPE. While Players 6,7,8,9 and 10 had strong positive relationships for motivation-to-train and RPE. Players 6 and 9 had the highest positive correlations for readiness and RPE (FIGURE 6.23 *graph g)*. Player 12 (0.64; 0.53 to 0.72) had the highest correlation with general muscle soreness and RPE.

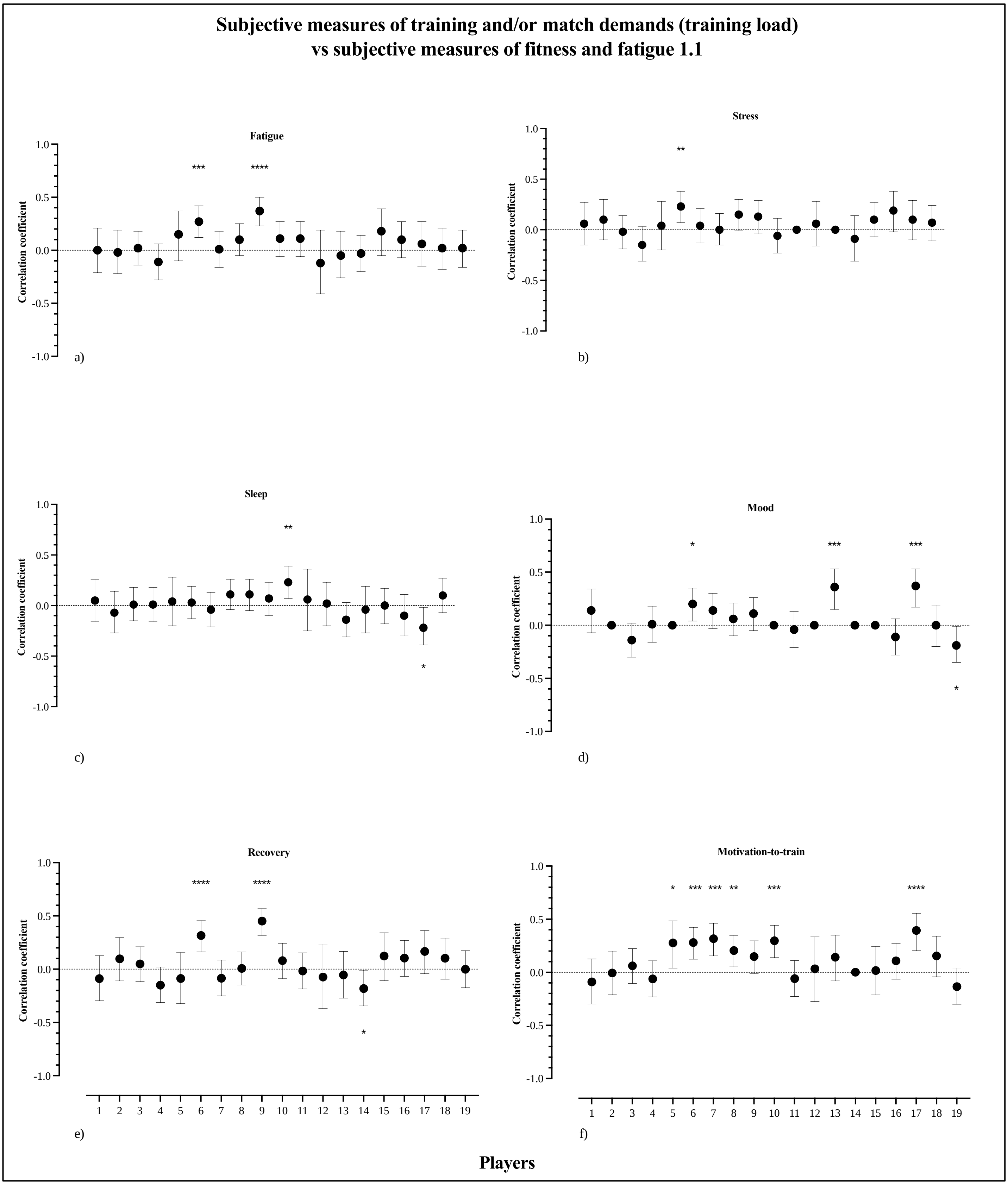
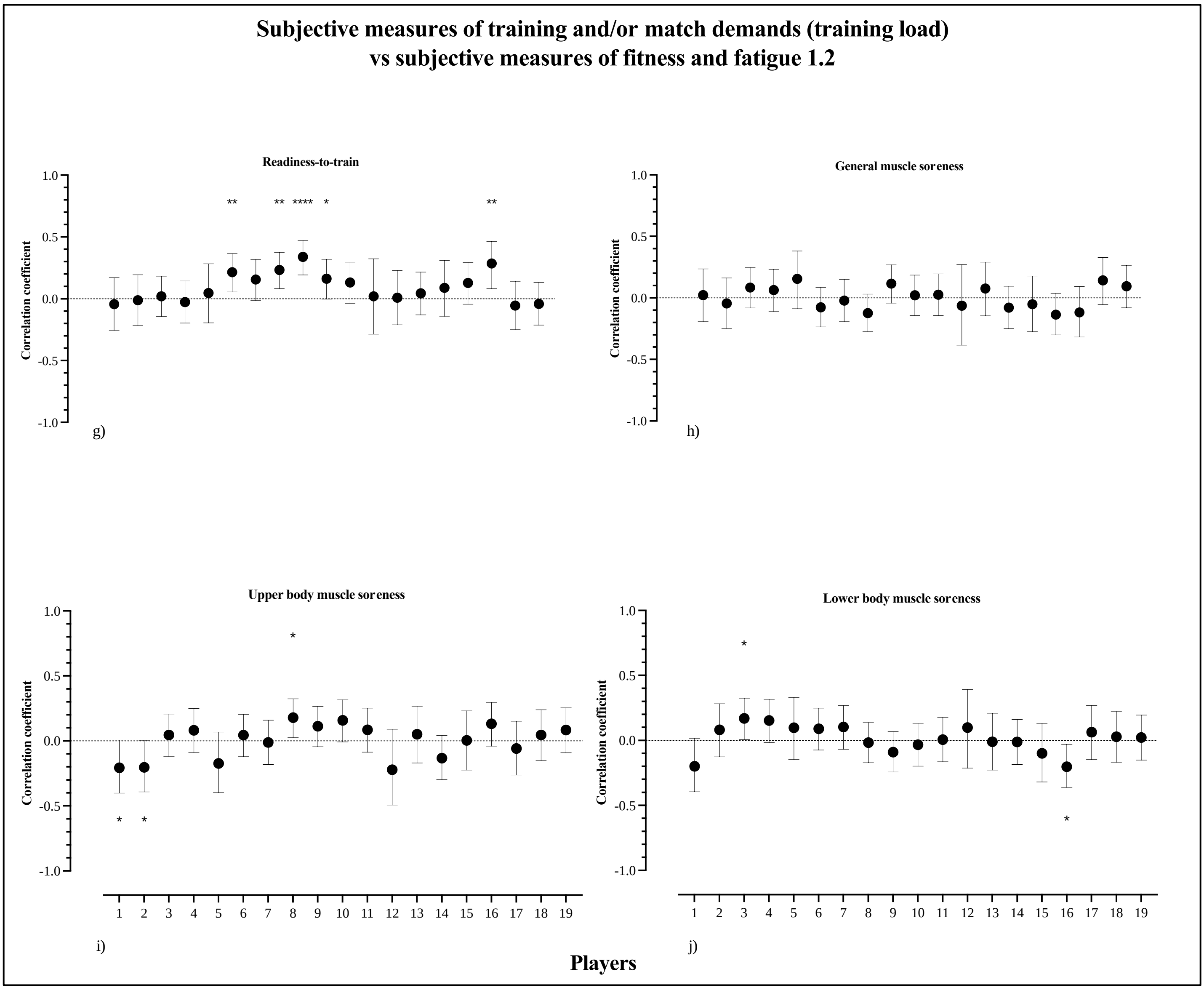


FIGURE 6. 20: Intra-individual correlation coefficient for each player for training load vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01; ***p = <0.0002; ****p = <0.0001



Subjective measures of training and/or match demands (training load) vs subjective measures of fitness and fatigue 1.2

FIGURE 6.21: Intra-individual correlation coefficient for each player for training load vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01; ****p = 0.0001

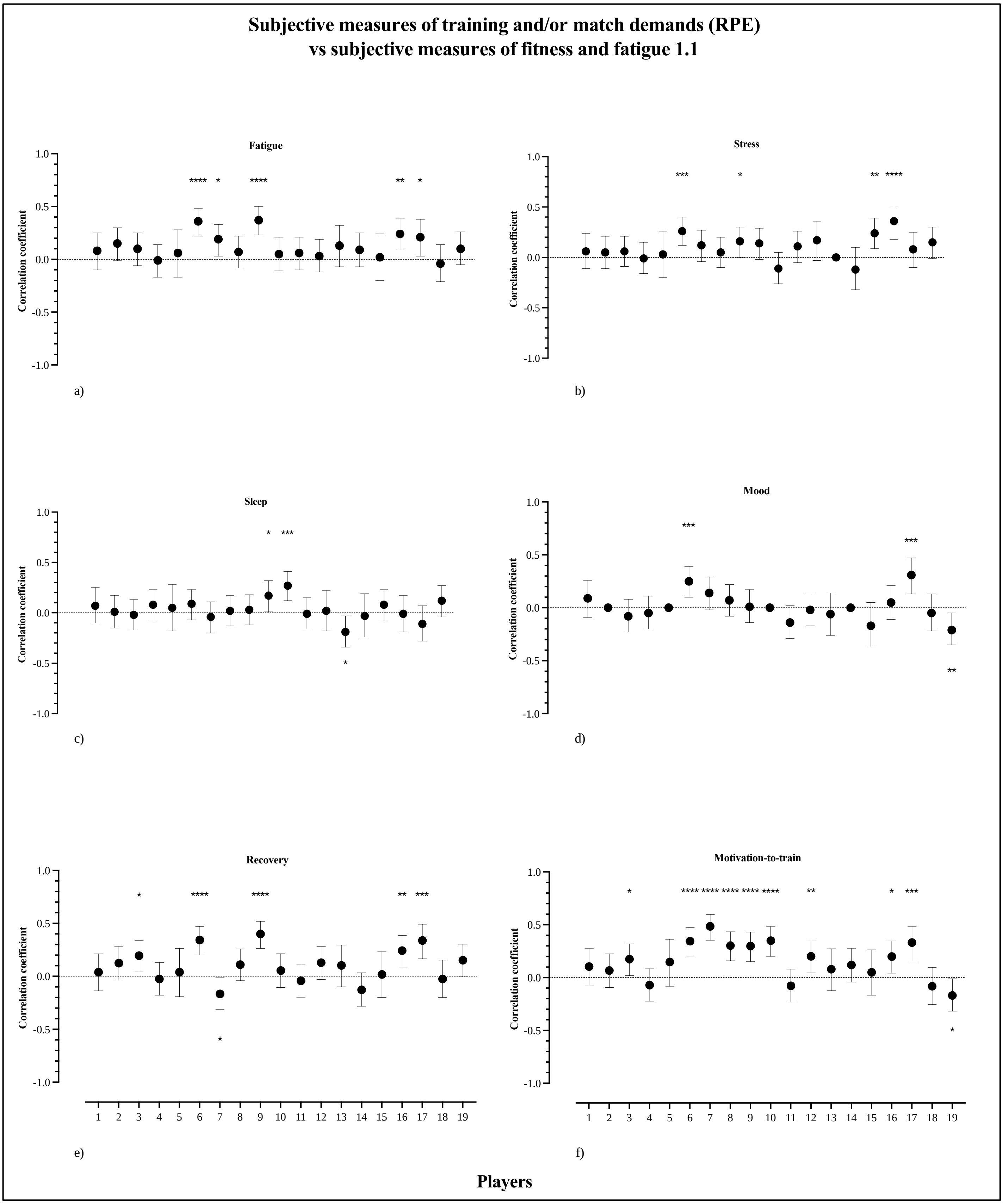


FIGURE 6.22: Intra-individual correlation coefficient for each player for RPE vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01; ***p = <0.0002; ****p = <0.0001

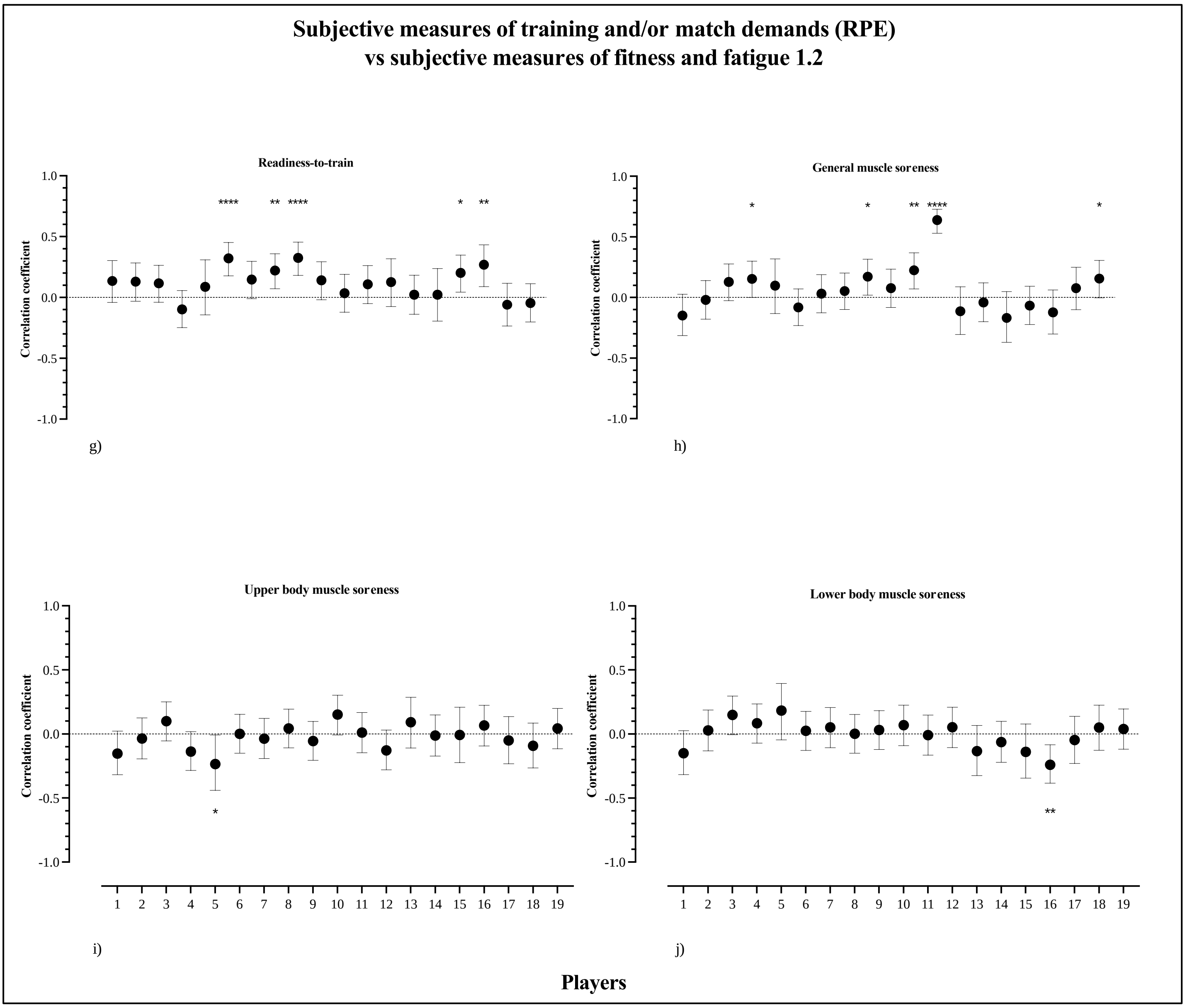


FIGURE 6.23: Intra-individual correlation coefficient for each player for RPE vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals

*p = <0.05; **p = <0.01; ****p = <0.0001

6.3.1.4 Subjective measures of training and/or match demands vs objective (CMJ) measures of fitness and fatigue

FIGURE 6.24 summarises the relationships between training load (AU) and RPE during the match and objective measures of fitness and fatigue. There were no relationships between training load and maximum force and training load and jump height. Also, there were no relationships between maximum force and RPE during the match. In six players there was a significant relationship between jump height and RPE during the match and seven players had a significant relationship between flight time and RPE during the match.

6.3.1.5 Subjective measures of training and/or match demands vs objective measures of training and/or match demands

Relationships between training load and GPS as well as RPE and GPS variables during the match are summarised in FIGURES 6.25 and 6.26 below. Eleven out of the 19 players had a relationship between training load and total distance during the match. Player 11 (0.49; 0.32 to 0.63) had the strongest relationship out of all the players. Only one player had a significant relationship between training load and high-speed running. Two players had a significant relationship between training load and number of sprints in a match, and three players had a significant relationship between training load and heart rate during a match.

There were significant relationships between bodyload and training load in 12 players. While 14 players had a significant relationship between training load and high intensity efforts. Players 3, 5, 6 and 7 had the strongest relationship between bodyload and training load. Despite the significant relationship, changes in bodyload accounts for approximately 9 – 13 % of the variance in training load. While Players 4, 6, 8, 11, 14 and 16 had the highest positive correlation between training load and high intensity efforts (FIGURE 6.25 *graph e*).

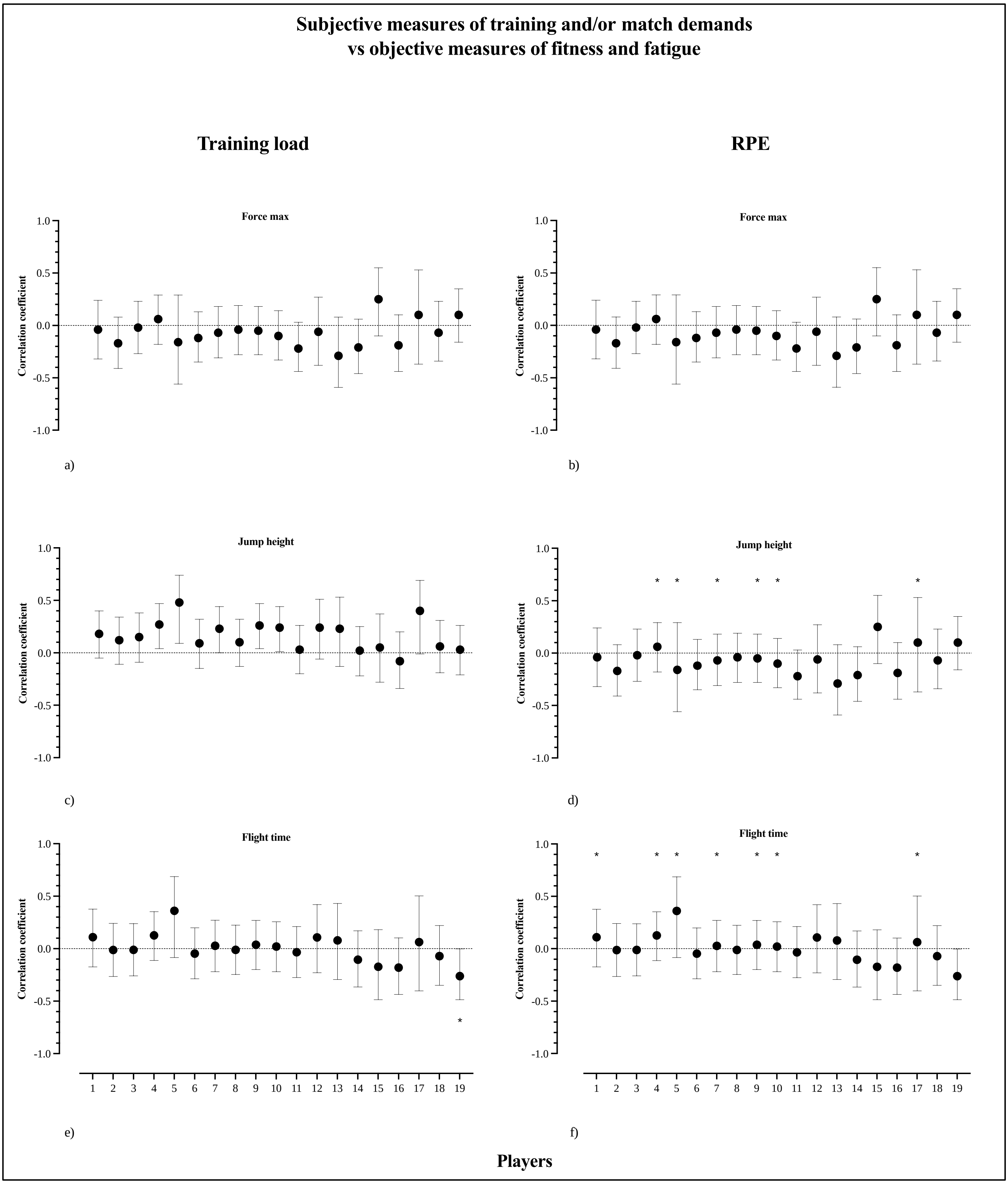


FIGURE 6.24: Intra-individual correlation coefficient for each player for RPE vs subjective measures of fitness and fatigue. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05

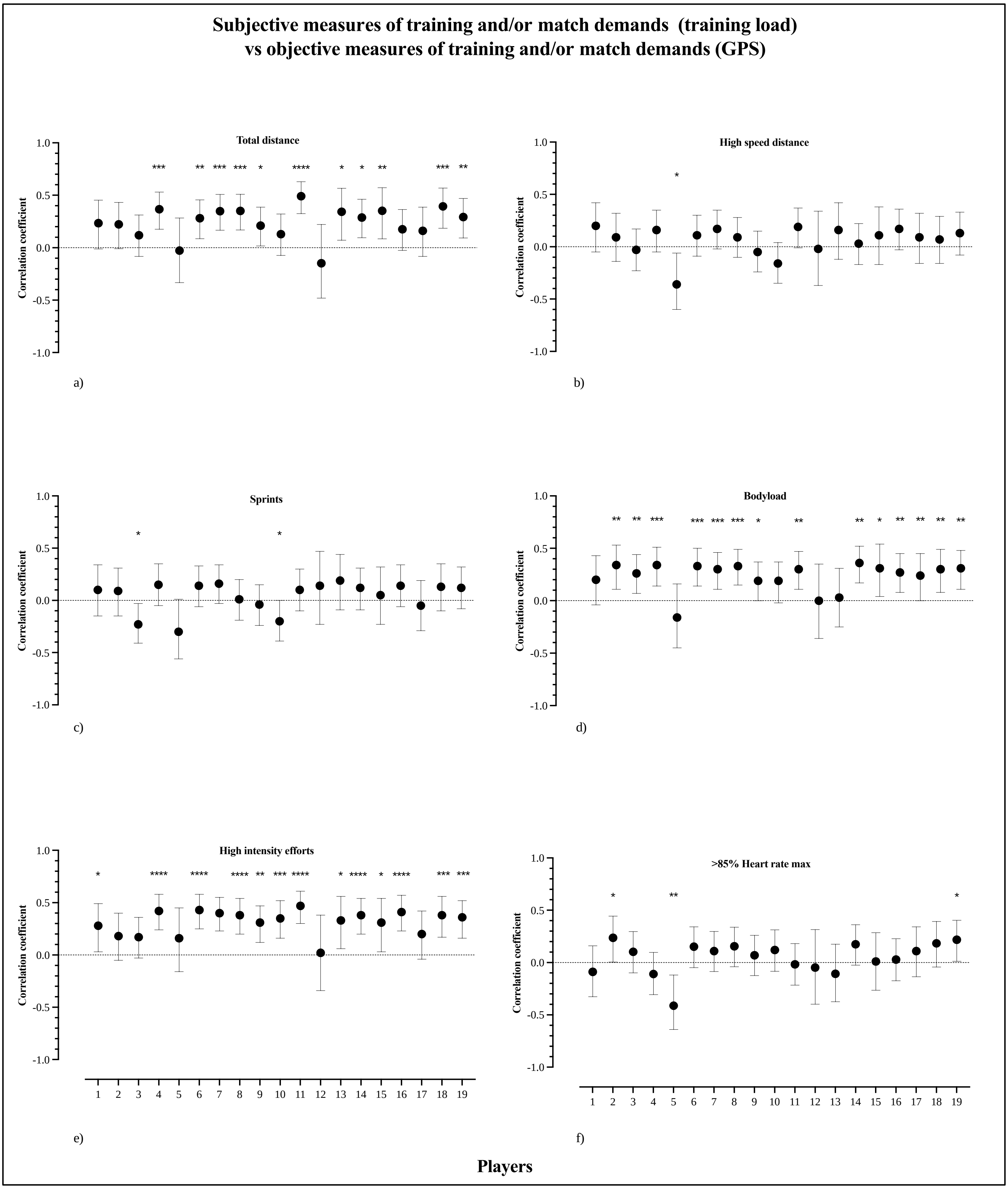


FIGURE 6.25: Intra-individual correlation coefficient for each player for training load vs objective measures of training and/or match demands. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01; ***p = <0.0002; ****p = <0.0001

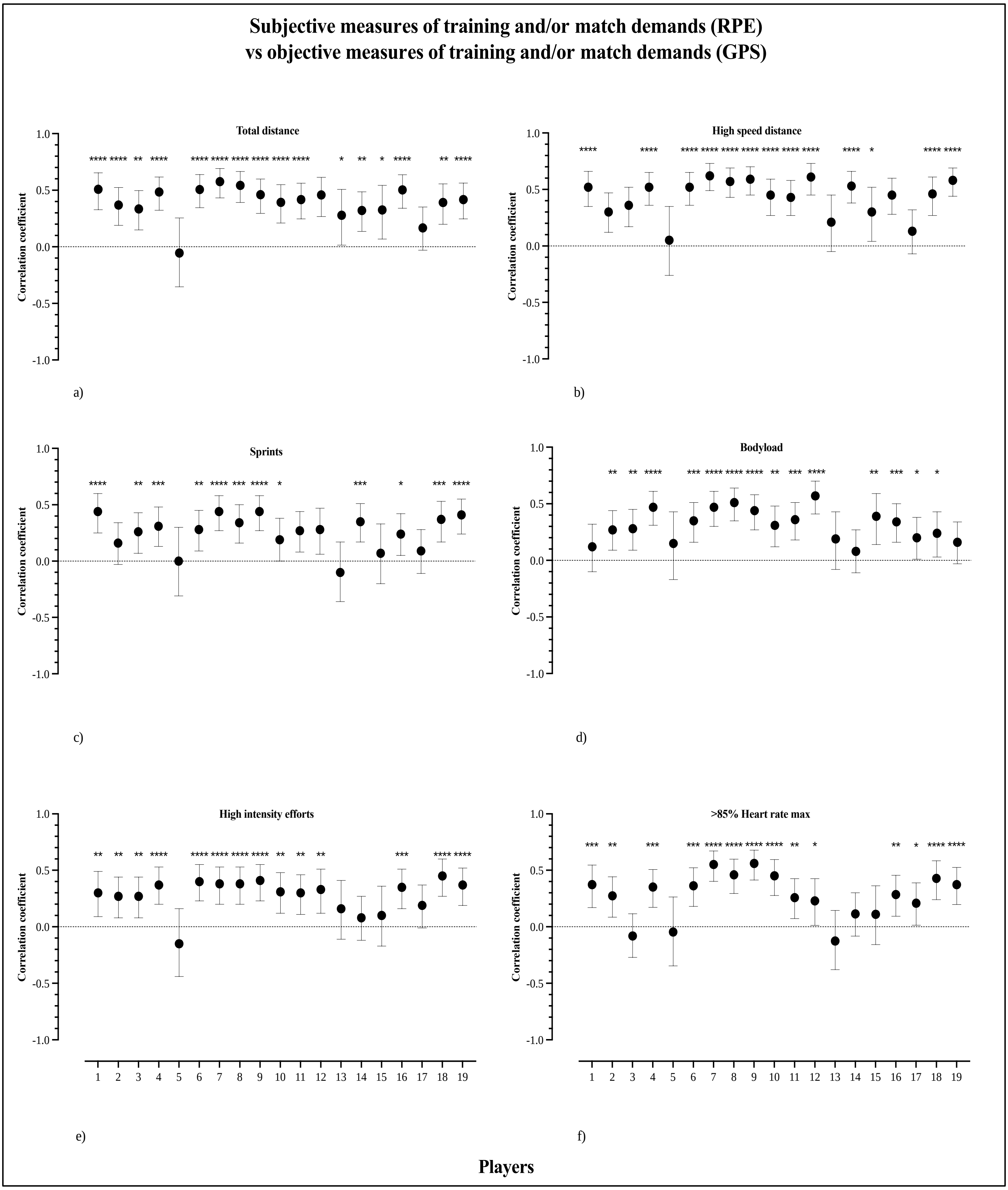


FIGURE 6.26: Intra-individual correlation coefficient for each player for RPE vs objective measures of training and/or match demands. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01; ***p = <0.0002; ****p = <0.0001

FIGURE 2.26 summarises the relationships between RPE during a match and all GPS variables. Most players had a significant correlation for RPE vs all GPS variables (FIGURE 6.26). While total distance and RPE seemingly having the strongest relationship. This relationship was not significant in only two out of the 19 players. Player 7 and Player 9 where the only two players having high significant correlations across all GPS variables and RPE.

6.3.1.6 Objective measures of fitness and fatigue (CMJ) vs objective measures of training and/or match demands (GPS)

FIGURES 6.27 to 6.29 summarise the relationships for each player between all countermovement jump variables measured before the match and the GPS variables measured during a match. The relationships for maximum force and GPS variables are shown in FIGURE 6.27. Only a few players showed a relationship between maximum force and GPS variables. For example, Player 5 (0.45; 0.01 to 0.75) was the only player to have a significant positive relationship between maximum force and total distance during a match. While Player 17 (0.73; 0.37 to 0.91) was the only player with a significant relationship between maximum force and high-speed running during a match. The variables, sprint efforts and bodyload each had only 1 player with a significant relationship (sprint efforts: Player 1 and bodyload: Player 17) (*Figure 6.27 c and d*). Players 3, 14 and 15 had the strongest positive correlation between maximum force and high intensity efforts. Four players had significant relationships between heart rate >85 % during a match and maximum force measured before the match. Players 1 (0.41; 0.15 to 0.62) and 10 (-0.35; -0.57 to -0.09) had the strongest relationships between heart rate >85 % and maximum force.

Jump height and flight time correlations are shown in FIGURE 6.28 and 6.29. Player 15 (-0.55; -0.79 to -0.17) had the strongest, although negative, correlation between jump height and total distance. There were three significant relationships for each of the following: jump height versus either high speed running, sprints, bodyload and high intensity effort. Out of all these, Player 18 (0.45; 0.17 to 0.67) had the strongest relationship, which was between jump height and bodyload. Player 10 (0.30; 0.04 to 0.54) was the only player to have a significant relationship between heart rate >85 % during a match and jump height.

Lastly, FIGURE 6.29 summarises the relationships between flight time measured during the countermovement jump before the match and all GPS variables measured during the match. Similar to jump height results, total distance, high speed running, bodyload and high intensity efforts all had three players with significant correlations with flight time. Two players had significant relationships between flight time and sprints and one player had a significant relationship between flight time and heart rate >85 % during a match. The strongest of all these correlations was between flight time and total distance for Player 15 (-0.55; -0.79 to -0.17) and between flight time and bodyload for Player 18 (0.45; 0.17 to 0.67).

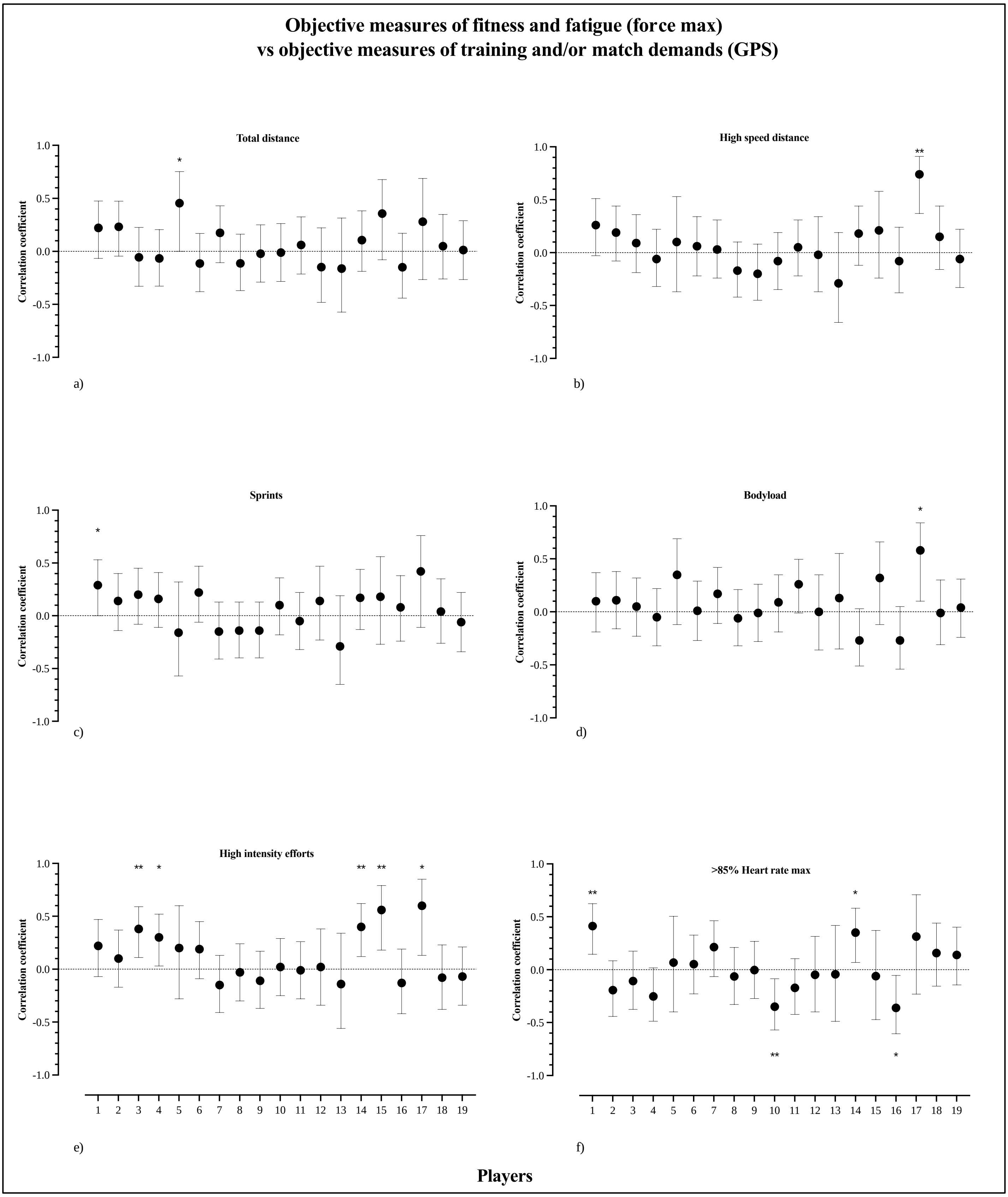


FIGURE 6.27: Intra-individual correlation coefficient for each player for maximum force vs objective measures of training and/or match demands. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01

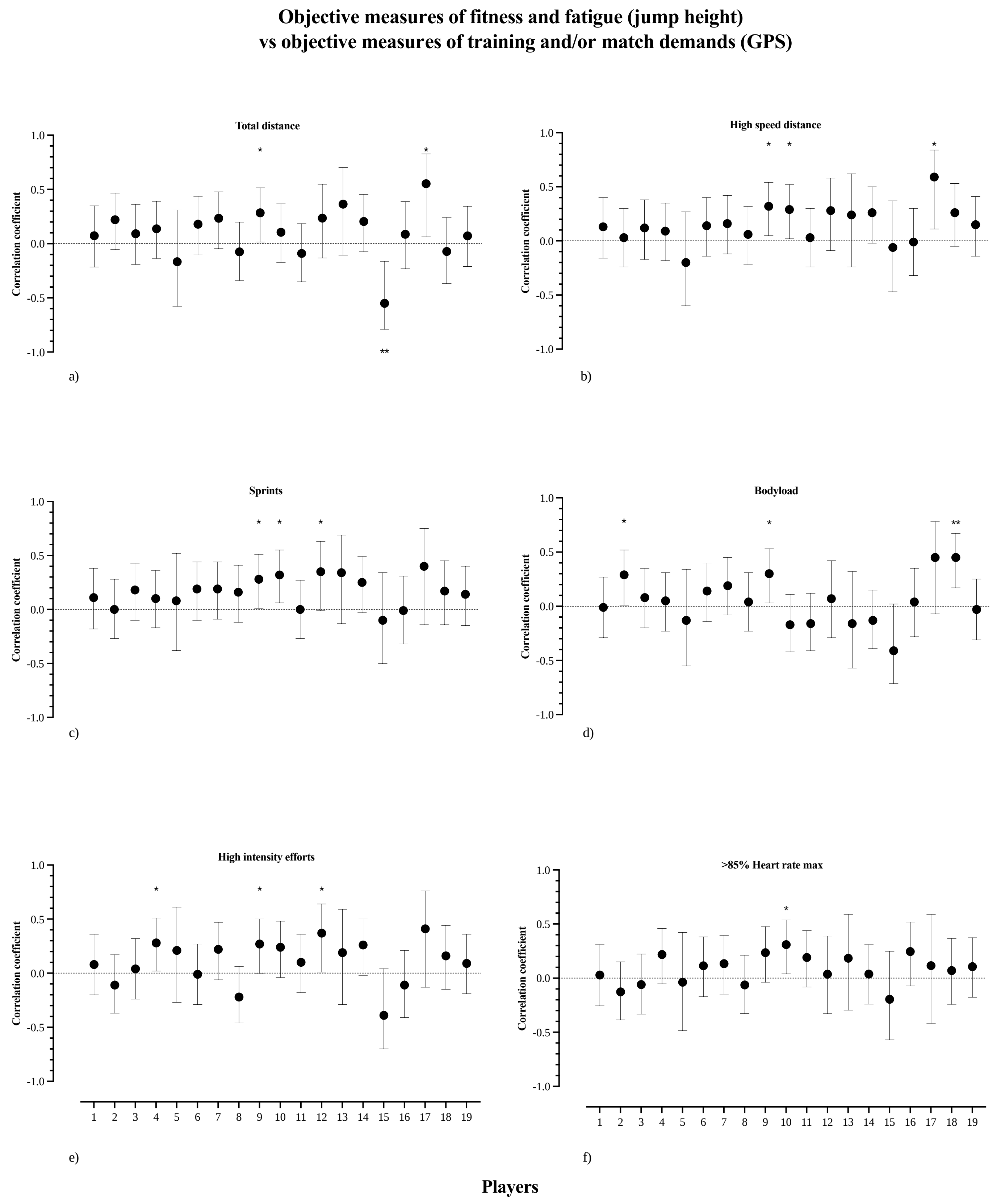


FIGURE 6.28: Intra-individual correlation coefficient for each player for jump height vs objective measures of training and/or match demands. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01

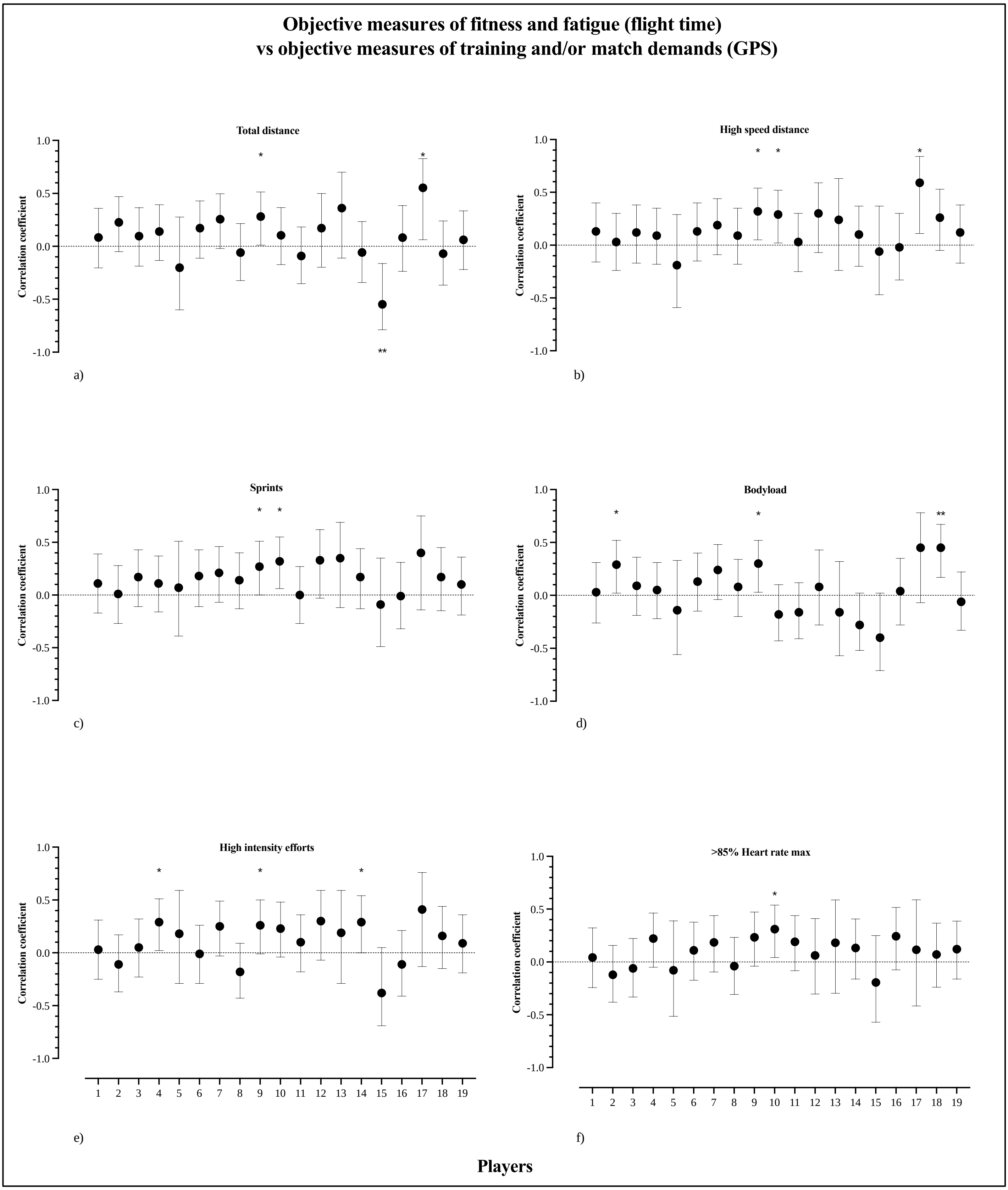


FIGURE 6.29: Intra-individual correlation coefficient for each player for flight time vs objective measures of training and/or match demands. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01

6.3.2 Whole group data analysis

A summary of the correlation counts for each variable are shown in TABLES 6.3 and 6.4. There was a total of 422 intra-individual significant correlation counts for all variables compared to each other. This equates to approximately 16 % of all possible relationships for the whole group. RPE was the variable with the most the significant correlations (n = 139 significant correlations). The highest number of significant correlations was between RPE and total distance (n = 16 players). Whereas for subjective measures of fitness and fatigue vs RPE during a match, the most relationships were for recovery (31 counts), motivation-to-train (39 counts) and readiness-to-train (30 counts). Training load accumulated the second most significant correlation counts, totalling 73 counts amongst all the players.

Total distance had the lowest number of relationships with all subjective measures of fitness and fatigue. When considering objective measures of fitness and fatigue (TABLE 6.3), jump height and flight time had the most significant relationships when compared to all subjective measures of fitness and fatigue responses. However, the objective measures of fitness and fatigue variables (countermovement jump) vs training or match demands all performed similarly. Sprint counts and heart rate >85 % had the most significant relationships when compared to subjective measures of fitness and fatigue.

The mean r values and 95 % upper and lower confidence intervals for the group are shown in TABLES 6.5 and 6.6. None of these grouped r values were significant for any subjective measures of fitness and fatigue (TABLE 6.5). Only weak relationships were shown for RPE vs total distance (r = 0.34; 0.22 to 0.46) and RPE vs high speed running (0.37; 0.23 to 0.51) (TABLE 6.6). These relationships only accounted for approximately 12 – 14 % of the variance respectively. None of the other variables showed any significant relationships in the grouped data.

TABLE 6.3: Intra-individual significant correlation counts for all subjective measures of fitness and fatigue vs all other variables.

		Subjective measures of fitness and fatigue										
Variables (likert rating)		Fatigue (1-5)	Stress (1-5)	Sleep (1-5)	Mood (1-5)	Recovery (1-5)	Motivation to train (1-5)	Readiness to train (6-35)	General muscle soreness (0-5)	Upper body soreness (0-5)	Lower body soreness (0-5)	Totals
Objective measures of fitness and fatigue	Max force (N)	2	3	2	1	1	1	0	3	1	1	**15**
	Jump height (cm)	2	1	0	0	3	4	3	4	4	3	**24**
	Flight time (ms)	2	1	0	1	3	4	3	3	5	1	**23**
Objective measures of training and / or match demands	Total distance (m)	0	0	1	0	2	2	1	1	1	1	**9**
	High speed running (m)	1	1	0	1	3	3	2	1	3	1	**16**
	Sprint counts	1	1	0	2	0	4	4	6	2	3	**23**
	Bodyload (AU)	2	2	3	0	3	0	1	0	1	1	**13**
	High intensity efforts	1	2	0	1	3	1	3	1	0	3	**15**
	Heart rate >85%	2	2	1	0	4	4	3	3	3	6	**28**
Subjective measures of training and / or match demands	Training load (AU)	2	1	2	4	3	6	5	0	3	2	**28**
	RPE	5	4	3	3	6	10	5	5	1	1	**43**
Total		**20**	**18**	**12**	**13**	**31**	**39**	**30**	**27**	**24**	**23**	**237**

TABLE 6.4: Intra-individual significant correlation counts for all objective measures of fitness and fatigue and objective measures of training and/or match demands vs all other variables.

Variables		Objective measures of training and / or match demands						Objective measures of fitness and fatigue			
		Total Distance (m)	**High speed running Distance (m)**	**Sprint counts**	**Bodyload (AU)**	**High intensity efforts**	**Heart rate >85%**	**Max force (N)**	**Jump height (cm)**	**Flight time (ms)**	**Totals**
Objective measures of fitness and fatigue	**Max force (N)**	1	1	1	1	5	4	-	-	-	**13**
	Jump height (cm)	3	3	3	3	3	1	-	-	-	**16**
	Flight time (ms)	3	3	2	3	3	1	-	-	-	**15**
Subjective measures of training and / or match demands	**Training load (AU)**	11	1	2	14	13	3	0	0	1	**45**
	RPE	16	13	12	14	14	14	0	6	7	**96**
Totals		**34**	**21**	**20**	**35**	**38**	**23**	**0**	**6**	**8**	**185**

TABLE 6.5: The relationships between subjective and objective measures of training load as well as objective fitness and fatigue with subjective measures of fitness and fatigue are summarised in table 6.5. Data are represented as mean r values and 95% upper and lower confidence intervals (n = 19).

		Subjective measures of fitness and fatigue									
	Variable (likert rating)	**Fatigue (1-5)**	**Stress (1-5)**	**Sleep (1-5)**	**Mood (1-5)**	**Recovery (1-5)**	**Motivation to train (1-5)**	**Readiness to train (1-5)**	**General muscle soreness (0-5)**	**Upper body soreness (0-5)**	**Lower body soreness (0-5)**
Objective measures of fitness and fatigue	**Max force (N)**	-0.02 (-0.10 to 0.05)	-0.04 (-0.11 to 0.03)	-0.03 (-0.11 to 0.05)	0.01 (-0.04 to 0.07)	0.01 (-0.06 to 0.08)	-0.01 (-0.07 to 0.05)	-0.04 (-0.10 to 0.01)	0.05 (-0.01 to 0.12)	0.03 (-0.04 to 0.09)	0.01 (-0.06 to 0.07)
	Jump height (cm)	0.09 (0.01 to 0.18)	0.04 (-0.03 to 0.10)	0.02 (-0.06 to 0.09)	0.03 (-0.02 to 0.07)	-0.02 (-0.12 to 0.07)	0.03 (-0.06 to 0.12)	0.08 (-0.01 to 0.16)	-0.07 (-0.16 to 0.02)	-0.03 (-0.14 to 0.07)	-0.02 (-0.12 to 0.08)
	Flight time (ms)	0.09 (0.01 to 0.17)	0.03 (-0.03 to 0.09)	0.03 (-0.04 to 0.10)	0.04 (-0.01 to 0.08)	-0.03 (-0.12 to 0.07)	0.03 (-0.06 to 0.12)	0.07 (-0.01 to 0.15)	-0.06 (-0.15 to 0.02)	-0.03 (-0.14 to 0.07)	-0.01 (-0.1 to 0.08)
Objective measures of training and / or match demands	**Total distance (m)**	0.04 (0.00 to 0.08)	0.06 (0.02 to 0.11)	-0.05 (-0.11 to 0.01)	0.00 (-0.04 to 0.04)	-0.01 (-0.07 to 0.05)	0.04 (-0.02 to 0.09)	-0.02 (-0.08 to 0.03)	0.05 (0.00 to 0.10)	0.01 (-0.04 to 0.06)	0.03 (-0.02 to 0.09)
	High speed running (m)	0.03 (-0.03 to 0.09)	0.07 (0.02 to 0.12)	-0.03 (-0.09 to 0.03)	0.00 (-0.04 to 0.04)	-0.02 (-0.09 to 0.04)	0.04 (-0.03 to 0.10)	-0.06 (-0.12 to 0.01)	0.08 (0.03 to 0.13)	-0.01 (-0.07 to 0.04)	0.03 (-0.02 to 0.09)
	Sprint counts	0.03 (-0.02 to 0.08)	0.04 (-0.01 to 0.10)	0.02 (-0.02 to 0.07)	0.02 (-0.03 to 0.08)	0.00 (-0.05 to 0.05)	0.06 (-0.01 to 0.13)	-0.03 (-0.09 to 0.04)	0.12 (0.04 to 0.19)	-0.01 (-0.06 to 0.03)	0.05 (-0.03 to 0.12)
	Bodyload (AU)	-0.02 (-0.08 to 0.04)	0.01 (-0.05 to 0.07)	-0.05 (-0.12 to 0.02)	0.01 (-0.04 to 0.05)	-0.03 (-0.1 to 0.04)	0.01 (-0.04 to 0.07)	-0.03 (-0.09 to 0.03)	0.04 (0.00 to 0.08)	0.01 (-0.04 to 0.06)	0.04 (-0.01 to 0.09)
	High intensity efforts	0.04 (-0.01 to 0.08)	0.03 (-0.02 to 0.09)	-0.01 (-0.06 to 0.05)	-0.01 (-0.05 to 0.03)	-0.02 (-0.08 to 0.05)	0.03 (-0.03 to 0.09)	0.03 (-0.04 to 0.09)	0.05 (-0.01 to 0.12)	0.03 (-0.02 to 0.08)	0.03 (-0.04 to 0.10)
	Heart rate >85%	0.03 (-0.04 to 0.10)	0.04 (-0.02 to 0.11)	-0.02 (-0.07 to 0.03)	0.00 (-0.04 to 0.03)	-0.03 (-0.12 to 0.06)	0.04 (-0.03 to 0.11)	0.00 (-0.09 to 0.09)	-0.04 (-0.12 to 0.03)	-0.04 (-0.12 to 0.03)	-0.05 (-0.13 to 0.03)
Subjective measures of training and / or match demands	**Training load (AU)**	0.02 (-0.04 to 0.09)	0.03 (-0.01 to 0.08)	0.00 (-0.05 to 0.05)	0.04 (-0.04 to 0.11)	-0.01 (-0.08 to 0.07)	0.09 (0.01 to 0.17)	0.05 (-0.01 to 0.12)	-0.01 (-0.05 to 0.04)	-0.01 (-0.07 to 0.05)	0.02 (-0.03 to 0.07)
	RPE	0.08 (0.01 to 0.15)	0.08 (0.01 to 0.14)	0.03 (-0.02 to 0.08)	0.01 (-0.06 to 0.07)	0.06 (-0.03 to 0.14)	0.12 (0.02 to 0.21)	0.08 (0.01 to 0.15)	0.04 (-0.05 to 0.13)	-0.02 (-0.07 to 0.03)	0.00 (-0.06 to 0.05)

TABLE 6.6: The relationships between subjective measures of training load, objective measures of fitness and fatigue with objective measures of training load and objective measures of fitness and fatigue are summarised in table 6.6. Data are represented as mean r values and 95% upper and lower confidence intervals (n = 19).

		Objective measures of training and / or match demands						Objective measures of fitness and fatigue		
Variables		**Total Distance (m)**	**High speed running Distance (m)**	**Sprint counts**	**Bodyload (AU)**	**High intensity efforts**	**Heart rate >85%**	**Max force (N)**	**Jump height (cm)**	**Flight time (ms)**
Objective measures of fitness and fatigue	**Max force (N)**	0.06 (-0.03 to 0.15)	0.08 (-0.02 to 0.18)	0.08 (-0.01 to 0.16)	0.08 (-0.02 to 0.18)	0.13 (0.02 to 0.24)	0.00 (-0.10 to 0.11)	-	-	-
	Jump height (cm)	0.07 (-0.05 to 0.19)	0.12 (0.02 to 0.21)	0.14 (0.06 to 0.22)	0.02 (-0.09 to 0.13)	0.08 (-0.02 to 0.19)	0.06 (-0.02 to 0.13)	-	-	-
	Flight time (ms)	0.05 (-0.06 to 0.17)	0.11 (0.02 to 0.21)	0.13 (0.05 to 0.21)	0.01 (-0.10 to 0.13)	0.08 (-0.02 to 0.18)	0.07 (-0.01 to 0.14)	-	-	-
Subjective measures of training and / or match demands	**Training load (AU)**	0.22 (0.13 to 0.31)	0.07 (0.00 to 0.13)	0.05 (-0.02 to 0.12)	0.21 (0.13 to 0.29)	0.28 (0.19 to 0.37)	0.04 (-0.04 to 0.11)	-0.06 (-0.13 to 0)	0.00 (-0.06 to 0.07)	0.00 (-0.07 to 0.06)
	RPE	0.34 (0.22 to 0.46)	0.37 (0.23 to 0.51)	0.21 (0.10 to 0.31)	0.26 (0.16 to 0.37)	0.23 (0.13 to 0.34)	0.21 (0.08 to 0.34)	-0.05 (-0.12 to 0.02)	0.14 (0.06 to 0.22)	0.14 (0.06 to 0.22)

6.4 Discussion

The primary aim of the study was to determine the intra-individual relationships of various subjective and objective measures of training status in elite level athletes. These relationships were quantified in terms of strength and prevalence within the group. Additionally, we also quantified the relationships between each of these variables for the whole group. The study was designed as a continuation of Study One (Chapter Three) and Study Two (Chapter Four). This design allowed for the transition from laboratory-based research to research in a "real-world" environment with elite level (well trained) athletes.

The main finding was that the relationship between the measurements varied for each player. For example, Players 6,7,8,9,17 and 18 had the highest number of individual significant correlations, ranging between 27 – 36 counts (or 19 – 26 % of the possibilities). The rest of the group (Players 1,2,3,4,5,10,11,12,13,14,15,16 and 19) ranged between 10 – 23 counts. This is an important consideration when choosing which variables are most sensitive to change. For example, if support staff can identify the most responsive variables, it would reduce the "noise" within the monitoring system designed for the team they are working in. Allowing support staff to "zone in" on the most relevant information for each individual athlete. Another reason for the low number of relationships in the present study, could be that the players were well adapted and resilient to the training and match demands, thus, able to tolerate these demands with minimal effect on their fatigue levels.

As discussed earlier (Chapter Two) using a countermovement jump as a monitoring tool to assess an athletes' training status is a common practice[242]. However, what has yet been explored is the intra-individual responsiveness of the countermovement jump metrics within a team setting. For example, when considering countermovement jump variables and their respective relationships with subjective measures of fitness and fatigue, we found that both jump height and flight time had the highest correlation counts with subjective measures of fitness and fatigue. However, practitioners could consider using one or the other, instead of both variables as jump height is a product of flight time and generally follows a linear relationship[223]. By focusing on the most responsive variables in a monitoring system, the "noise" of the measurements will be reduced. Based on this logic, subjective recovery, motivation-to-train, readiness-to-train, and general muscle soreness had the highest significant correlations for individual players, when compared to all variables. Also, maximum force had the highest significant correlations with subjective stress and general muscle soreness. These findings are similar to the findings of previous monitoring studies, indicating that variables such as maximum force and subjective measures may detect different forms of fatigue[291,322]. Importantly, although not all significant, many players showed that a higher state of fatigue and stress was associated with a lower maximum force output. This suggests that altered subjective measures may be associated with a negative effect on the neuromuscular performance of these individuals. This can be explained by central regulation which causes a downregulation of muscle recruitment under certain circumstances[72]. The opposite also occurred in other players where neuromuscular function was not affected in the presence of a higher state of subjective fatigue. The explanation for this phenomenon is unclear. These diverse findings indicate that practitioners should utilise monitoring information in conjunction with their understanding of each individual and the time of season and training phase they are in.

An important observation is the differing significant correlations between variables. For example, some players had a negative correlation while other players had a positive correlation for the same variables. Again, indicating the importance of understanding each individual player’s response not only to training load, but also how responsive various monitoring variables are for each player within a team environment. This could be seen as the “specificity of monitoring”. Based on this concept, monitoring processes should be selected on an individual basis rather than a global construct. For example, when considering markers of neuromuscular performance, Player 6 showed a significant positive correlation between sleep and maximum force, while the opposite is true for Player 3. This may indicate that for both players sleep has an important performance modulating effect. While for others, although there may not be any statistically significant relationship, we should consider sleep duration and quality as part of a holistic monitoring strategy. This is in accordance with previous research showing that sleep is an important consideration in elite athlete performance[323]. The effects of subjective stress and fatigue have previously been investigated[47,52,122,324]. However, their relationship with objective markers of neuromuscular status have yet to be described. Interestingly, in the current study both fatigue and stress showed only minor effects on maximum force and jump height. This implies that if athletes are well trained to meet the demands imposed on them, they can negate the negative effects of subjective fatigue and/or stress. These sentiments have been shared in previously published research on increasing athletes’ athleticism and fatigue resistance to enhance performance[117,170,185,325,326]. These training strategies prepare the athlete for the demands they encounter during training and competitions. Another interesting observation in the current study is that a low perceived score for upper, lower, and general muscle soreness seems to have a positive effect on jump height in some players but not others. When compared to previous research on the effects of delayed onset muscle soreness on performance, similar findings have been suggested, where lower body muscle soreness decreases neuromuscular performance[327].

Wellness measurements such as subjective fatigue, stress, mood, and sleep seemed to have little to no effect on performance on the field (training or match), as represented by total distance. This is in contrast to previous research showing that subjective wellness responses significantly affected on-field performance[104]. While there was a positive association between motivation-to-train and objective measures of match or training demands such as high-speed running, sprint counts and heart rate above 85 % of heart rate max. This is interesting, as in the majority of the players it can be concluded that regardless of the subjective and/or objective readiness of players, if they still possess the right amount of “motivation to train” their on-field performance should still reflect positively. Again, this is similar to other studies looking at mood states and performance outcomes in elite athletes[52,119,328].

Lastly, both RPE and subjective training load have strong positive correlations with motivation-to-train, recovery, and fatigue. This is suggestive that at the very minimum, elite sports teams should implement a monitoring system that captures athlete subjective measures of match and training demands as well as fitness and fatigue. These measures would allow support staff not only to plan subsequent training sessions but also better understand how players are adapting to the demands they are exposed to. This is similar to what has been suggested by previous research groups looking at subjective wellness and training load implications in teams sports[18,100,110,111,151,165].

A limitation with field-based research involving elite level athletes preparing for competition is that a player’s load and intensity are adjusted according to the feedback the support staff get from the data. Thus, it is possible that negative training responses are blunted by early training load and intensity modifications as per the data being collected. This would have an impact on the relationships between variables.

6.5 Conclusion

An important finding of this study is that there is no “silver bullet” that can be used for monitoring. This study also introduces the novel concept of “monitoring specificity” and the individualisation of monitoring strategies. In turn, reducing the “noise” around various monitoring systems and increasing the accuracy of data in a team sport environment. In accordance with this logic, TABLE 6.7 below details the most robust GPS variables that we will use as we progress into Study Four.

Lastly, in team sports like hockey, where the schedules are dominated by tournaments, it is important to identify how players are coping within these tournaments. Thus, monitoring the pre, intra and post-match subjective and objective measures of fitness and fatigue for each individual during tournaments would aid support staff in identifying any possible “red-flags” early and allow informed decisions regarding the specific individuals to be made.

TABLE 6.7: GPS variables evaluation matrix of acceptability in monitoring changes in training status. The “traffic-light” rating scale represents an evaluation of “useability” of each GPS variable used, that would be most valid and reliable in a team sport environment.

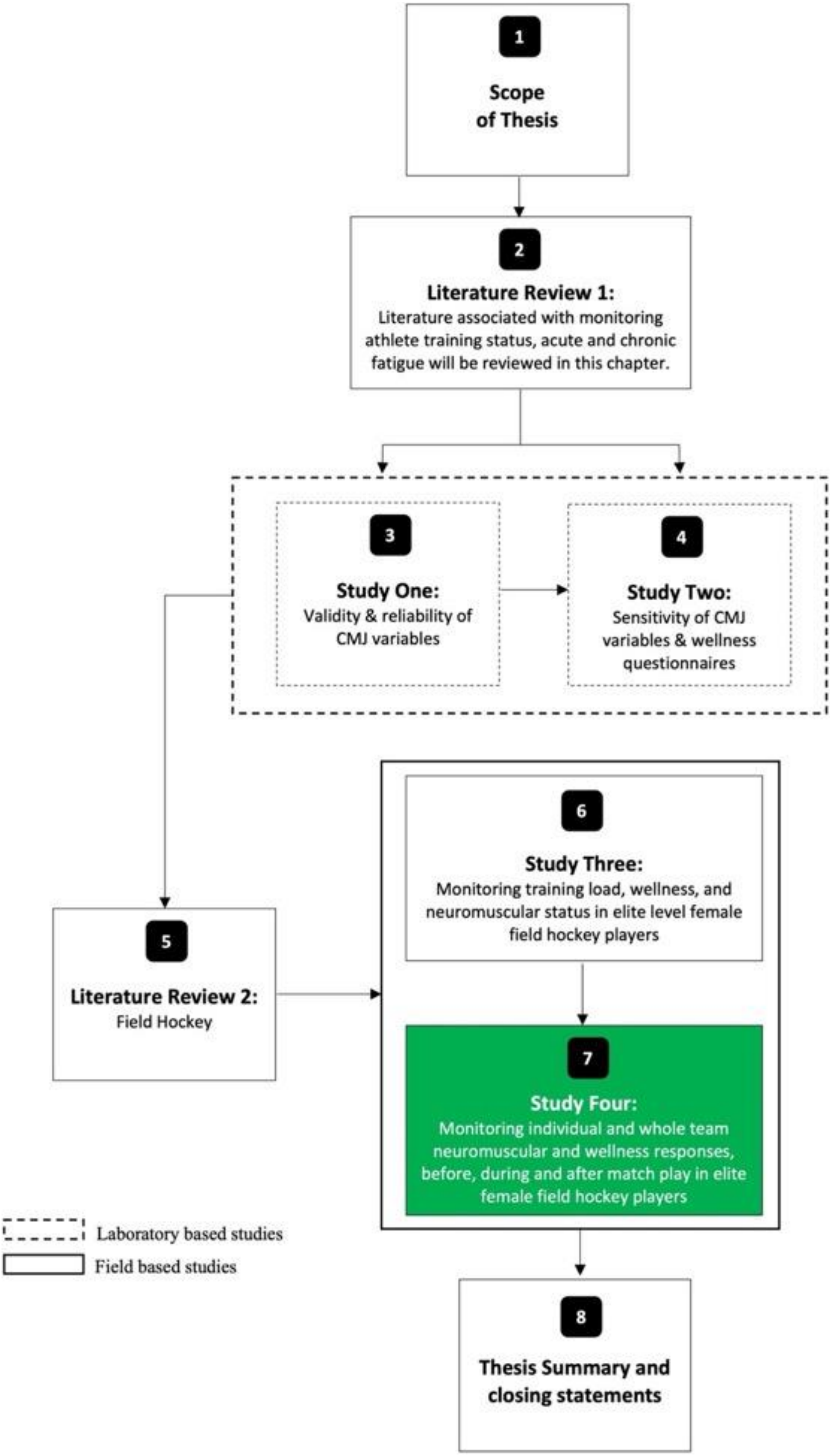
Global positioning system candidate variable	**An absolute measure of match / training load?**	**A relative measure of match / training load?**	**A measure of neuromuscular load?**	**A measure of intensity?**	**High quality of data acquisition**
Total distance (m)	🟢	🔴	🟢	🟢	🟢
High speed distance (m)	🟢	🔴	🟢	🟢	🟢
High intensity efforts	🟢	🔴	🟢	🟢	🟠
Sprint counts	🟢	🔴	🟢	🟢	🟠
Bodyload	🟢	🔴	🟢	🟢	🟠
>85% HR_{max} time (min)	🟢	🔴	🟢	🟢	🟠
High intensity efforts per minute	🟠	🟢	🟠	🟢	🟠
Sprints per minute	🟠	🟢	🟠	🟢	🟠
Bodyload per minute	🟠	🟢	🟠	🟢	🟠
Meters per minute	🟠	🟢	🟠	🟢	🟠

The traffic light rating system represents an evaluation for the use of specific countermovement jump variables as determined by Chapters three and four for a robust transition from laboratory based to field side research.

🟢	Favourable
🟠	Less than favourable
🔴	Unfavourable

6.6 Chapter Six – Summary points

1. Monitoring specificity and individualization should be considered when setting up a monitoring system in team sports.
2. The collection of a wide variety of specifically identified variables provides the support staff with a better understanding of the training adaptations of athletes.
3. Motivation-to-train, readiness-to-train, recovery, and general muscle soreness should be included as part of the subjective measures of fitness and fatigue within an athlete monitoring system.
4. Total distance, high intensity efforts and bodyload should be included as objective markers of match and training demands.
5. Jump height and maximum force should be considered as measures of neuromuscular training status.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Scope of Thesis
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Literature Review 1:
Literature associated with monitoring athlete training status, acute and chronic fatigue will be reviewed in this chapter.
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Study One:
Validity & reliability of CMJ variables
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7. Chapter Seven

Study Four: Monitoring individual and whole team neuromuscular and wellness responses before, during and after match play in international female field hockey players

7.1 Introduction

Periodisation for teams' sports which have multiple tournaments during the year rather than weekly matches can prove challenging for support staff [8,329,330]. One of the main reasons for this is that there is generally no scheduled "off-season". Instead, in sports such as hockey, players are exposed to multiple blocks of pre and in season type work throughout the year. Thus, managing players' accumulated fatigue and understanding how they are adapting to the demands they are exposed to, may prove crucial for support staff in these environments. Furthermore, international tournaments generally consist of multiple games being played over a few days, which reduces recovery times between matches[304,331,332]. Adding to this, the demands of training for hockey or playing matches exposes players to multiple accelerations, decelerations, high intensity efforts and changes of direction[296]. These physical demands may lead to an increase in lower body neuromuscular fatigue during a match and post-match, and later, delayed onset muscle soreness[81,104,108]. As a result, it is advisable that various strategies be implemented to monitor a player's training status. As discussed previously in Chapter Six, tools such as the countermovement jump, should be used to objectively assess a player's neuromuscular status[251,333,334], while wellness questionnaires should be used to assess a player subjective readiness-to-train[131]. By measuring both subjective and objective measures of fitness and fatigue, support staff are better able to make informed decisions on player's training status and match readiness.

Furthermore, internal, and external load should also be quantified in team sports athletes[335]. As shown in Chapter Six, Global Positioning System (GPS) variables such as total distance, high intensity efforts (HIE) and bodyload are commonly used to quantify external training and match demands of field hockey players[213,215,301,336]. Whereas internal load can be quantified through the subjective Rating of Perceived Exertion (sRPE) method[37,337].

Lastly, it is well documented that individuals within a team sport environment respond differently to the same external load[7]. Thus, monitoring changes on an individual basis may prove prudent for athletes in team sports. Chapter Six showed, amongst other things, that monitoring specificity and individualization should be considered when setting up a monitoring system in team sports. These recommendations were reached after examining the relationship between variables for each player through training and competition. It is not known whether the same conclusion can be reached focussing on variables associated only with matches (before, during and after).

Therefore, the overall aim of this study was to monitor the in-competition neuromuscular and wellness responses in elite female field hockey players. In particular, the aim was to determine the group and intra-individual relationships between pre, during and post-match measurements, of subjective and objective measures of fitness and fatigue as well as subjective and objective measures of match demands.

7.1 Methods

The study was designed as a direct follow up to Study Three presented in Chapter Six. Most methodological processes were the same as those described in Chapter Six. These are summarised below with an emphasis on any differences.

7.1.1 Participants

Nineteen female national field hockey players participated in this study. Ethical approval was obtained through the University of Cape Town (UCT) Human Research Ethics Committee (Ref No.: R024/2017; Appendix 6 and 7). Participant characteristics have previously been summarised in TABLE 6.1. in Chapter Six.

7.1.2 Study Period

The study was conducted over a period incorporating six tournaments, which had a total of 37 matches (FIGURE 6.1, Chapter Six).

7.1.3 Subjective Data Collection

The players completed the wellness questionnaire (see TABLE 6.2, Chapter Six; Appendix 8), on the morning of each match. While RPE was measured directly after each match.

7.1.4 CMJ Data Collection

Individual neuromuscular performance was measured as per the protocol described in Section 6.2.4 in Chapter Six. Jump height and maximum force data were collected for each countermovement jump during the pre-match priming session.

7.1.5 GPS Data Collection

GPS data were collected as described earlier in Chapter Six, Section 6.2.5. Total distance, high intensity efforts and bodyload were recorded for each player during each match.

7.1.6 Statistical Analysis

A Spearman’s correlation analysis was used to establish group and intra-individual relationships. In particular, the relationships between the measurements pre-match were compared to match demands. The match demands were compared to RPE and training load during the match. All post-match measurements of objective and subjective fitness and fatigue were recorded the following day (24h post-match). These analyses were done at a group and individual level for each match in each tournament. An analysis of variance was used to determine differences between tournaments. The magnitude of differences between average data of each match/ tournament were represented by Cohen’s effect size (*d*). Effect sizes were defined as <0.2 (*trivial*), >0.2 to <0.5 (*small*), ≥0.5 to <0.8 (*moderate*) and ≥0.8 (*large*). Descriptive data were presented as mean ± standard deviation (x ± SD)[338]. The coefficient of variation was calculated for each player for each variable. Correlations were presented as r (95 % confidence intervals (CI)). Statistical significance was defined as $P < 0.05$. The variation in the measurement was represented as coefficient of variation (CV).

7.2 Results

Details of the participant characteristics have previously been described in Chapter Six, TABLE 6.1.

7.2.1 Match day descriptive data analysis

7.2.1.1 Subjective measures of fitness and fatigue

Subjective measures of fitness and fatigue for each match day are described and summarised in TABLES 7.1 to 7.4. Subjective recovery scores varied vastly between individual players. The group coefficient of variation (CV) for recovery scores was 19 %, indicating a high variance from match day to match day (TABLE 7.1).

TABLE 7.1: Individual player “recovery” scores per match. Data are arbitrary units (AU) and represented as Means ± SD.
(Scale: 1 – “not recovered at all” to 5 – “very fresh”)

Player	Mean ± SD	Range	CV	n
1	3.5 ± 0.6	2.0 - 4.0	18	34
2	3.9 ± 0.2	3.0 - 4.0	6	35
3	3.9 ± 0.4	3.0 - 5.0	11	35
4	3.1 ± 0.3	3.0 - 4.0	10	35
5	2.2 ± 0.7	1.0 - 4.0	33	13
6	3.9 ± 0.4	2.0 - 4.0	9	37
7	3.2 ± 0.4	3.0 - 4.0	13	37
8	3.1 ± 0.3	3.0 - 4.0	11	37
9	3.9 ± 0.3	3.0 - 4.0	8	37
10	3.3 ± 0.5	2.0 - 4.0	16	37
11	4.0 ± 0.0	4.0 - 4.0	0	36
12	2.7 ± 0.5	2.0 - 4.0	20	31
13	3.3 ± 0.5	3.0 - 4.0	15	12
14	3.0 ± 0.0	3.0 - 3.0	0	37
15	3.0 ± 0.4	2.0 - 4.0	13	15
16	3.1 ± 0.3	3.0 - 4.0	9	36
17	3.3 ± 0.5	3.0 - 4.0	14	19
18	2.2 ± 0.4	2.0 - 3.0	19	27
19	3.1 ± 0.4	2.0 - 4.0	13	36
Whole Group	*3.3 ± 0.6*	*1.0 - 5.0*	*19*	*586*

A group mean score of 3.3 AU of subjective recovery, indicating the group was in a general state of "recovered". Player 5 (33 %) had the highest CV, while Players 11 and 14 had no variation in subjective recovery on match days. TABLE 7.2 summarises individual player match day subjective motivation-to-train. Players 11,13 and 14 all had no variance in motivation-to-train scores on match day. While Player 16 had a 20 % CV and a mean score of 3.3 AU, indicating a score of "normal" as described in TABLE 6.2 in Chapter Six. The whole group had a CV of 15 % with a mean score of 3.9, indicating a general score of "motivated" for match day subjective motivation-to-train.

TABLE 7.2: Individual player "motivation-to-train" scores per match. Data are arbitrary units (AU) and represented as Means ± SD. (Scale: 1 – "not at all" to 5 – "very motivated")

Player	Mean ± SD	Range	CV	n
1	3.2 ± 0.4	3.0 - 4.0	13	34
2	4.0 ± 0.2	4.0 - 5.0	4	35
3	4.2 ± 0.6	3.0 - 5.0	14	35
4	3.2 ± 0.5	3.0 - 5.0	14	35
5	3.9 ± 0.3	3.0 - 4.0	7	13
6	4.2 ± 0.4	4.0 - 5.0	9	37
7	3.9 ± 0.4	3.0 - 5.0	10	37
8	4.0 ± 0.5	3.0 - 5.0	12	37
9	4.4 ± 0.5	4.0 - 5.0	11	37
10	3.9 ± 0.2	3.0 - 4.0	6	37
11	4.0 ± 0.0	4.0 - 4.0	0	36
12	3.8 ± 0.4	3.0 - 4.0	11	31
13	5.0 ± 0.0	5.0 - 5.0	0	12
14	4.0 ± 0.0	4.0 - 4.0	0	37
15	3.1 ± 0.3	3.0 - 4.0	8	15
16	3.3 ± 0.7	3.0 - 5.0	20	36
17	4.0 ± 0.6	3.0 - 5.0	14	19
18	4.0 ± 0.2	4.0 - 5.0	5	27
19	4.7 ± 0.5	3.0 - 5.0	11	36
Whole Group	*3.9 ± 0.6*	*3.0 - 5.0*	*15*	*586*

Readiness-to-train is summarised in TABLE 7.3. Each player had an overall low CV (<10%). The whole group had an average 9 % CV with a mean score of 25.3 AU, which equates' to 71 % readiness-to-train score overall. Players 11 and 15 had the lowest CV (2 %), while Players 12 and 17 had the highest CV (9 %). Finally, subjective general muscle soreness measured before the match had the highest coefficient of variation (53 %) out of all the subjective measures of fitness and fatigue (TABLE 7.4). The whole group had a mean score of 2.0 AU before matches. This can be contextualised on the scale where 0 = no muscle soreness and 5 = extreme muscle soreness. This indicates a relatively low muscle soreness score for the whole group on match days. Player 11 had the highest mean score (3 / 5), with the lowest CV of 6 %, when compared to other players.

TABLE 7.3: Individual player "readiness-to-train" scores per match. Data are arbitrary units (AU) and represented as Means ± SD.

Player	Mean ± SD	Range	CV	n
1	24.9 ± 1.4	22.0 - 28.0	6	34
2	26.7 ± 1.4	24.0 - 30.0	5	35
3	26.5 ± 2.2	21.0 - 31.0	8	35
4	23.1 ± 1.5	22.0 - 28.0	6	35
5	22.9 ± 1.0	21.0 - 24.0	4	13
6	29.1 ± 1.5	23.0 - 31.0	5	37
7	24.4 ± 1.8	23.0 - 31.0	8	37
8	25.2 ± 1.3	24.0 - 31.0	5	37
9	26.3 ± 0.9	24.0 - 28.0	3	37
10	25.1 ± 1.9	21.0 - 28.0	8	37
11	25.2 ± 0.6	24.0 - 27.0	2	36
12	22.5 ± 2.1	17.0 - 26.0	9	31
13	28.6 ± 1.5	27.0 - 31.0	5	12
14	25.3 ± 1.1	22.0 - 27.0	4	37
15	25.9 ± 0.6	24.0 - 27.0	2	15
16	24.7 ± 1.8	23.0 - 30.0	7	36
17	24.8 ± 2.2	22.0 - 29.0	9	19
18	23.6 ± 1.2	22.0 - 26.0	5	27
19	25.6 ± 1.8	21.0 - 31.0	7	36
Whole Group	*25.3 ± 2.2*	*17.0 - 31.0*	*9*	*586*

TABLE 7.4: Individual player "general muscle soreness" scores per match. Data are arbitrary units (AU) and represented as Means ± SD. (Scale: 0 – "no muscle soreness" to 5 – "extreme muscle soreness")

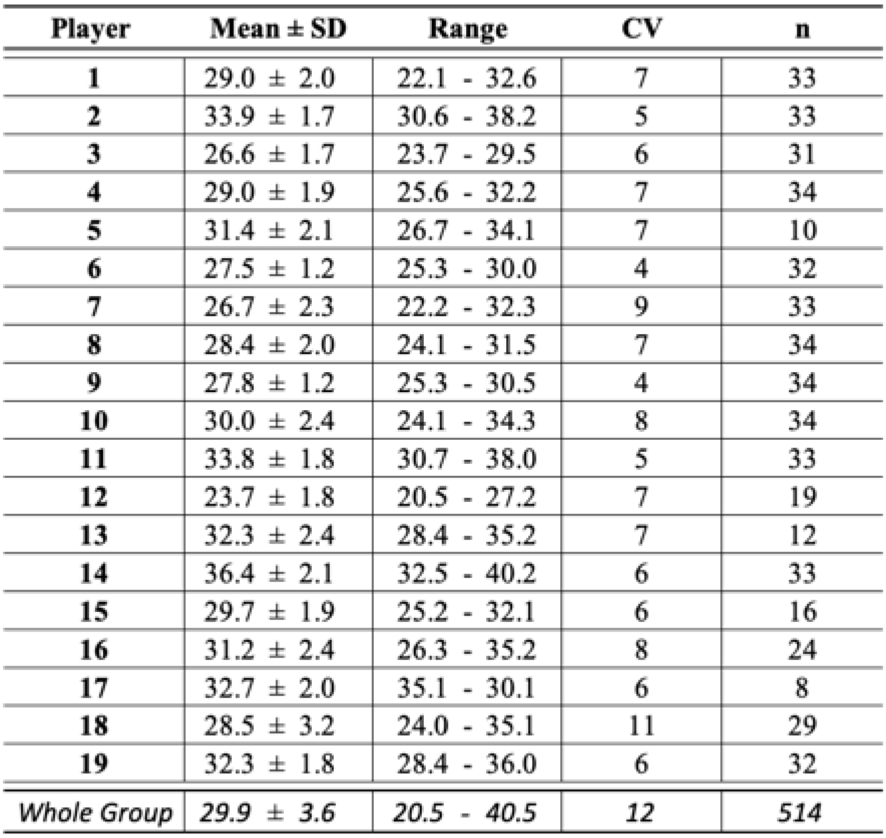
Player	Mean ± SD	Range	CV	n
1	1.8 ± 0.7	1.0 - 3.0	37	34
2	1.7 ± 1.0	0.0 - 3.0	56	35
3	2.6 ± 0.7	1.0 - 4.0	29	35
4	2.5 ± 0.6	1.0 - 3.0	23	35
5	2.9 ± 0.5	2.0 - 4.0	17	13
6	0.6 ± 0.7	0.0 - 3.0	115	37
7	2.4 ± 0.7	0.0 - 3.0	29	37
8	2.0 ± 0.5	0.0 - 3.0	25	37
9	2.9 ± 0.2	2.0 - 3.0	8	37
10	2.7 ± 0.6	2.0 - 4.0	23	37
11	3.0 ± 0.2	2.0 - 3.0	6	36
12	2.4 ± 0.7	0.0 - 3.0	30	31
13	0.1 ± 0.3	0.0 - 1.0	346	12
14	0.7 ± 1.0	0.0 - 2.0	138	37
15	0.1 ± 0.5	0.0 - 2.0	387	15
16	1.6 ± 1.0	0.0 - 3.0	63	36
17	2.2 ± 0.7	0.0 - 3.0	32	19
18	2.5 ± 0.7	1.0 - 3.0	28	27
19	1.8 ± 0.8	0.0 - 3.0	45	36
Whole Group	*2.0 ± 1.1*	*0.0 - 4.0*	*53*	*586*

7.2.1.2 Objective measures of fitness and fatigue

Both jump height and maximum force data are summarised in TABLES 7.5 and 7.6 respectively.

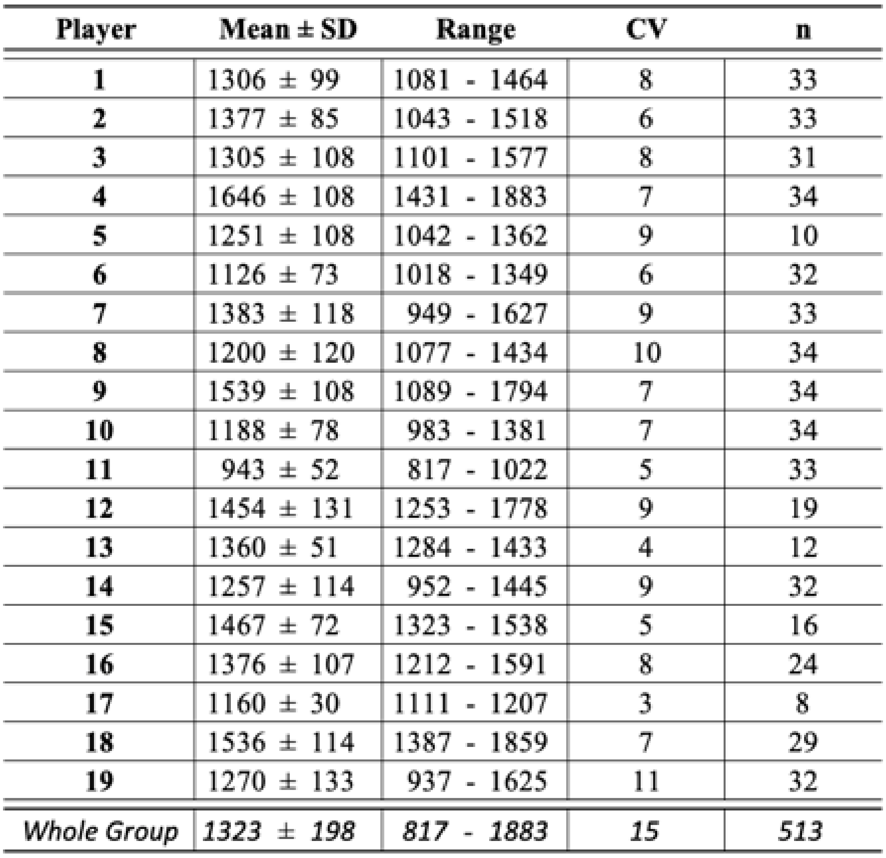
All individual pre-match day jump height data are described in TABLE 7.5. The whole group had a mean jump height of 29.9 cm with a CV 12 %. Player 14 achieved the highest mean score of 36.4 cm, while Player 12 had the lowest mean jump height of 23.7 cm. The lowest CV for jump height was shown in Players 6 and 9 (4 %), while Player 18 had the highest variation at 11 %. The whole group mean maximum force was 1323 N pre-match. The CV for maximum force measured pre-match for the whole group was 15 % (TABLE 7.6). Player 17 had the lowest variance for maximum force, with a mean maximum force of 1160 N, while Player 19 had the highest CV (11 %) with a mean maximum force of 1270 N.

TABLE 7.5: Individual player "jump height" (cm) per match. Data are represented as Means ± SD.



Player	Mean ± SD	Range	CV	n
1	29.0 ± 2.0	22.1 - 32.6	7	33
2	33.9 ± 1.7	30.6 - 38.2	5	33
3	26.6 ± 1.7	23.7 - 29.5	6	31
4	29.0 ± 1.9	25.6 - 32.2	7	34
5	31.4 ± 2.1	26.7 - 34.1	7	10
6	27.5 ± 1.2	25.3 - 30.0	4	32
7	26.7 ± 2.3	22.2 - 32.3	9	33
8	28.4 ± 2.0	24.1 - 31.5	7	34
9	27.8 ± 1.2	25.3 - 30.5	4	34
10	30.0 ± 2.4	24.1 - 34.3	8	34
11	33.8 ± 1.8	30.7 - 38.0	5	33
12	23.7 ± 1.8	20.5 - 27.2	7	19
13	32.3 ± 2.4	28.4 - 35.2	7	12
14	36.4 ± 2.1	32.5 - 40.2	6	33
15	29.7 ± 1.9	25.2 - 32.1	6	16
16	31.2 ± 2.4	26.3 - 35.2	8	24
17	32.7 ± 2.0	35.1 - 30.1	6	8
18	28.5 ± 3.2	24.0 - 35.1	11	29
19	32.3 ± 1.8	28.4 - 36.0	6	32
Whole Group	*29.9 ± 3.6*	*20.5 - 40.5*	*12*	*514*

TABLE 7.6: Individual player "maximum force" scores per match (N). Data are represented as Means ± SD.



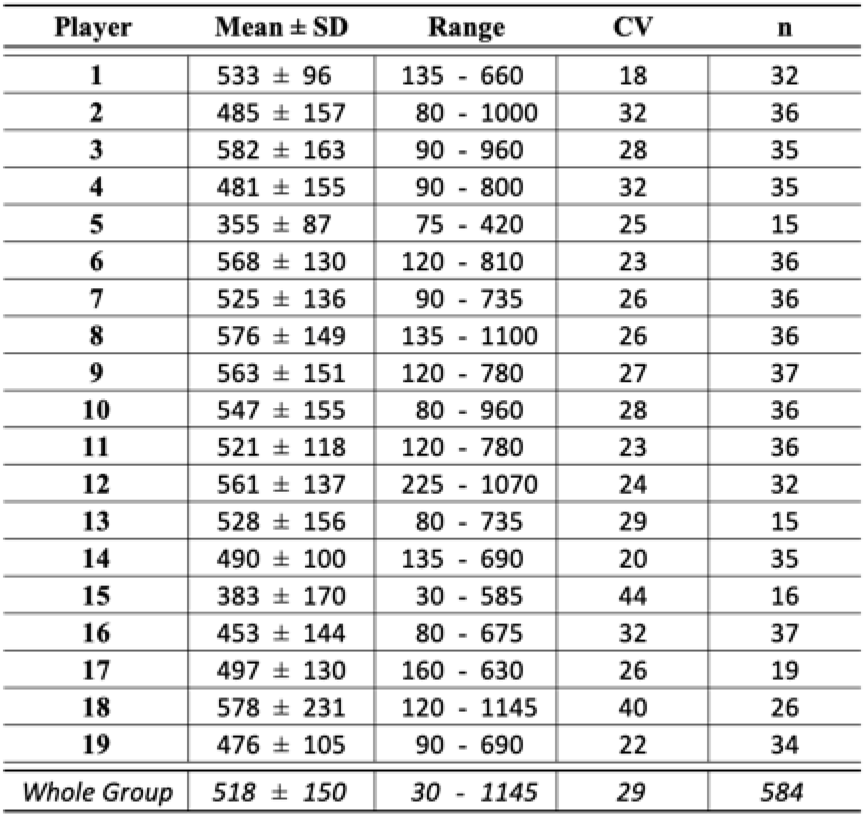
Player	Mean ± SD	Range	CV	n
1	1306 ± 99	1081 - 1464	8	33
2	1377 ± 85	1043 - 1518	6	33
3	1305 ± 108	1101 - 1577	8	31
4	1646 ± 108	1431 - 1883	7	34
5	1251 ± 108	1042 - 1362	9	10
6	1126 ± 73	1018 - 1349	6	32
7	1383 ± 118	949 - 1627	9	33
8	1200 ± 120	1077 - 1434	10	34
9	1539 ± 108	1089 - 1794	7	34
10	1188 ± 78	983 - 1381	7	34
11	943 ± 52	817 - 1022	5	33
12	1454 ± 131	1253 - 1778	9	19
13	1360 ± 51	1284 - 1433	4	12
14	1257 ± 114	952 - 1445	9	32
15	1467 ± 72	1323 - 1538	5	16
16	1376 ± 107	1212 - 1591	8	24
17	1160 ± 30	1111 - 1207	3	8
18	1536 ± 114	1387 - 1859	7	29
19	1270 ± 133	937 - 1625	11	32
Whole Group	*1323 ± 198*	*817 - 1883*	*15*	*513*

7.2.1.1 Subjective measures of match demands

Both training load and RPE are summarised in TABLES 7.7 and 7.8 respectively. Individual match day training loads ranged between 30 – 1145 AU. The group CV averaged 29 %, while Players 15 and 18 had a large CV of 44 % and 40 % respectively. The highest mean match day training loads were reported for Player 3 (582 AU) and Player 18 (578 AU).

RPE data for each individual for each match are summarised in TABLE 7.8. A group mean of 7.4 AU and CV of 24 % was reported for the whole group. Players 1, 6 and 12 had the highest mean perceived exertion scores per match. Player 15 had the highest variation in rating of perceived exertion scores (40 %), while Player 12 had the lowest CV of 13 %.

TABLE 7.7: Individual player “training load” scores per match. Data are arbitrary units (AU) and represented as Means ± SD.



Player	Mean ± SD	Range	CV	n
1	533 ± 96	135 - 660	18	32
2	485 ± 157	80 - 1000	32	36
3	582 ± 163	90 - 960	28	35
4	481 ± 155	90 - 800	32	35
5	355 ± 87	75 - 420	25	15
6	568 ± 130	120 - 810	23	36
7	525 ± 136	90 - 735	26	36
8	576 ± 149	135 - 1100	26	36
9	563 ± 151	120 - 780	27	37
10	547 ± 155	80 - 960	28	36
11	521 ± 118	120 - 780	23	36
12	561 ± 137	225 - 1070	24	32
13	528 ± 156	80 - 735	29	15
14	490 ± 100	135 - 690	20	35
15	383 ± 170	30 - 585	44	16
16	453 ± 144	80 - 675	32	37
17	497 ± 130	160 - 630	26	19
18	578 ± 231	120 - 1145	40	26
19	476 ± 105	90 - 690	22	34
Whole Group	*518 ± 150*	*30 - 1145*	*29*	*584*

TABLE 7.8: Individual player “RPE” scores per match. Data are represented as Means ± SD.
(Scale: 0 – nothing at all to 10 – absolute maximum)

Player	Mean ± SD	Range	CV	n
1	8.3 ± 1.5	3.0 - 10.0	18	32
2	6.5 ± 1.8	2.0 - 10.0	28	36
3	7.8 ± 1.6	2.0 - 9.0	21	35
4	7.0 ± 2.0	2.0 - 10.0	29	35
5	5.9 ± 0.8	5.0 - 7.0	14	15
6	8.4 ± 1.7	3.0 - 10.0	20	36
7	7.8 ± 1.8	2.0 - 10.0	23	36
8	7.6 ± 1.3	3.0 - 10.0	17	36
9	7.8 ± 1.7	3.0 - 9.0	22	37
10	7.9 ± 1.6	2.0 - 9.0	20	36
11	7.2 ± 1.4	3.0 - 9.0	19	36
12	8.0 ± 1.0	5.0 - 10.0	13	32
13	6.5 ± 1.5	2.0 - 8.0	23	15
14	7.1 ± 1.1	3.0 - 9.0	16	35
15	5.7 ± 2.3	1.0 - 9.0	40	16
16	6.6 ± 2.0	2.0 - 10.0	30	37
17	7.8 ± 1.8	4.0 - 10.0	23	19
18	7.4 ± 2.1	3.0 - 10.0	29	26
19	7.1 ± 1.4	2.0 - 9.0	20	34
Whole Group	*7.4 ± 1.7*	*1.0 - 10.0*	*24*	*584*

7.2.1.2 Objective measures of match demands

Individual player total distance, high intensity efforts and bodyload are shown in TABLES 7.9 to 7.11 below.

Individual player total distance ranged between 1114 m – 8874 m per match. The mean total distance for the whole group was 5362 m ± 1296 m with a CV of 24 %. Player 3 (6537 m ± 1329 m) covered the most distance on average per match. While Player 18 (3914 m ± 1293 m) covered the lowest average distance per match. Player 13 also had the highest CV of 34 %.

The whole group averaged 56 ± 21 high intensity efforts per match with a CV of 37 % (TABLE 7.10). Player 19 accumulated the most, high intensity efforts with an average of 96 ± 17 efforts per match and a CV of 18 %, while Player 15 (33 ± 12) accumulated the lowest high intensity efforts per match with CV 36 %.

TABLE 7.9: Individual player "total distance" (m) per match. Data are represented as Means ± SD.

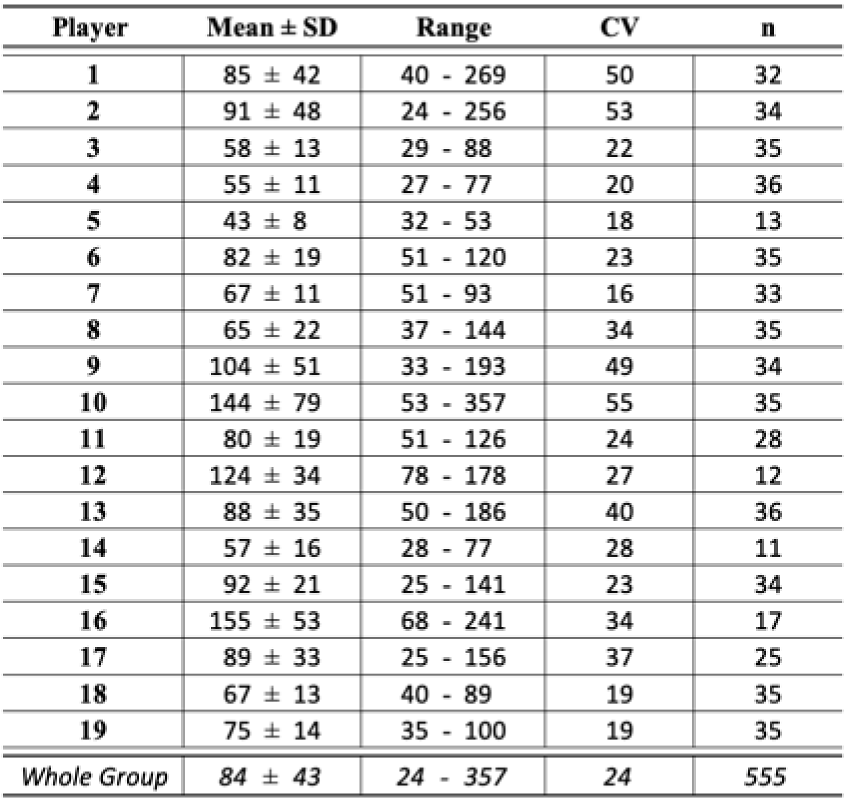
Player	Mean ± SD	Range	CV	n
1	5418 ± 876	3488 - 7398	16	32
2	5963 ± 1171	1544 - 7417	20	34
3	6537 ± 1329	2892 - 8589	20	35
4	6011 ± 923	3296 - 8105	15	36
5	4477 ± 781	3283 - 5635	17	13
6	5926 ± 700	4280 - 7195	12	35
7	6396 ± 1282	2634 - 8874	20	35
8	5008 ± 901	3700 - 6971	18	33
9	4754 ± 781	2790 - 5953	16	35
10	4720 ± 952	2573 - 6722	20	34
11	4227 ± 879	2531 - 6010	21	35
12	5007 ± 693	3505 - 6227	14	28
13	4784 ± 1636	2482 - 7530	34	12
14	4533 ± 697	3292 - 6025	15	36
15	4110 ± 1287	1855 - 5452	31	11
16	6186 ± 1236	2143 - 7886	20	34
17	5802 ± 1400	2605 - 7944	24	17
18	3914 ± 1293	1141 - 6314	33	25
19	6077 ± 1020	3963 - 8813	17	35
Whole Group	*5362 ± 1296*	*1141 - 8874*	*24*	*555*

TABLE 7.10: Individual player "high intensity efforts" scores per match. Data are represented as Means ± SD.

Player	Mean ± SD	Range	CV	n
1	40 ± 13	12 - 73	32	32
2	49 ± 13	19 - 71	27	34
3	41 ± 14	10 - 80	35	35
4	65 ± 15	30 - 103	24	36
5	62 ± 9	48 - 76	15	13
6	59 ± 10	39 - 82	17	35
7	65 ± 21	23 - 102	32	35
8	53 ± 14	34 - 90	27	33
9	45 ± 11	25 - 64	25	35
10	54 ± 15	26 - 93	27	34
11	62 ± 14	26 - 90	23	35
12	38 ± 11	19 - 54	28	28
13	56 ± 15	26 - 78	27	12
14	67 ± 15	34 - 117	23	36
15	33 ± 12	13 - 47	36	11
16	48 ± 18	9 - 92	37	34
17	43 ± 20	14 - 95	46	17
18	60 ± 23	11 - 99	38	25
19	96 ± 17	64 - 128	18	35
Whole Group	*56 ± 21*	*9 - 36*	*37*	*555*

Lastly, there was a range of scores for bodyload as shown in TABLE 7.11. The group mean for bodyload was 84 ± 43 AU per match, with a CV of 24 %. Player 16 had the highest mean bodyload (155 ± 53) recorded per match with a CV of 34 %. Player 5 had the lowest mean bodyload per match (43 ± 8) with a CV of 18 %.

TABLE 7.11: Individual player "bodyload" (AU) scores per match. Data are represented as Means ± SD.



Player	Mean ± SD	Range	CV	n
1	85 ± 42	40 - 269	50	32
2	91 ± 48	24 - 256	53	34
3	58 ± 13	29 - 88	22	35
4	55 ± 11	27 - 77	20	36
5	43 ± 8	32 - 53	18	13
6	82 ± 19	51 - 120	23	35
7	67 ± 11	51 - 93	16	33
8	65 ± 22	37 - 144	34	35
9	104 ± 51	33 - 193	49	34
10	144 ± 79	53 - 357	55	35
11	80 ± 19	51 - 126	24	28
12	124 ± 34	78 - 178	27	12
13	88 ± 35	50 - 186	40	36
14	57 ± 16	28 - 77	28	11
15	92 ± 21	25 - 141	23	34
16	155 ± 53	68 - 241	34	17
17	89 ± 33	25 - 156	37	25
18	67 ± 13	40 - 89	19	35
19	75 ± 14	35 - 100	19	35
Whole Group	*84 ± 43*	*24 - 357*	*24*	*555*

7.2.2 Pre, intra and 24 h post-match data analysis

7.2.2.1 Pre-match data analysis

All pre-match data are represented in FIGURES 7.1 to 7.3. This analysis shows all measurements before match play to determine players' relative readiness and the relationships between each variable and match outputs for each player.

FIGURE 7.1 and 7.2 summarise the relationships between all subjective measures of fitness and fatigue (wellness) as well as objective measures of match demands (GPS). There were no significant relationships between subjective readiness-to-train and total distance, readiness-to-train and high intensity efforts, subjective recovery and high intensity efforts, muscle soreness and total distance as well as muscle soreness and high intensity efforts. Players 1 (0.45; 0.09 to 0.71) and 5 (-0.60; -0.84 to -0.05) had a significant positive and negative relationship respectively between recovery and total distance (FIGURE 7.1 *graph b*). Player 16 (0.36; 0.01 to 0.63) had significant relationship with readiness-to-train and bodyload (Figure 7.1 *graph e*) and Player 7 (-0.39; -0.64 to -0.05) had significant relationship between recovery and bodyload (FIGURE 7.1 *graph f*). Player 9 had a significant relationship between motivation-to-train and total distance (0.38; 0.04 to 0.64), muscle soreness and bodyload (-0.40; -0.66 to -0.07) as well as motivation-to-train and bodyload (0.35; 0.01 to 0.62) (FIGURE 7.2 *graphs h, k and l*). While Player 3 (-0.43; -0.68 to -0.09) was the only player to have any significant relationship between motivation-to-train and high intensity efforts (FIGURE 7.2 *graph j*).

FIGURE 7.3 summarises the correlation coefficients of all pre-match objective measures of fitness and fatigue (CMJ) and objective measures of match demands (GPS). No significant relationship was shown between jump height and high intensity efforts.

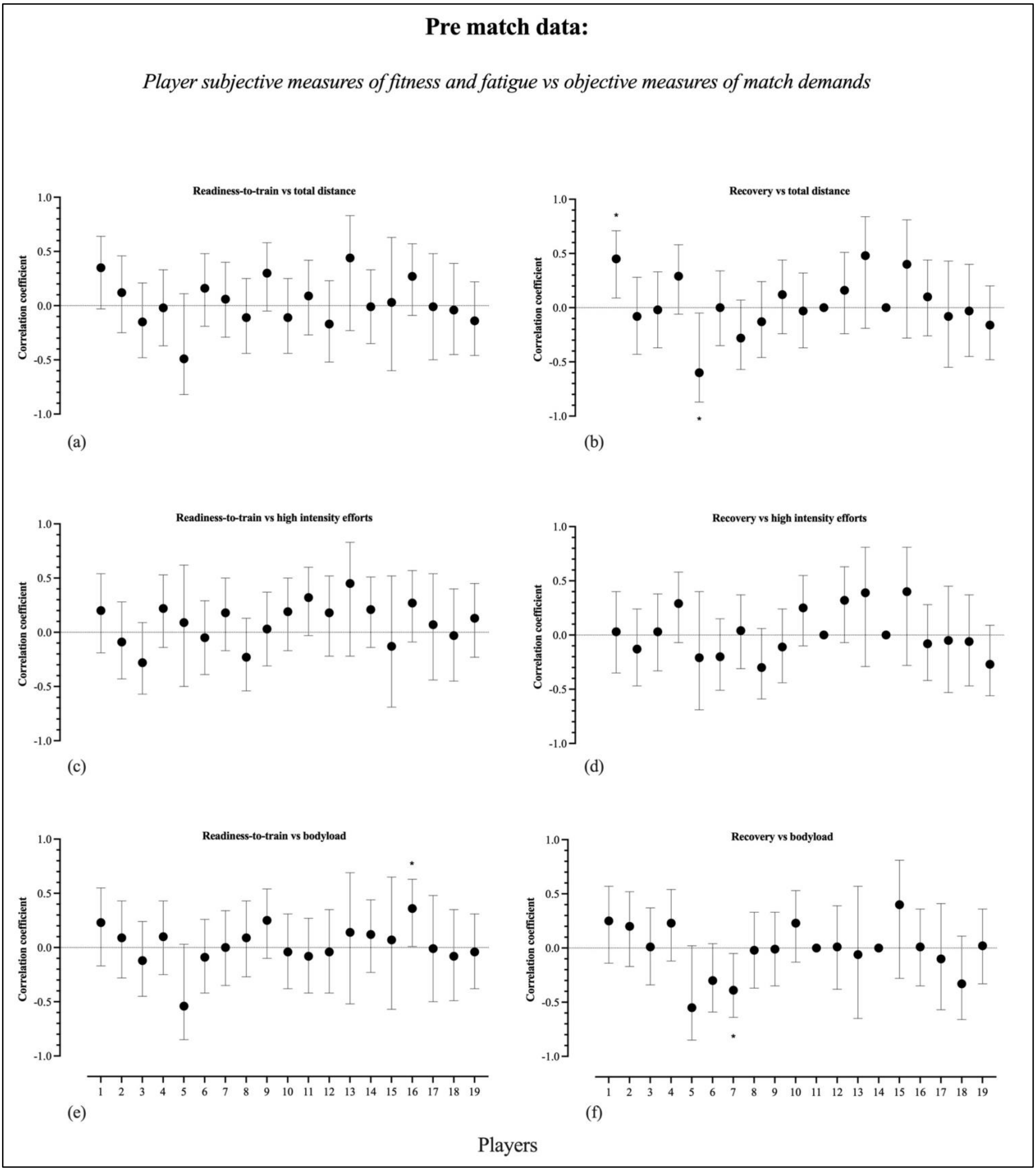


FIGURE 7.1: Intra individual correlation coefficients for each player's pre-match subjective measures of fitness and fatigue vs objective measures match demands. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05

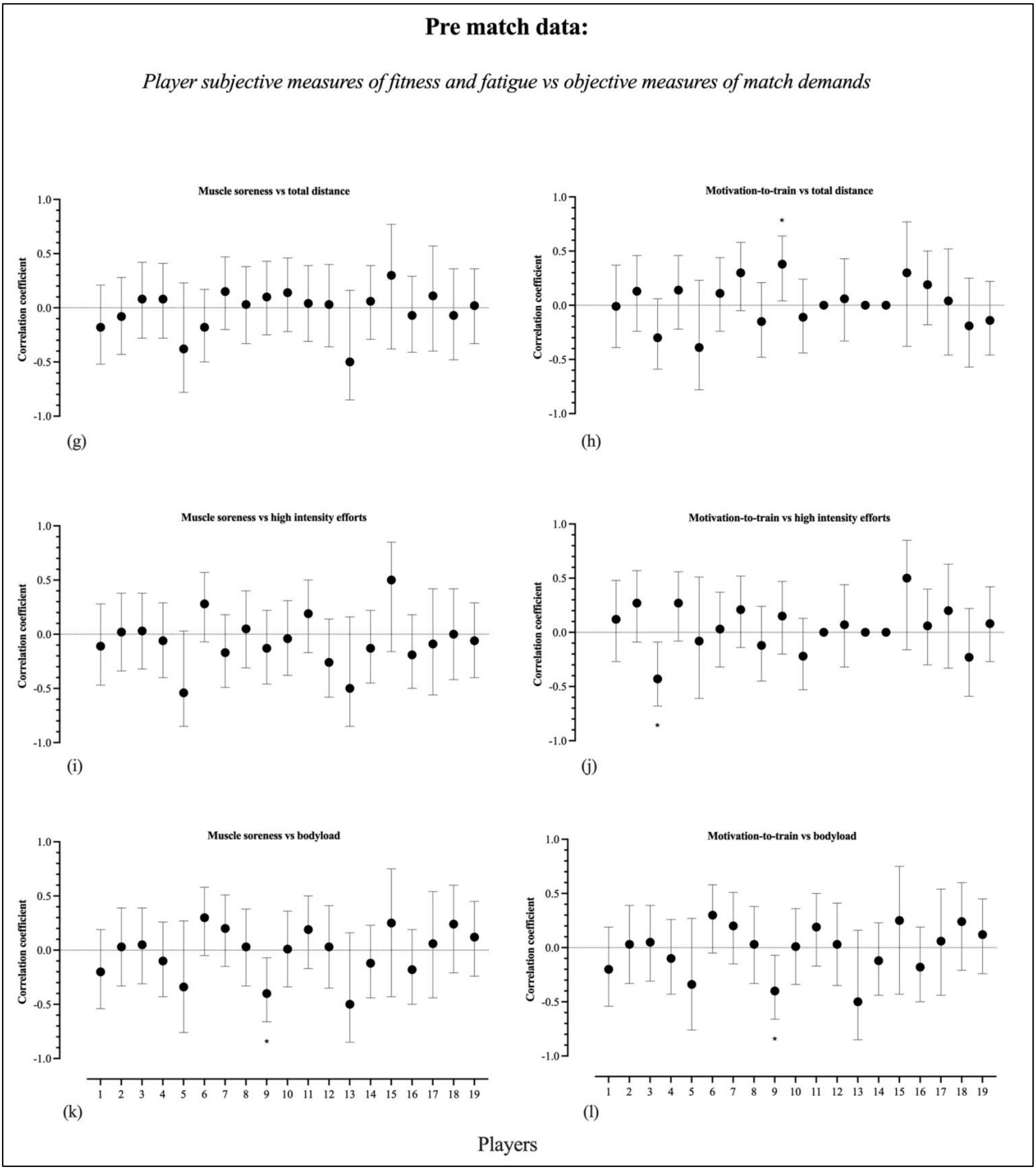


FIGURE 7.2: Intra individual correlation coefficients for each player's pre-match subjective measures of fitness and fatigue vs objective measures match demands. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05

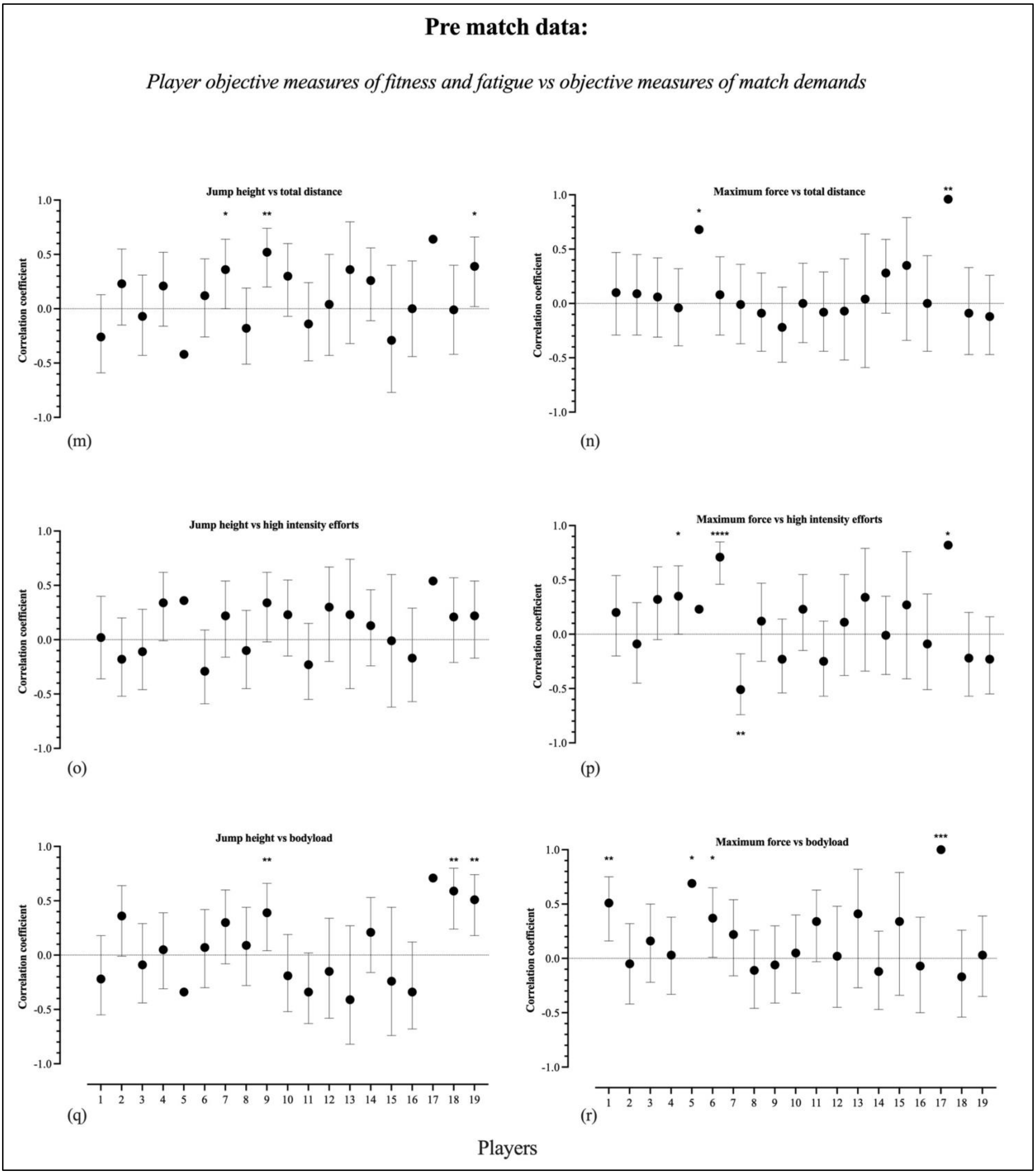


FIGURE 7.3: Intra individual correlation coefficients for each player's pre-match objective measures of fitness and fatigue vs objective measures match demands. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01; ***p = <0.0002; ****p = <0.0001

Players 7 (0.36; 0.00 to 0.64), 9 (0.52; 0.20 to 0.74) and 19 (0.39; 0.02 to 0.66) had significant relationships between jump height and total distance (FIGURE 7.3 *graph m*). While Players 5 (0.68; 0.00 to 0.00) and 17 (0.96; 0.00 to 0.00) had a significant relationship between maximum force and total distance (FIGURE 7.3 *graph n*). Interestingly, maximum force accounted for 92 % of the variance in total distance for player 17. Four players had a significant relationship between maximum force and high intensity efforts (FIGURE 7.3 *graph p*). Player 6 (0.71; 0.46 top 0.85) had the strongest positive relationship of all players, explaining for 50 % of the variance in high intensity efforts. Players 9, 18 and 19 all had significant relationship between jump height and bodyload (FIGURE 7.3 *graph q*). Players 1, 5, 6 and 17 had significant relationships between maximum force and bodyload (FIGURE 7.3 *graph r*). Player 17 had the strongest positive relationship between maximum force and bodyload (1.0; 0.00 to 0.00) explaining for 100 % of bodyload. It's important to note that this result may be largely due to the small sample size of Player 17 (n = 8).

7.2.2.2 Intra-match data analysis

FIGURE 7.4 summarises the individual intra-match correlation coefficient for all subjective and objective measures of match demands. Eight of the 19 players had a significant relationship between RPE, and total distance measured during the match as well as for RPE and high intensity efforts measured during the match. Player 8 had the strongest (positive) relationship between RPE and total distance (0.72; 0.49 to 0.86), (FIGURE 7.4 *graph a*), and Player 16 for RPE and high intensity efforts (0.58; 0.29 to 0.77) (FIGURE 7.4 *graph c*). Players 8 (0.63; 0.35 to 0.81) and 16 (0.57; 0.28 to 0.77) had the strongest relationships for RPE and bodyload (FIGURE 7.3 *graph e*). While seven out of the 19 players had significant correlations between training load and total distance (FIGURE 7.4 *graph b*). Player 7 had the strongest relationship between training load and bodyload (0.61; 0.34 to 0.79) (FIGURE 7.4 graph *f*).

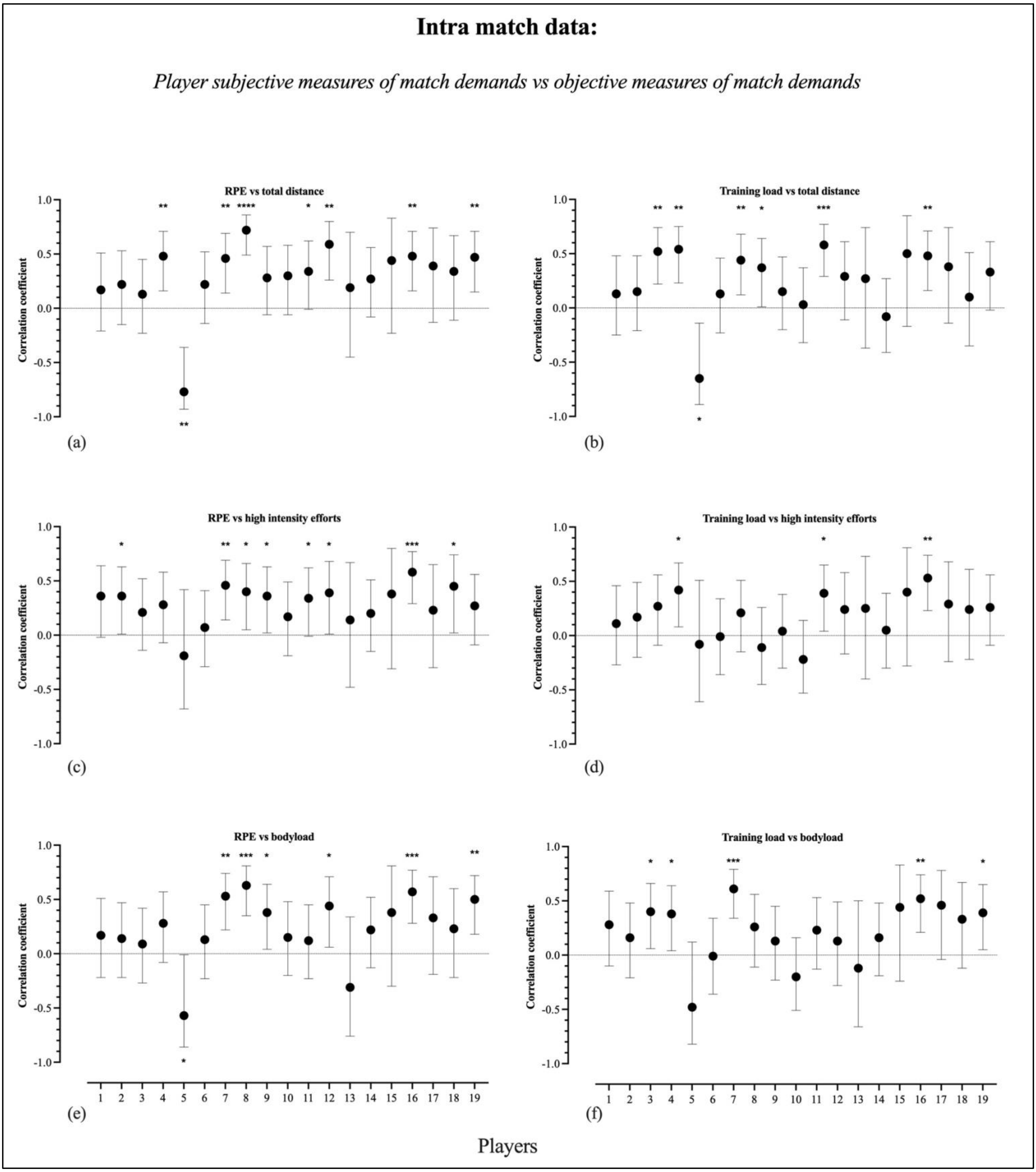


FIGURE 7.4: Intra individual correlation coefficients for each player's pre-match objective measures of fitness and fatigue vs objective measures match demands. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01; ***p = <0.0002; ****p = <0.0001

7.2.2.3 24 h post-match data analysis

FIGURES 7.5 to 7.9 illustrate all the individual correlation coefficients for all 24 h post-match data. There were no significant relationships between total distance and readiness-to-train (FIGURE 7.5 *graph b*), high intensity efforts and general muscle soreness (FIGURE 7.6 *graph k*), high intensity efforts and motivation-to-train (FIGURE 7.6 *graph l*), maximum force and total distance (FIGURE 7.7 *graph b*), maximum force and bodyload (FIGURE 7.7 *graph f*), RPE and recovery (FIGURE 7.8 *graph a*), and training load and motivation-to-train (FIGURE 7.9 *graph h*). Player 4 had the strongest relationship (-0.63; -0.81 to -0.34) between total distance vs recovery. Only one player had a significant relationship between total distance and general muscle soreness (Player 1), total distance and motivation-to-train (Player 7) and bodyload and readiness-to-train (Player 16). In FIGURE 7.6, Player 12 (0.53; 0.14 to 0.78) had the strongest relationship between high intensity efforts and readiness-to-train, with Player 18 (-0.61; -0.84 to -0.19) having the strongest (negative) relationship between high intensity efforts and recovery. Five players had a significant relationship between jump height and total distance (FIGURE 7.7 *graph a*). When considering maximum force and high intensity efforts, Player 7 (-0.63; -0.83 to -0.31) had the strongest relationship out of the 3 players with significant responses. Players 11 (-.035; -0.66 to -0.05) and 16 (-0.59; -0.83 to -0.18) both had the highest correlations between jump height and bodyload. Player 4 had the strongest negative relationship between RPE and readiness-to-train (FIGURE 7.8 *graph b)*. While Players 1, 3 and 4 all had a significant positive relationship between RPE and general muscle soreness (FIGURE 7.8 graph *c*). Lastly, for training load and recovery in FIGURE 7.9 *graph e*, only Player 3 (-0.49; -0.73 to -0.14) had a significant correlation. Three players had a significant relationship with training load and readiness-to-train (FIGURE 7.9 *graph f*). Only two players had a significant correlation between training load and general muscles soreness (FIGURE 7.9 *graph g*).

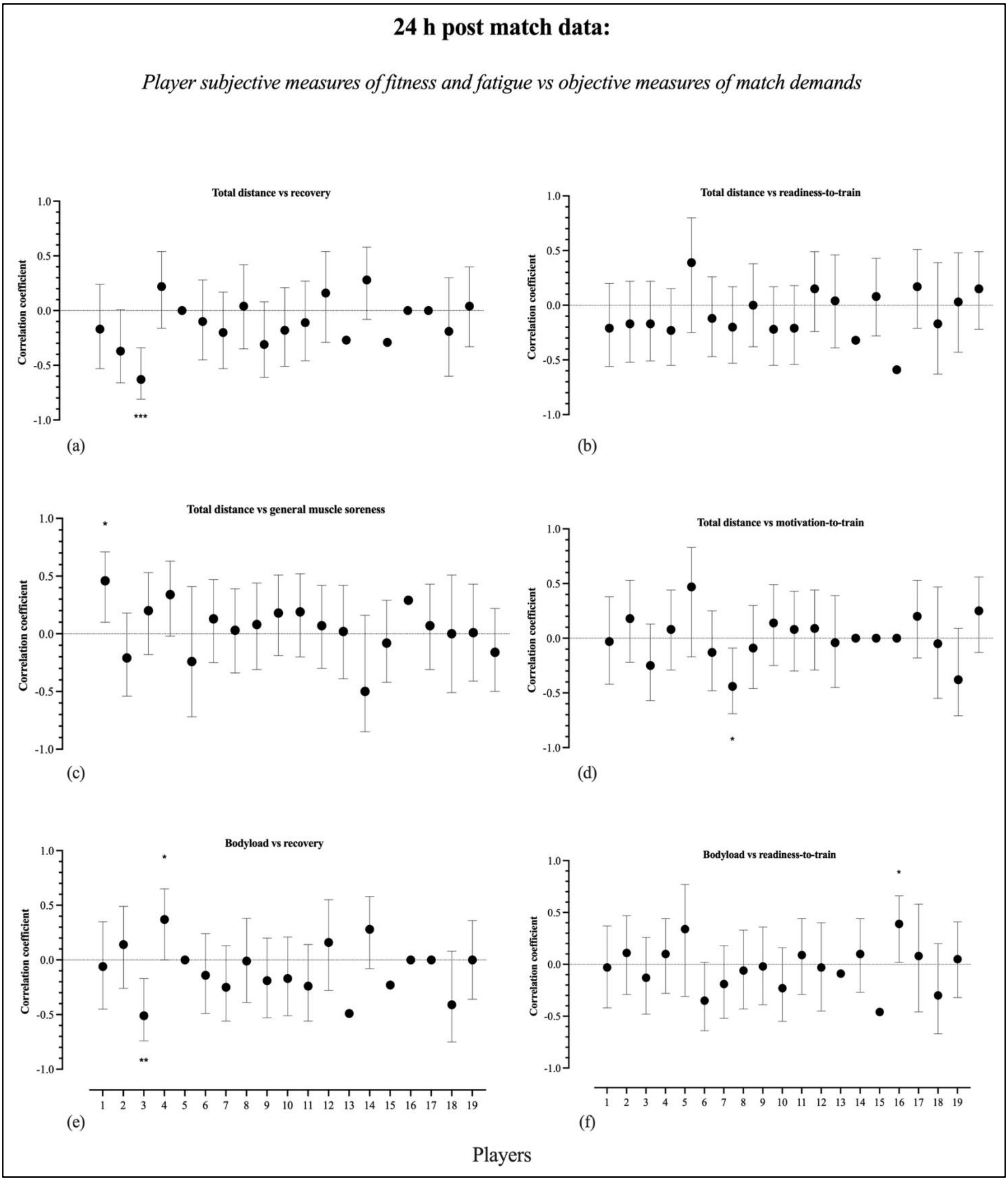


FIGURE 7.5: Intra individual correlation coefficients for each player's 24 h post-match subjective measures of fitness and fatigue vs objective measures match demands. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01; ***p = <0.0002

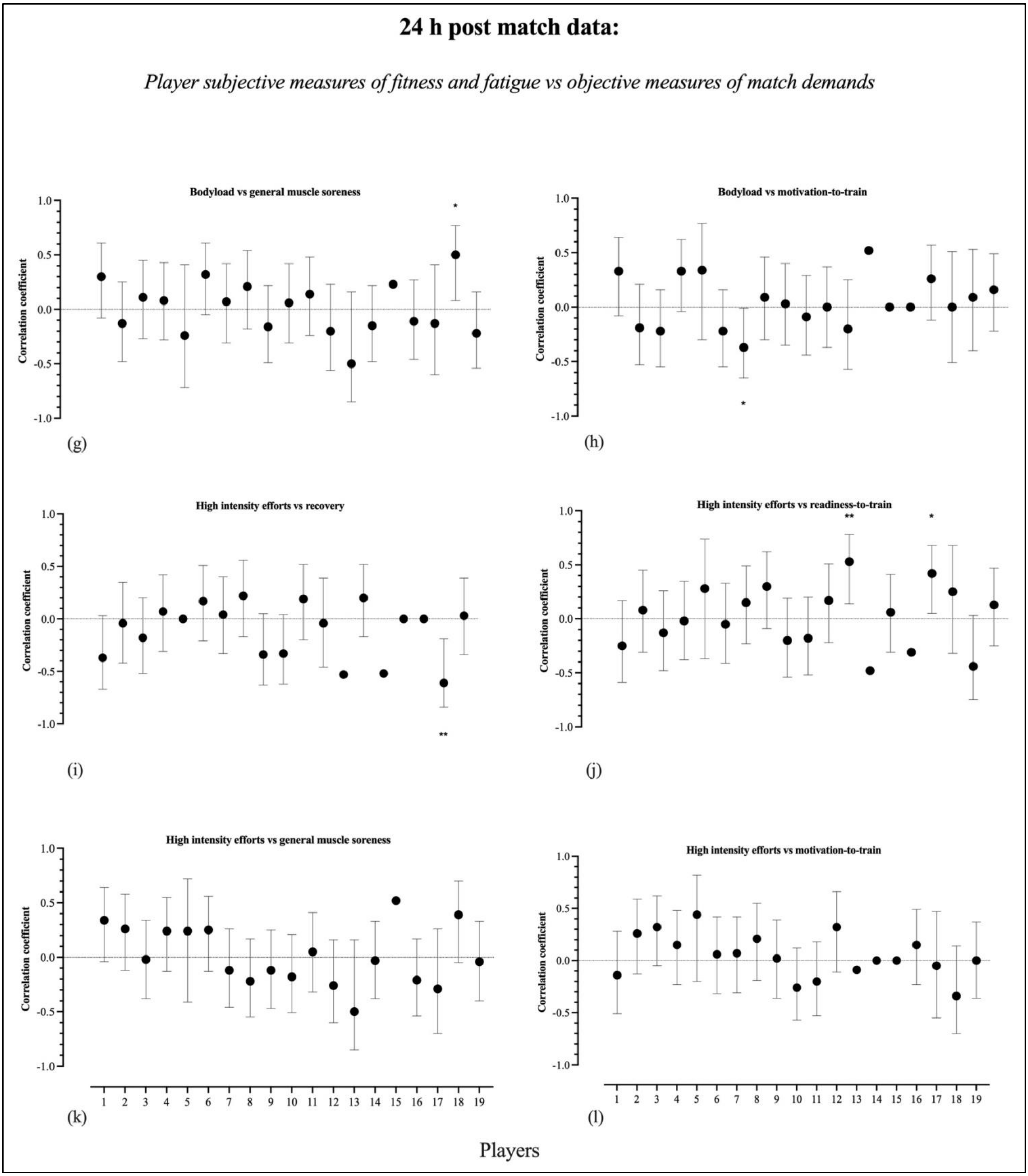


FIGURE 7.6: Intra individual correlation coefficients for each player's 24 h post-match subjective measures of fitness and fatigue vs objective measures match demands. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01

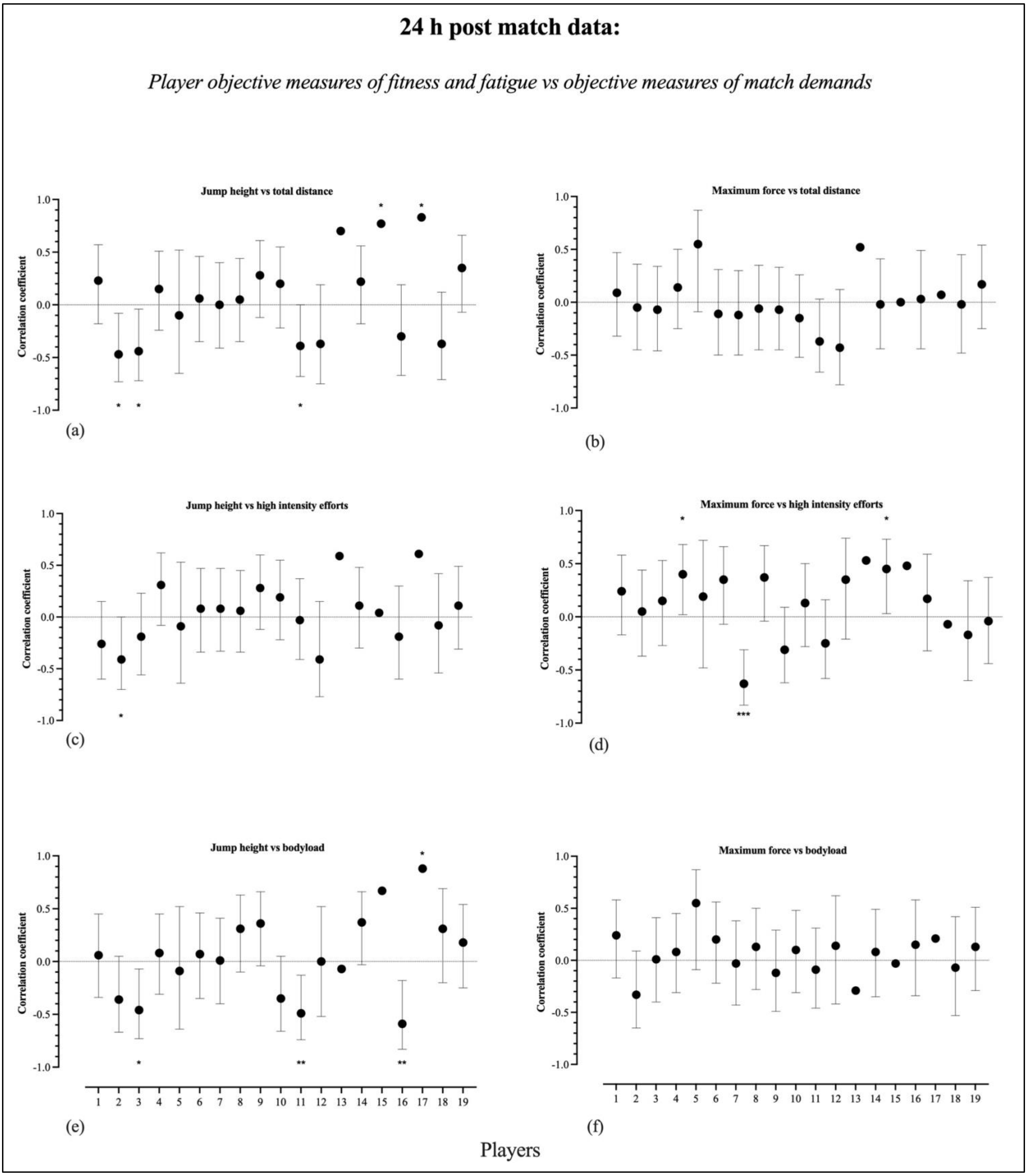


FIGURE 7.7: Intra individual correlation coefficients for each player's 24 h post-match objective measures of fitness and fatigue vs objective measures match demands. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01; ***p = <0.0002

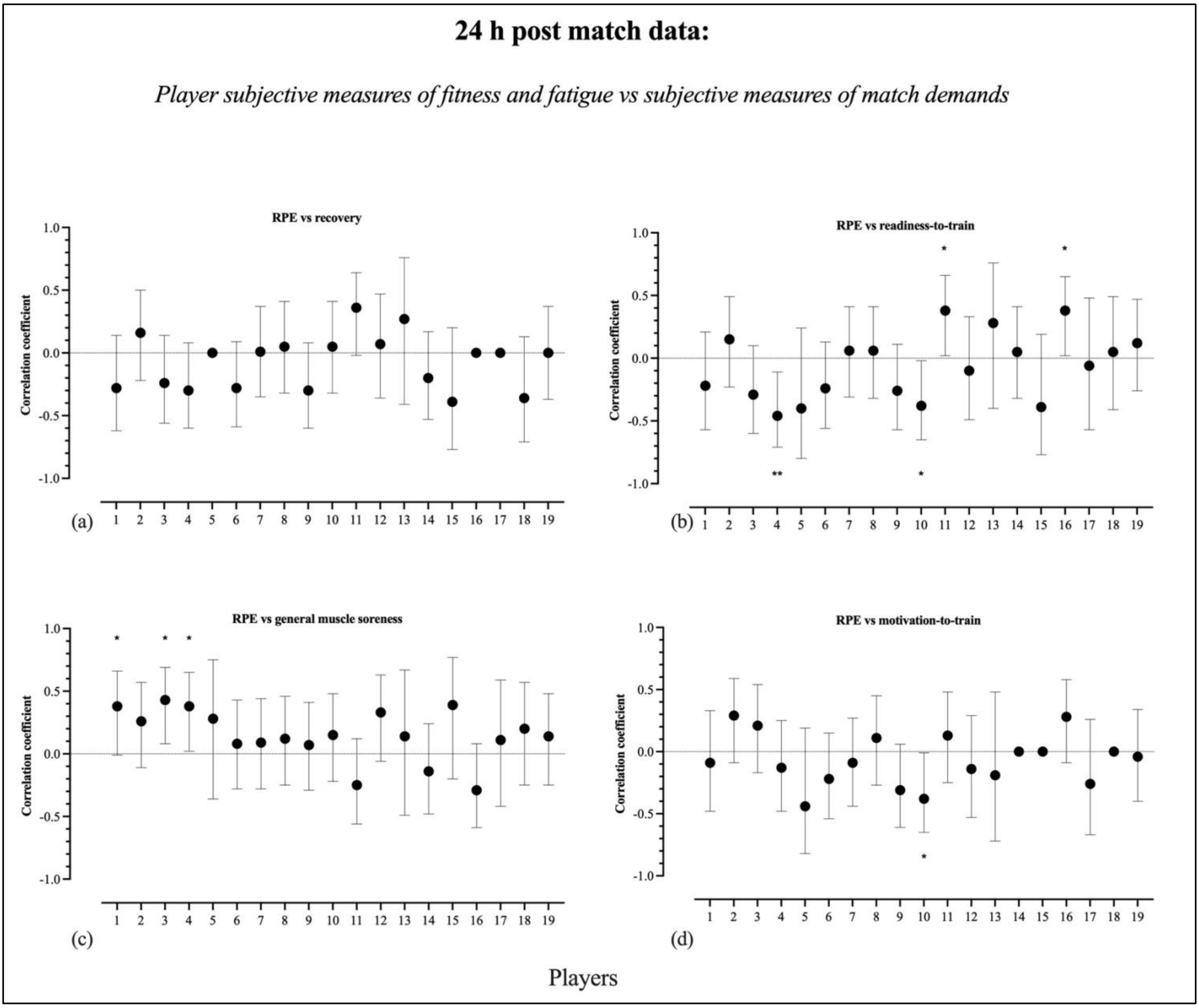


FIGURE 7.8: Intra individual correlation coefficients for each player's 24 h post-match subjective measures of fitness and fatigue vs subjective measures match demands. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01

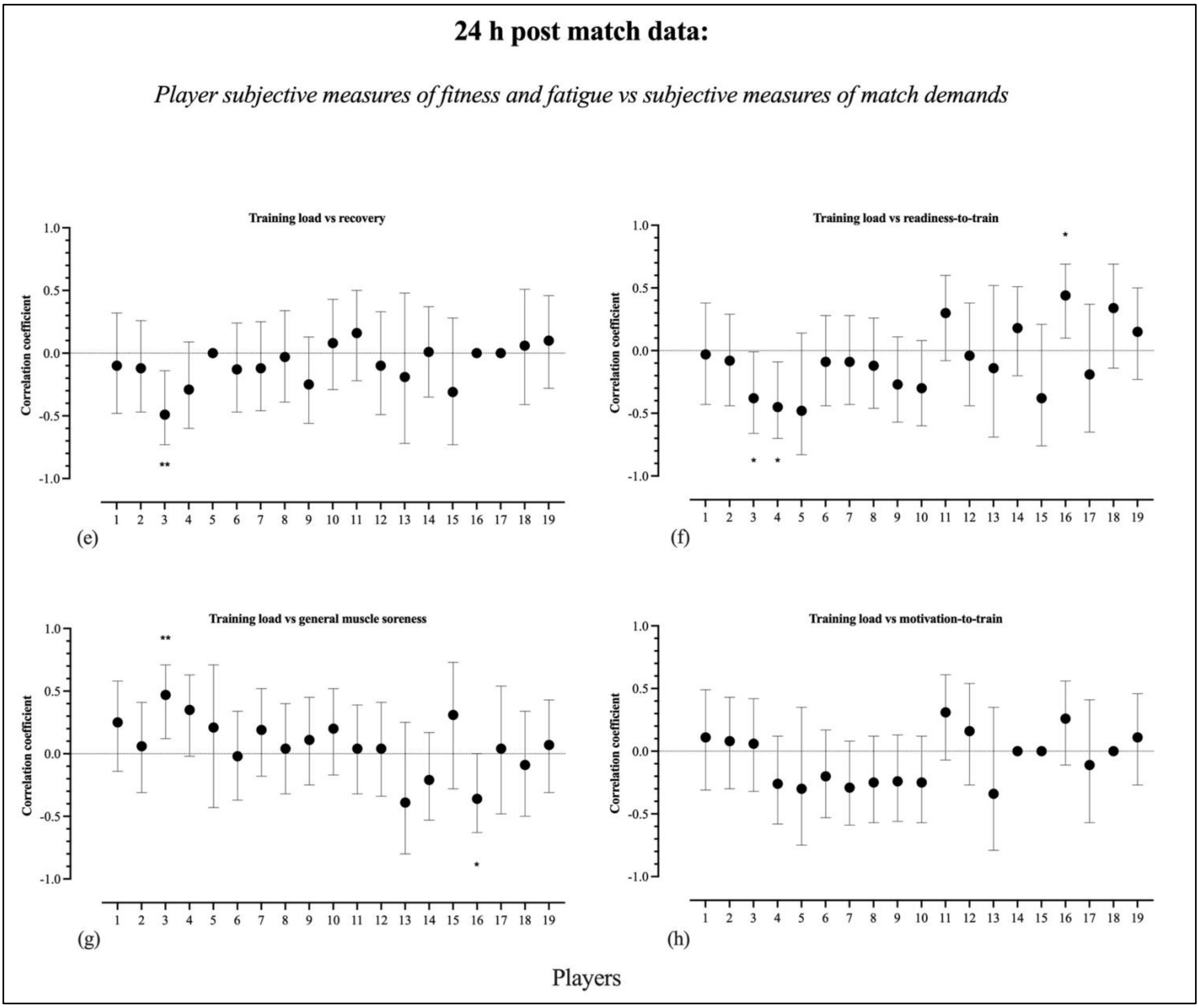


FIGURE 7.9: Intra individual correlation coefficients for each player's 24 h post-match subjective measures of fitness and fatigue vs subjective measures match demands. Data are represented as r values with 95 % upper and lower confidence intervals.

*p = <0.05; **p = <0.01

7.3 Discussion

The main finding of the study was that match demands affect the fitness and fatigue of each player differently. Furthermore, pre-match fitness and fatigue measures may contribute to decisions about an athletes' training status but should be interpreted on an individual basis. Lastly, the relationship between objective match demands and subjective measures, such as RPE and training load share a strong relationship, but again should be interpreted on an individual player basis.

7.3.1 Pre-match data analysis

One of the primary aims of high-performance support staff is to determine the relative readiness of each individual to perform at their best on match day[138,339]. Secondly, the ability to interpret monitoring data for any possible "red flags" that may lead to performance decrements and guide possible recovery interventions is of utmost importance in keeping the best players playing[104,339]. For example, FIGURE 7.3 shows that neuromuscular measures such as jump height and maximum force seem to have an association with some player's match outputs, such as, total distance, bodyload and high intensity efforts. Most of these relationships indicate that with a better pre-match neuromuscular status, players may produce better match outputs. This is similar to previous studies examining pre-match neuromuscular training status of athletes[108,333,334]. However, the majority of the players showed no significant relationships between pre-match measures and match demands.

Only a few statistically significate correlations were noted for pre-match subjective measures and match outputs. There are possible explanations for this. Firstly, players were well prepared for the demands of a congested match schedule, thus reducing the variance in subjective data submissions. The low variance may also be explained by the players pacing themselves for the tournament. Secondly, it may also indicate that the subjective measures are not sensitive enough to affect match output on the day. This however contrasts with what has been described in the literature previously, where subjective measures have been shown to be sensitive to demands of training as well as affecting match performance[104,132].

7.3.2 Intra-match data analysis

The strong relationship between RPE and match outputs in the current study was similar to previous findings. For example, on an individual level, many players showed a strong relationship between RPE, total distance, high intensity efforts and bodyload. These correlations suggest that with an increase in any one of the objective measures of match demands, that there is a concomitant increase in the player's RPE. This suggests that the use of RPE as a proxy measure for match demands is valid and reliable. This is not novel as it has been reported before[37,151,165,340]. But it is noteworthy to support the future use of RPE in similar athletic populations. There were similar findings for subjective training load and match demands. However, there were a lower number of correlations present between these two variables. This may be due to playing time variations from match-to-match and also variations in playing times within each individual player. Again, support staff should consider capturing subjective training load data to help guide progressions, recovery, and overload within a season as a whole. Subjective training load data has received a vast amount of attention over the past 10 years and been shown to be an important component of a holistic monitoring system as a global measure of match or training demands[37,92,152,341–343].

7.3.3 24 h Post-match data analysis

Monitoring 24 h post-match data has two significant roles. Firstly, to help identify how the demands of the game have affected each individual player's overall fitness and fatigue. Secondly, in sports like field hockey, the data is important to determine the pre-match training and neuromuscular status of players when confronted with back-to-back matches. These data allow support staff to determine what recovery modalities should be used post-match to enhance their readiness for the next match[324,344]. Also, these data can be used to individualise players pre-match priming sessions to help potentiate players on pitch physical performance[344–346].

As observed with pre-match data, there were only a few significant relationships between subjective measures of fitness and fatigue and match demands. This suggests that players were well prepared to meet the demands of the game and also recovered near optimally 24 h or less post-match. When considering the effects of match demands on neuromuscular performance 24 h post-match, again there were only a few significant relationships. For example, jump height had the most intra-individual relationships, showing a general decline in jump height with an increase in match demands. This is similar to other studies on rugby league, basketball, handball and soccer showing a decrease in neuromuscular performance with higher training or match loads[87,108,249,279,334,347,348]. Maximum force did not seem to change as frequently[115,223,227,242,349,350] among individual players as did jump height. This may indicate that changes in jump height and maximal force are associated with different aetiologies causing fatigue. For example, even though players may be able to maintain their jump height, they might not be able to maintain their maximum force[227,242,322,350]. Thus, it is recommended that practitioners monitor both variables to better understand the neuromuscular training status of elite level athletes. Importantly, the data suggests that monitoring total distance and bodyload via GPS, to quantify external load is important. This is based on the finding that total distance and bodyload have the highest number of individual players correlations. Lastly, only a few relationships were shown between subjective measures of match demands and subjective measures of fitness and fatigue 24 h post-match. As previously mentioned, this may indicate that players were physically prepared to meet the demands of the matches they were exposed to. Another interpretation is that the subjective measure of fitness and fatigue were not sensitive enough to detect small changes. However, this contrasts with what has been reported previously by Saw et al, showing that subjective measures are sensitive to changes in training loads and intensities[132].

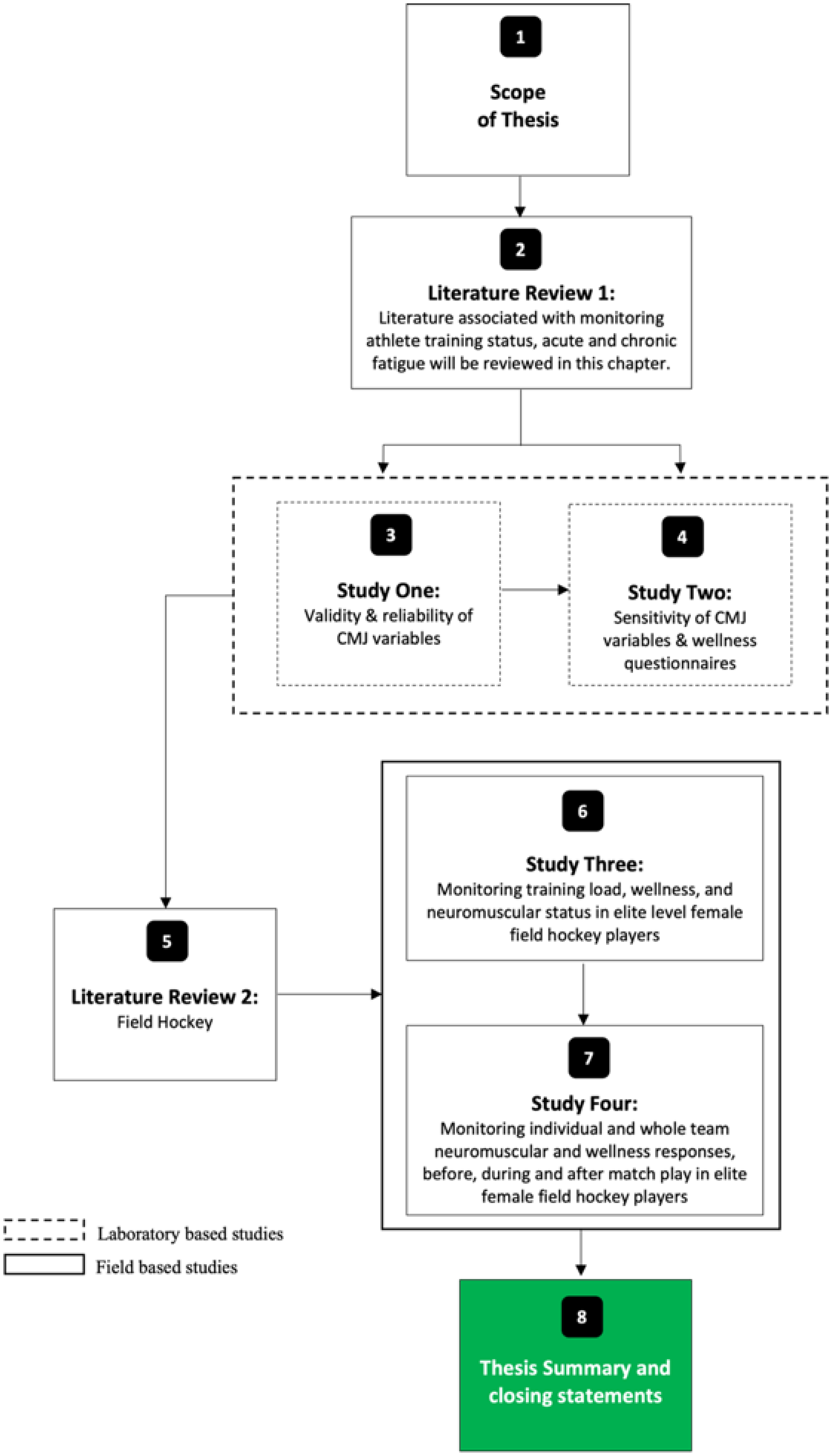
7.4 Conclusion

Findings of the current study support the notion of monitoring specificity and individualisation as alluded to in Chapter Six. The ability to identify responders and non-responders[7] to various monitoring tools will help reduce the “noise” associated with various monitoring tools. The idea of collecting a wide range of data but reporting “narrow” to reduce the “noise” is a pragmatic approach in monitoring the training status of elite level athletes. This means that a wide range of data may be useful in interpreting the final data reported to the support staff. From this study it is recommended that for team-based ball sports characterised by intermittent bouts of short duration, high intensity exercise, external load can be quantified objectively with GPS variables, such as total distance and bodyload. Furthermore, RPE and subjective training load can be used as a proxy measure of intensity and external load respectively. Additionally, jump height can be added as an objective measure of neuromuscular training status. Lastly, subjective measures of neuromuscular training status, although showing weak correlations in this study, should be used to gain a deeper understanding of each individual athletes’ subjective fitness and fatigue.

The ability to conjugate these data, will allow support staff to give meaningful input to coaches on the daily training status of individual athletes. Accordingly, informed decisions on the days training can be made.

7.5 Chapter Seven – Summary points

1. Even in a relatively homogenous group, the descriptive data indicates that everyone has varying exposure and responses to match demands.
2. Pre-match data should be considered to help support staff better understand player readiness-to-train.
3. Variables such as subjective recovery measured 24 h post-match have a significant relationship with bodyload in a few players.
4. Total distance during a match was associated with reductions jump height and maximum force measured post-match in a few players
5. Maximum force measured pre match also had a strong relationship with high intensity efforts during the match in a few players.
6. RPE and training load should be considered as proxy measures of match demands along with GPS variables.
7. Jump height seems to be the most sensitive variable to changes in match demands at 24 h post-match.


1
Scope of Thesis
2
Literature Review 1:
Literature associated with monitoring athlete training status, acute and chronic fatigue will be reviewed in this chapter.
3
Study One:
Validity & reliability of CMJ variables
4
Study Two:
Sensitivity of CMJ variables & wellness questionnaires
5
Literature Review 2:
Field Hockey
6
Study Three:
Monitoring training load, wellness, and neuromuscular status in elite level female field hockey players
7
Study Four:
Monitoring individual and whole team neuromuscular and wellness responses, before, during and after match play in elite female field hockey players
8
Thesis Summary and closing statements
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8. Chapter Eight

Summary and closing statements

8.1 Introduction

This thesis was compiled with specific objectives. One of these objectives was to be able to identify variables to monitor neuromuscular performance and subjective wellness that can be used in and outside a laboratory setting. A further objective was to identify the intra-individual relationships of these monitoring variables in elite athletes, within a real-world sporting environment. With the ever-changing environment and competitive nature of elite sport optimal player management is dependent on being able to determine an athletes' training status, through the implementation of monitoring systems that incorporate multiple valid and reliable variables.

The notion that everyone responds differently to the same training demands has been understood for many years[7]. This concept of individual differences should also be considered when deciding which monitoring strategies and/or variables will be used in team sports. Thus, "monitoring specificity", is an important concept that should be considered when selecting the most appropriate variables. However, an important differentiation needs to be drawn between the concept of monitoring specificity vs individualised physiological adaptations to external and internal load. The first refers to certain individuals being more responsive to specific objective or subjective monitoring variables and the second refers to individuals adapting at different rates following exposure to the same bout of exercise. It is plausible to suggest that further research needs to be conducted, to identify a battery of monitoring specific tests to better understand which variables are more suited to specific athletes within a team. In this manner we can minimise the "noise" within a monitoring system, by reducing the number of “non-responsive” variables for each athlete and focussing on the more responsive variables.

This thesis consists of four separate, yet interrelated studies that set out to answer specific questions related to monitoring, wellness, training loads and neuromuscular performance. The next section is a summary of the questions and answers arising from the experimentation. Each question, defined at the beginning of the thesis, is highlighted followed by a succinct answer. Where relevant the practical applications that support staff of elite sporting teams can use on a day-to-day basis are also discussed.

8.1.1 Question 1 (Study One)

Are countermovement jump variables measured on a force plate valid and reliable?

This question was answered by calculating the typical error of measurement and intra-class correlation coefficient for participants of varying training age (Chapter Three).

8.1.1.1 Answer to Question 1 (Study One)

The countermovement jump variables extracted from the force plates software were maximum force, time to maximum force, rate of force development, jump height and flight time. A key finding of the study was that all countermovement jump variables measured, were valid and reliable in a heterogenous group. The important messages from the study included:

1) The TEM for maximum force was 84 N or 0.3 % for the whole group. The trained group had the lowest measurement error and the highest consistency (ICC = 0.96). Importantly, *small* changes can be detected in maximum force.
2) The TEM for time to maximum force was 0.03 s or 0.74 % for the whole group. While the semi-trained group had the lowest variation (0.55 %) and highest

consistency. *Small* and *medium* changes can be detected in time to maximum force.

3) RFD had a TEM of 385 N.s^{-1} or 0.4 %. The trained group had the lowest measurement error (0.3 %) and highest consistency. *Small* (trained group) and *medium* changes can be detected in the RFD measurement.
4) The TEM for jump height was 1.06 cm or 0.18 % for the whole group. The trained group again had the lowest variation (0.19 %) and highest consistency. Interestingly, jump height displayed enough precision to detect *trivial* changes in trained individuals.
5) Flight time had a TEM of 0.01 s or 0.18 % for the whole group. The trained group again displayed the lowest measurement error and highest consistency. There was sufficient precision in the measurement of flight time to detect *trivial* changes.

8.1.1.2 Practical applications (Study One)

High performance support staff wanting to use the countermovement jump as a tool to monitor neuromuscular performance should understand the precision of each variable they are using. The above analysis allows support staff to better interpret the data, identifying if the observed changes are true performance changes or changes due to measurement error. The measurement had sufficient precision to detect *small* changes in most cases. Lastly, the countermovement jump seems to have the highest level of validity and reliability in trained individuals. This suggests the variables associated with the countermovement jump are appropriate for measuring the neuromuscular profile of elite athletes.

8.1.2 Question 2 (Study Two)

Are countermovement jump variables and subjective responses to a wellness questionnaire, sensitive enough to detect changes induced by acute exercise fatigue?

Note: The type of exercise-inducing fatigue could be equated to the demands of a soccer match (Chapter Four).

8.1.2.1 Answer to Question 2 (Study Two)

In this study, we observed *trivial* changes in countermovement jump variables at 24 h post and 48 h after exercise-induced fatigue. None of these changes were statistically significant changes.

However, there were significant changes in subjective responses to various wellness questions following exercise-induced fatigue. For example, the responses to **"***Do you feel physically strong today***",** were significantly lower at 24 h post. While the responses to, *"Do you feel mentally strong today?",* were significantly lower at 48 h after exercise-induced fatigue. Lastly, subjective responses to *"Do you have any muscle soreness today?",* indicated increased muscle soreness at both 24 h and 48 h after exercise-induced fatigue. These findings suggest that subjective measures of fitness and fatigue, assessed by a wellness questionnaire, are more sensitive to acute exercise-induced fatigue than variables associated with the countermovement jump.

8.1.2.2 Practical applications (Study Two)

These results imply that monitoring systems should include a subjective wellness questionnaire to measure the athlete's subjective fitness and fatigue status. Although no changes were detected in any countermovement jump variables in this study, there is enough evidence to show it should still be considered as a marker of neuromuscular performance. Variables such as maximum force, jump height and flight time seem to be the most appropriate variables to use from the countermovement jump test.

Moreover, it may be argued that athletes' subjective feelings of readiness-to-train differs to their actual physiological readiness-to-train. It seems prudent to conclude that both these subjective and objective markers provide information the support staff can use to better manage their players.

8.1.3 Question 3

What are the intra-individual relationships between variables associated with training load, wellness, and neuromuscular performance in female athletes in a real-world elite level sporting environment?

A detailed analysis of various intra-individual relationships of each monitoring tool were explored in Chapter Six. These results can translate into practical value for support staff managing the players' readiness-to-train

8.1.3.1 Answer to Question 3

The main outcome of this study was that the relationship between variables differed between players. Countermovement jump variables such as jump height and maximum force seem to be good markers of an athletes' neuromuscular performance or status. Subjective measures of fitness and fatigue (wellness questionnaires) had significant correlations with RPE and training load, in various individual players and should be considered when establishing a monitoring system in team sports. The differing nature of individual responses to monitoring variables, suggests that 1) each individual adapts differently to external and internal loads, 2) each individual responds differently to monitoring tools, and 3) monitoring data should be interpreted on an individual athlete level.

8.1.3.2 Practical applications (Study Three)

Support staff working with elite level athletes should choose their monitoring variables carefully. They need to understand the responsiveness of the measure at the group level, and on an individual athlete level. When considering monitoring neuromuscular performance under the conditions of the study, the preferred variables of a countermovement jump are jump height and maximum force. Furthermore, subjective responses to wellness questions should be implemented to gain deeper insight into an athlete’s subjective readiness-to-train. Data obtained from GPS, such as total distance, bodyload and high intensity efforts are important to consider as part of a holistic monitoring system. These data will allow for accurate quantification of external load. In conditions where GPS wearables are not available, RPE and subjective training load data should be used to quantify internal and external training load.

8.1.4 Question 4

How can monitoring data be used to inform decision-making before, during and after match play in elite level female field hockey players?

The intra-individual relationships between various monitoring tools before, during and after match play are explored in Chapter Seven.

8.1.4.1 Answer to Question 4

There were two primary aims of this study; 1) which monitoring tools are best suited for pre-match, intra-match and 24 h post-match, and 2) what is the intra-individual responsiveness to these markers of training status?

For a few players both jump height and maximum force measured before the match had an association with their match outputs. Thus, its plausible to suggest that understanding a player’s pre-match neuromuscular status may prove valuable to support staff working in team sports. RPE and training load measured post-match are valid and reliable surrogates to quantify match demands. Bodyload and total distance should be considered to quantify intensity and load of match play. Jump height as a marker of neuromuscular status 24 h post-match is recommended.

8.1.4.2 Practical applications (Study Four)

Team support staff working with elite athletes should consider using pre, intra and post-match play monitoring strategies to better understand a player's fitness and fatigue status. This should be done on a whole group basis and at an individual level. Players showing signs of impaired performance or lack of recovery after the match can be managed appropriately. The novel concept of "monitoring specificity" is important to consider. Understanding which measurements are most appropriate for each player will reduce the "noise" around the measurement and provide more information about the training status of each individual. Thus, the implementation of a monitoring system that includes the variables motioned above (in the answer to Question 4) should be considered.

8.2 Thesis closing statement

As stated earlier in this thesis, there is a fine balance between fitness and fatigue in elite sporting environments. A well-designed monitoring system should gather information about training load and recovery of each player so their readiness-to-train can be managed. This thesis confirms the notion that there is no single marker that can be used to better understand the delicate relationship between fitness and fatigue. It follows that monitoring systems should be more holistic in nature, including a variety of subjective and objective markers.

Most importantly, the novel concept of “monitoring specificity” suggests that variables representing fitness and fatigue should be specifically selected, and data should be analysed and interpreted at an individual athlete level. Refining athlete monitoring systems to the level of intra-individual relationships between training demands and monitoring variables; 1) reduces the noise that may be associated with the variable, 2) provides a deeper understanding of each player’s fitness and fatigue relationship, and 3) allows for a comparison to be made between individual players and the whole group. This strategy improves the chances of identifying responders and non-responders in the team. A summary of the flow of data collection and decision-making conceptual model for effective monitoring is shown in FIGURE 8.1 below. In this figure, the concept of “When to Push” or “When to Pull”[138] is introduced. This concept simplifies the message derived from the monitoring and translates the message into an action. For example, when the athlete is experiencing decrements in any one or more of the monitoring parameters, it would be advisable that certain modifications (e.g., decrease in training intensity or load) are made to their subsequent training sessions. However, when they are showing positive adaptations in both their subjective and objective measures, it may be plausible to increase their load and intensity to take advantage of their “primed” state of readiness[138].

In closing, this thesis provides the novel concept of “monitoring specificity” integrating a deeper understanding of the importance of intra-individual relationships between fitness and fatigue and monitoring variables. The information that has been presented allows coaches, sports scientists, and athletes to better understand the process of monitoring at a more intricate individual level. Variables such as jump height, maximum force, wellness questionnaires, total distance, bodyload, RPE and training load should all be considered as part of a holistic approach to monitoring athlete readiness and maximising performance. It is important to consider that “real-world” decision-making should be based on principles of evidence-based best practice. For example, a non-significant finding may not automatically suggest that the strategy used is not useful in a particular setting. Therefore, it is suggested that each team do their due diligence in identifying the most effective monitoring strategies within their team environment. Research such as this study will help practitioners decide on the variables that should be included in a holistic monitoring system.

Finally, considering the principle of “Theory reductionism”, it can be suggested that older monitoring strategies should not necessarily be replaced by newer systems[72]. But rather through refining and a better understanding of which “system” fits better into which context, and which relationships explain which outcomes, support staff are able to see the whole “picture” and understand the individual contributions within these relationships.

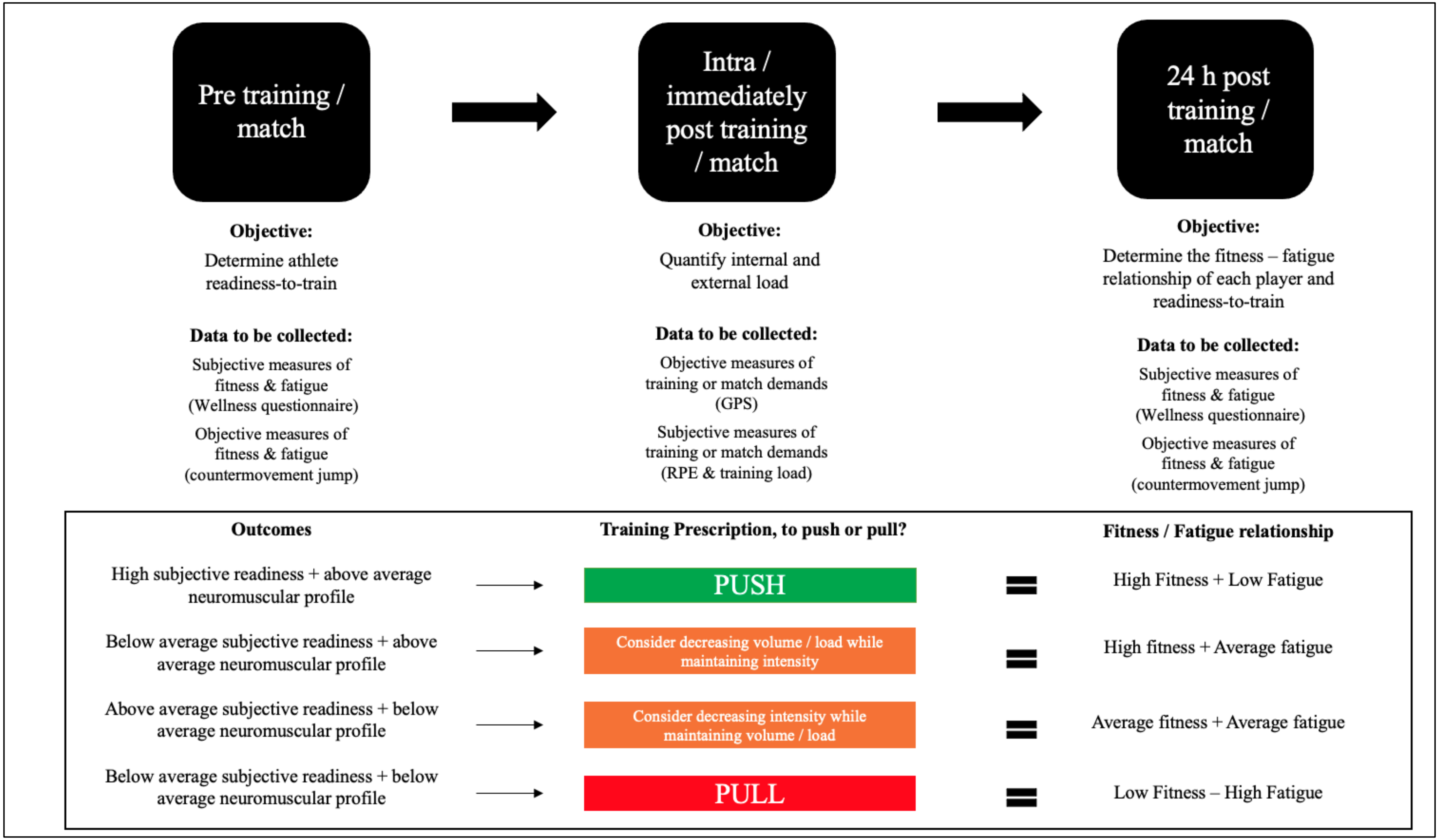

FIGURE 8.1: Monitoring data collection flow and decision-making conceptual model. The model conceptualises the possible monitoring data outcomes to decisions made on training prescription based on the monitoring data as well as the possible fitness – fatigue relationships associated with each.

9. Chapter Nine

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10. Chapter Ten

Appendices

10.1 Appendix 1: Study One & two

American Heart Association (AHA) / American College of Sports Medicine ACSM) Health/Fitness Facility Pre-participation Screening Questionnaire*

Asses your health needs by marking all *true* statements

History

You have had:
__ a heart attack
__ heart surgery
__ cardiac catheterisation
__ coronary angioplasty (PTCA)
__ pacemaker/implantable cardiac defibrillator/rhythm disturbance
__ heart valve disease
__ heart failure
__ heart transplantation
__ congenital heart disease

Symptoms

__ You experience chest discomfort with exertion
__ You experience unreasonable breathlessness
__ You experience dizziness, fainting, or blackouts
__ You take heart medications.

Other health issues

__ You have diabetes.
__ You have asthma or other lung disease.
__ You have burning or cramping sensation in your lower legs when walking short distances.
__ You have musculoskeletal problems that limit your physical activity
__ You have concerns about the safety of exercise.
__ You take prescription medication(s).
__ You are pregnant.

If you marked any of the statements in this section, consult your physician or other appropriate health care provider before engaging in exercise. You may need to use a facility with a ***medically qualified staff***

Cardiovascular Risk Factors

__ You are a man older than 45 years.
__ You are a woman older than 55 years, have had a hysterectomy, or are postmenopausal.
__ You smoke, or quit smoking within the previous 6 months.
__ Your blood pressure is > 140/90 mm Hg.
__ You do not know your blood pressure
__ You take blood pressure medication.
__ Your blood cholesterol level is > 200 mg/dL.
__ You do not know your cholesterol level
__ You have a close blood relative who had a heart attack or heart surgery before age 55 (father or brother) or age 65 (mother or sister).
__ You are physically inactive (i.e., you get < 30 minutes of physical activity on at least 3 days per week)
__ You are > 20 pounds (9.07185 kg) overweight.

If you marked two or more of the statements in this section, you should consult your physician or other appropriate healthcare provider before engaging in exercise. You might benefit by using a facility with a professionally qualified exercise staff to guide your exercise programme.

__ None of the above is true.

You should be able to exercise safely without consulting your physician or other appropriate health care provider in a self-guided programme or almost any facility that meets your exercise programme needs.

Participant name:	
Signature	Date

10.2 Appendix 2: Study One & Two

Wellness Questionnaire

1) **Did you train yesterday?**
    - **a.** Yes
    - **b.** No

2) **Do you feel physically strong today?**
    - **a.** Strongly agree
    - **b.** Agree
    - **c.** Undecided
    - **d.** Disagree
    - **e.** Strongly disagree

3) **Do you feel mentally strong today?**
    - **a.** Strongly agree
    - **b.** Agree
    - **c.** Undecided
    - **d.** Disagree
    - **e.** Strongly disagree

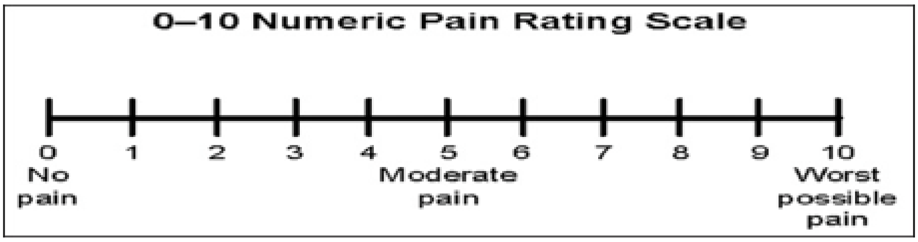
4) **How would you describe your health today?**
    - **a.** Excellent
    - **b.** A little off (but I can still train)
    - **c.** Poor (I don't think I can train)
    - **d.** Very poor (I should see a doctor)

5) **How would you describe your appetite over the past 24h?**
    - **a.** Extremely hungry
    - b. Hungry
    - **c.** Normal
    - **d.** Eating less than normal
    - **e.** Not hungry

6) **How, would you describe your sleep quality over the past 24h?**
    - **a.** Great
    - **b.** Good
    - **c.** Average
    - **d.** Poor

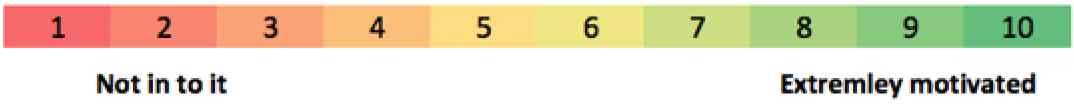
7) **Do you have any muscle soreness today?**
   a. No
   b. Yes
      If yes, please specify:

If yes, please specify and rate the severity of muscle soreness according to the below scale:



- Quads ____________
- Hamstrings ____________
- Calves ____________
- Glutes ____________

8) **Rate your motivation to train today.**



10.3 Appendix 3: All Studies

INFORMED CONSENT FORM

University of Cape Town / Hockey India database

UCT Division of Exercise Science and Sports Medicine
Department Of Human Biology, Faculty of Health Sciences
University Of Cape Town

Dear Athlete,

During the course of your training and competition, information is collected regarding your total exercise time, intensity, load, strength, fitness, recovery, injuries etc. We are requesting your permission to store this information in a database, which may be used at some time in the future for research purposes. The specifics of the research have not been established at this time.

Why is this database being formed?

Your data might provide researchers with important information relating to hockey performance and the health and safety of players and potential ways in which performance, health and safety might be improved.

What will happen if you participate?

Your information (as described above) will be stored in an electronic database. Your participation in this database will not influence how the information is collected or stored by the team during their routine duties. It will also not influence your training or medical treatment in any way whatsoever. From time to time when a specific research study is designed and approved by the UCT Human Research Ethics Committee (HREC), relevant information from the database relating to your training or any injuries you have sustained may be extracted.

How your data will be shared with researchers:

When data is requested for a specific research project, a researcher will access your records and copy the important information relating to the study by filling in a research form or by copying this data into another electronic format such as an Excel spread sheet or similar document. During the transfer of this information your name and any details, which could identify you, will be removed from the data.

What will happen to my data and test results?

All information that is extracted from the database for research will remain confidential.

You retain the right at all times to request that your data be removed from the database.

All data that are extracted for research projects will be stored in a single password protected electronic database for a period of 48 months after which it will be erased.

Will you receive any reward for taking part in this database?

There is no financial compensation for sharing your data in this database. However, any research studies generated from the database may improve coaching and medical management of hockey participants around the World.

What happens if I refuse to take part?

You are under no obligation to take part. If you decide not to take part, you will not be penalised.

What if something goes wrong?

There will not be any expected adverse effects as this study will only be an observation and will not affect any activities that you perform with the club on a daily basis.

Questions or Concerns:

If at any time you have any questions about the database, please feel free to contact any of the individuals listed below. You are assured that all inquiries will remain confidential.

Professor Mike Lambert

Physical Address:Sports Science Institute South Africa

Boundary Road, Newlands

Tel number: 021 650 4558

Email: mike.lambert@uct.ac.za

Professor Marc Blockman

Chairperson, Faculty of Health Sciences Human Research Ethics Committee, University of Cape Town

Tel number: (021) 4066492

E-mail: marc.blockman@uct.ac.za

By placing your signature below, it serves as confirmation that you have had adequate time to read through this information, that you have understood the consent form and that you are willing to participate in sharing your information with this database. You have the right to withdraw at any time and you may ask questions at any time. All information removed from the database for research will remain confidential, and you will not be identified in any research that is published. Your signature is confirmation that you have read this informed consent and agree to participate in this database and any research study that might be generated from this.

______________________	______________________	_______________
Signature	Name (Please Print)	Date

10.4 Appendix 4: Study One

UNIVERSITY OF CAPE TOWN
Faculty of Health Sciences
Human Research Ethics Committee

Room E52-24 Old Main Building
Groote Schuur Hospital
Observatory 7925
Telephone [021] 406 6338 • **Facsimile** [021] 406 6411
Email: nosi.tsama@uct.ac.za
Website: www.health.uct.ac.za/fhs/research/humanethics/forms

13 July 2017

REF NO: R024/2017

Mr W Lombard
Division of Exercise Science & Sports Medicine
3rd Floor, SSISA
Boundary Road
Newlands

Dear Mr Lombard

PROJECT TITLE: Hockey Indian, Senior Women's Team

Thank you submitting your registry to the Faculty of Health Sciences Human Research Ethics Committee for review.

The HREC has **approved** the registration of your registry.

Please Note: All research, including that undertaken for a master's or doctoral degree, using registered databases, registries and repositories, requires submission as a new study. It requires an application form (FHS013) and a protocol which has undergone departmental review. The study will receive its own HREC REF number which will be linked to the main database or repository.

The registration of this database is valid until **28 July 2020**

Please quote the HREC reference number in all your correspondence.

Yours sincerely

Signature Removed

PROFESSOR M BLOCKMAN
CHAIRPERSON, FHS HUMAN RESEARCH ETHICS COMMITTEE

10.5 Appendix 5: Study Two

UNIVERSITY OF CAPE TOWN
Faculty of Health Sciences
Human Research Ethics Committee

Room E52-24 Old Main Building
Groote Schuur Hospital
Observatory 7925
Telephone [021] 406 6492 • **Facsimile** [021] 406 6411
Email: Sumayah.ariefdien@uct.ac.za
Website: www.health.uct.ac.za/fhs/research/humanethics/forms

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04 June 2015

HREC/REF: 282/2015

Prof M Lambert
Human Biology
Exercise Science and Sports Medicine
Newlands

Dear Prof Lambert

Project Title: THE EFFECTS OF EXERCISE INDUCED NEUROMUSCULAR FATIGUE ON RATE OF FORCE DEVELOPMENT, HEART RATE RECOVERY AND A SUBJECTIVE READINESS-TO-TRAIN SCORE: A NOVEL PROTOCOL IN MONITORING TRAINING STATUS? (Sub-study linked to 281/2014) PhD candidate Mr W Lombard

Thank you for your response letter dated 01 June 2015, addressing the issues raised by the Human Research Ethics Committee (HREC).

It is a pleasure to inform you that the HREC has **formally approved** the above mentioned study.

Approval is granted for one year until the 30 June 2016.

Please submit a progress form, using the standardised Annual Report Form, if the study continues beyond the approval period. Please submit a Standard Closure form if the study is completed within the approval period.

We acknowledge that the following student:-Wayne Lombard is also involved in this project.

Please note that the on-going ethical conduct of the study remains the responsibility of the principal investigator.

Please quote the HREC REF in all your correspondence.

Yours sincerely

Signature Removed

PROFESSOR M BLOCKMAN
CHAIRPERSON, HSF HUMAN ETHICS

Hrec/ref: 282/2015

10.6 Appendix 6: Study Three & Four

APPENDIX A

UNIVERSITY OF CAPE TOWN
Faculty of Health Sciences
Human Research Ethics Committee

Room E52-24 Old Main Building
Groote Schuur Hospital
Observatory 7925
Telephone [021] 406 6338 • **Facsimile** [021] 406 6411
Email: nosi.tsama@uct.ac.za
Website: www.health.uct.ac.za/fhs/research/humanethics/forms

13 July 2017

REF NO: R024/2017

Mr W Lombard
Division of Exercise Science & Sports Medicine
3rd Floor, SSISA
Boundary Road
Newlands

Dear Mr Lombard

PROJECT TITLE: Hockey Indian, Senior Women's Team

Thank you submitting your registry to the Faculty of Health Sciences Human Research Ethics Committee for review.

The HREC has **approved** the registration of your registry.

Please Note: All research, including that undertaken for a master's or doctoral degree, using registered databases, registries and repositories, requires submission as a new study. It requires an application form (FHS013) and a protocol which has undergone departmental review. The study will receive its own HREC REF number which will be linked to the main database or repository.

The registration of this database is valid until **28 July 2020**

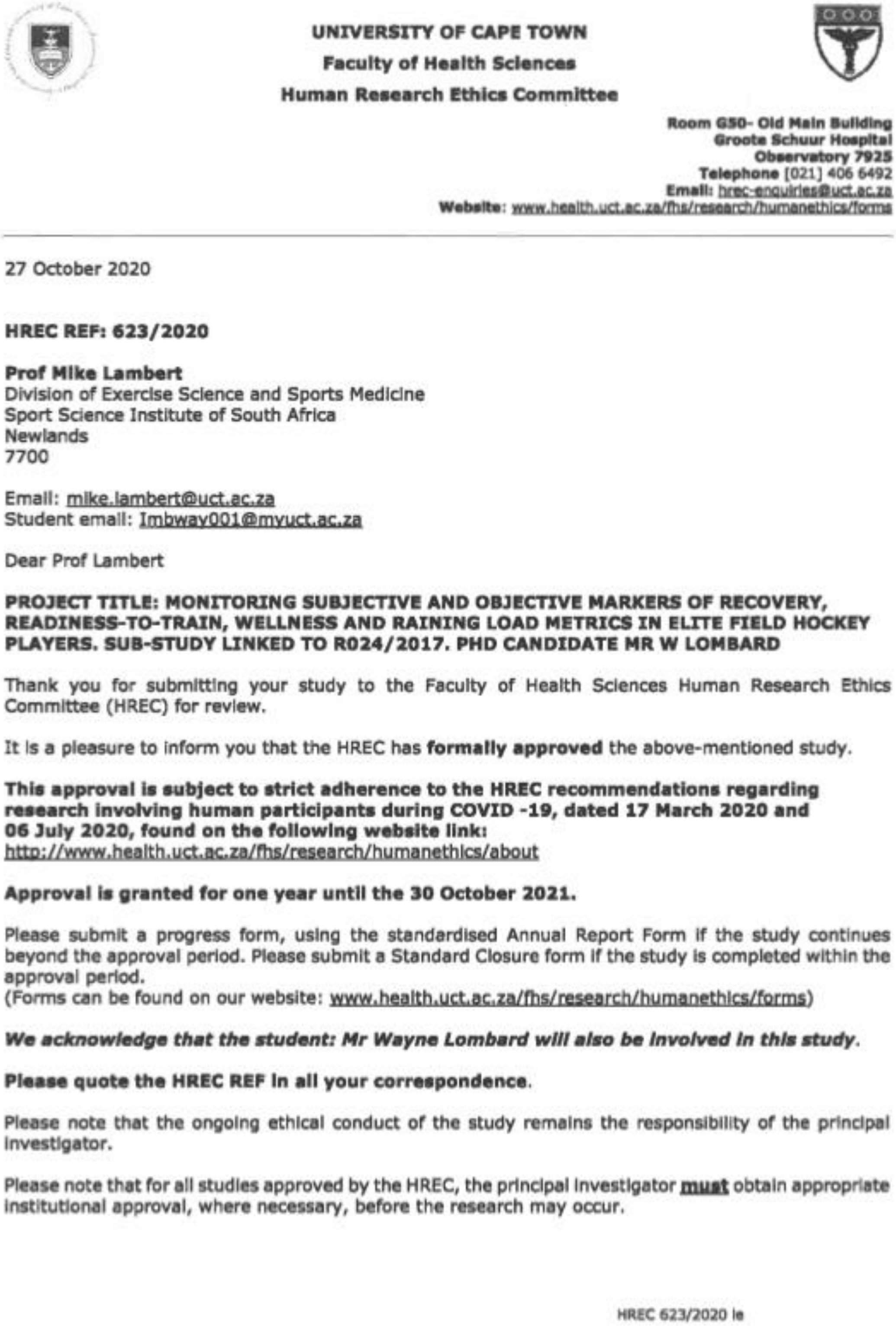
Please quote the HREC reference number in all your correspondence.

Yours sincerely

Signature Removed

PROFESSOR M BLOCKMAN
CHAIRPERSON, FHS HUMAN RESEARCH ETHICS COMMITTEE

10.7 Appendix 7: Study Three & Four



UNIVERSITY OF CAPE TOWN
Faculty of Health Sciences
Human Research Ethics Committee

Room G50- Old Main Building
Groote Schuur Hospital
Observatory 7925
Telephone [021] 406 6492
Email: hrec-enquiries@uct.ac.za
Website: www.health.uct.ac.za/fhs/research/humanethics/forms

27 October 2020

HREC REF: 623/2020

Prof Mike Lambert
Division of Exercise Science and Sports Medicine
Sport Science Institute of South Africa
Newlands
7700

Email: mike.lambert@uct.ac.za
Student email: lmbway001@myuct.ac.za

Dear Prof Lambert

PROJECT TITLE: MONITORING SUBJECTIVE AND OBJECTIVE MARKERS OF RECOVERY, READINESS-TO-TRAIN, WELLNESS AND RAINING LOAD METRICS IN ELITE FIELD HOCKEY PLAYERS. SUB-STUDY LINKED TO R024/2017. PHD CANDIDATE MR W LOMBARD

Thank you for submitting your study to the Faculty of Health Sciences Human Research Ethics Committee (HREC) for review.

It is a pleasure to inform you that the HREC has **formally approved** the above-mentioned study.

This approval is subject to strict adherence to the HREC recommendations regarding research involving human participants during COVID -19, dated 17 March 2020 and 06 July 2020, found on the following website link:
http://www.health.uct.ac.za/fhs/research/humanethics/about

Approval is granted for one year until the 30 October 2021.

Please submit a progress form, using the standardised Annual Report Form if the study continues beyond the approval period. Please submit a Standard Closure form if the study is completed within the approval period.
(Forms can be found on our website: www.health.uct.ac.za/fhs/research/humanethics/forms)

We acknowledge that the student: Mr Wayne Lombard will also be involved in this study.

Please quote the HREC REF in all your correspondence.

Please note that the ongoing ethical conduct of the study remains the responsibility of the principal investigator.

Please note that for all studies approved by the HREC, the principal investigator **must** obtain appropriate institutional approval, where necessary, before the research may occur.

HREC 623/2020 le

10.8 Appendix 8: Study Three & Four

Hockey India Wellness Questionnaire (Senior Women’s Team)

Please make sure you answer these questions each morning by the time you have finished breakfast.

It is important that you answer these questions honestly.

Make sure you answer each question with your own answer.

None of this data will be used against you but it is here to help me understand how you are adapting to the training.

1 **Player name:**

2. **What is your Body Weight this Morning? (Before Breakfast)** *

3 **Do you have any of these symptoms of illness this morning?** * *Mark only one oval.*

Headache
Sinusitis
Sore Throat
Flu / Cold
Nausea / Vomiting
Diarrhoea
Fever
Urinary problems
Cough
None of the above

4. **How TIRED (FATIGUED) are you feeling this morning?** * *Mark only one oval.*

   Extremely tired
   More tired than normal
   Normal
   Fresh
   Very fresh

5. **How STRESSED are you this morning?** * *Mark only one oval.*

   Very stressed
   Somewhat stressed
   Normal
   Relaxed
   Very relaxed

6. **On a scale of 0 - 5 do you have any general MUSCLE SORENESS (0 = No Soreness; 5 = Extreme Muscle Soreness)** * *Mark only one oval.*

   0 1 2 3 4 5

7 **Any specific MUSCLES that are SORE? Only select the areas that are most sore.** *Mark only one oval per row.*

	Very sore (5)	Sore (4)	Some muscle soreness (3)	Normal (2)	No muscle soreness (1)
Neck	○	○	○	○	○
Shoulder	○	○	○	○	○
Upper Back	○	○	○	○	○
Lower Back	○	○	○	○	○
Glutes	○	○	○	○	○
Hamstrings	○	○	○	○	○
Adductors	○	○	○	○	○
Quad	○	○	○	○	○
Hip Flexor	○	○	○	○	○
Calves	○	○	○	○	○

8. How well did you SLEEP last night? (Sleep Quality)

Very restless (> 4 hours)
Restless (> 6 hours)
Difficulty falling asleep (6 hours)
Good (> 6 hours)
Very restful (> 8 hours)

9. **How would you describe your MOOD this morning?** * *Mark only one oval.*

   Very annoyed and down

   Irritable

   Less interested than usual

   Positive

   Very positive

10. **How RECOVERED are you feeling this morning?** * *Mark only one oval.*

    Not recovered at all

    Partially recovered

    Recovered

    Fresh

    Very fresh

11 **How MOTIVATED are you to train this morning?** * *Mark only one oval.*

   Not at all

   Less than normal

   Normal

   Motivated

   Very motivated