Force-time analysis of the countermovement jump as an indicator of fatigue status in professional academy footballers

A Thesis Submitted for the Degree of Master of Philosophy

By

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Abstract

Purpose: A by-product of the greater financial rewards in elite football is that teams have tended to increase the volume and frequency of their physical training. To reduce the risk of injury and overtraining in players, football coaches need accurate, easy-to-use, and time-efficient monitoring tools for measuring the physical condition of the player. Vertical jump tests are commonly used to determine the player's neuromuscular fatigue status. However, it is suspected that some skilled players can modify their jumping technique to maintain jump height even when fatigued. Therefore, variables from a jump test other than jump height might be more sensitive indicators of the player's fatigue state. The aim of this study was to identify the jump metrics that are most sensitive to the delayed neuromuscular fatigue induced by a competitive football match.

Methods: This study used a quasi-experiment design with a linear regression analysis of the individual player. Twenty male elite academy footballers performed countermovement jump tests the day before and two days after a competitive match for 20 consecutive weeks during the competition season. After exclusion, data from eight participants were used for the analysis. Seven jump variables related to jump height and jumping technique were selected for analysis. The physical match load variables, very high-speed running and high-intensity decelerations, were plotted separately against the change in each jump variable due to the match. Following an initial visual analysis, a linear regression fit to the data was used to determine the strength of the relationships.

Results: Jump height and other countermovement jump variables showed no significant findings when assessing the change from pre- to post-match and there were no universally consistent relationships between the change in a jump variable and the physical match load on a player. Multiple individual differences were observed in the strength of the associations and the direction of these relationships between the jump variables and match load.

Conclusion: The absence of statistically significant changes of the countermovement jump variables used in the study suggest that they are not sufficiently sensitive measures to indicate neuromuscular fatigue. However, large individual differences suggest that coaches could utilise countermovement jump monitoring to inform on the altered movement strategy used in the presence of neuromuscular fatigue on an individual level.

List of figures

Figure 1. Taken from Knicker et al. (2011). The three levels of fatigue assessment.

Figures 2-6. Plot of match fatigue against match load using some standard values.

Figure 7. Example image of the position of the GPS tracking device on a participant**.**

Figure 9. Magnitude of change from pre-match matchday -1 and post-match matchday +2 (mean and standard deviation) for countermovement depth (top) and jump height (bottom). Black lines represent the responses from each participant (n=8).

Figure 10. Effect size (with confidence interval) for all countermovement jump variables between pre-match matchday -1 and post-match matchday +2 results. Small effect size thresholds are represented as dashed lines.

Figure 11. Graphical representation of the relationship between change in countermovement depth and jump height plotted against both physical match load variables. Each graph shows a line of best fit and 95% confidence intervals (dotted lines). Signal-to-noise ratio is shown on the graph. Each data point represents a participant (n=8).

Figure 12. Participant 1: Plots of all relationships between the physical load variables and the countermovement jump variables. The solid line is a linear regression fit and the dashed lines show the 95% confidence intervals. Only the relationship between countermovement depth and high intensity decelerations had a signal-to-noise ratio (SNR) of greater than ±1.0.

Figure 13. All participants: Plots for relationships between a match load variable and countermovement depth and eccentric mean braking force in which the signal-to-noise ratio was greater than ±1.0. The solid line is a linear regression fit and the dashed lines show the 95% confidence intervals.

List of tables

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Chapter 1: Introduction

1.1 Rationale for the Research

In a football match, the players perform many eccentric actions which can cause muscle damage that lasts for three to five days after the match (Andersson et al., 2008; Bangsbo et al., 2006). Given that players typically play matches interspersed by five to seven days with additional training in between, the reported negative effect on performance in response to match load (as a result of neuromuscular fatigue) can impair physical performance during subsequent training and matches and increase the risk of injury (Cormack et al., 2013; Silva et al., 2014; Thorpe et al., 2015). Therefore, it is important that players are given sufficient time to recover from the potential multiple micro-traumas to muscles and tendons, and the significant metabolic and neuromuscular strain placed upon the players from training and competition, as extended periods of overtraining can cause poor performance and longer term debilitating effects (Nimmo & Ekblom, 2007).

Subsequently, coaches and sport scientists require sensitive and time-efficient performance-related screening batteries to measure fatigue status. This information is important to be able to inform the coach in the decision-making process regarding individual player programmes to design recovery strategies, to plan appropriate training post-match to prepare the player for the following match and to decide when a player is ready to resume full training. Therefore, increasing attention has been given to evaluating the sensitivity of fatigue-monitoring tests to determine the most efficient testing modalities to inform on a players recovery status or readiness to train (Gathercole et al., 2015a).

Assessment of neuromuscular function via various jump tests to measure fatigue status has been widely employed within team sports due to the specificity of the test activity and the applicability of the recorded measures to performance (Coutts et al., 2007; Twist et al., 2012). The countermovement jump has been reported as a practical athlete monitoring tool, with high practicality and low physiological strain, which allows for a time-efficient examination of neuromuscular fatigue on multiple athletes. The height obtained from a countermovement jump is commonly used in team sports as an objective marker to monitor neuromuscular fatigue due to the transition from eccentric to concentric muscular contraction utilising the stretch-shortening cycle during a multi-joint activity (Kennedy &

Drake, 2017). However mixed results have been disseminated in the literature regarding which countermovement jump variables are more sensitive to neuromuscular fatigue. The sensitivity of traditional metrics obtained from a countermovement jump such a vertical jump height and peak power to inform on fatigue status remain equivocal (Andersson et al., 2008). Previous research has observed small, non-significant correlations between high-intensity running distance during training and matches over a week and jump height performance from elite football players (Thorpe et al., 2015). These findings could be indicative of the limitations of using jump height from a countermovement jump as a daily monitoring tool of fatigue status. It is possible that using the performance-related variables in multi-joint activities as a measure of neuromuscular function may be insensitive to neuromuscular fatigue as well-trained performers are able to apply compensatory mechanisms which allow them to achieve the same performance outcome irrespective of fatigue status. Modifications to jump mechanics following fatiguing exercise may represent a change in the force or time properties during the eccentric phase of the countermovement jump in the absence of significant changes in jump height (Cormack et al., 2008a; Gathercole et al., 2014). Gathercole et al. (2014) also suggested that observing the mechanics of a countermovement jump may provide insight into the eccentric loading strategy, which is typically overlooked in traditional countermovement jump analysis. The eccentric phase of the countermovement jump may be of interest in fatigue monitoring in football as a result of the aforementioned high amount of eccentric actions and stretch shortening cycle movements performed during a match. These actions cause a significant amount of the muscle damage and can impair performance in subsequent tasks requiring eccentric muscular contraction (de Hoyo et al., 2016; Komi, 2000)

The subsequent fatigue related to using the stretch-shortening cycle and neuromuscular function during athletic performance may be related to a number of peripheral and central fatigue processes. The complexity of neuromuscular fatigue is also evident from previous literature reporting that some countermovement jump variables may be indicative of improved neuromuscular function in a fatigued condition (Boullosa et al., 2011; Cormack et al., 2008a; Johnston et al., 2013). This may in part be as a result of the bi-phasic nature of the recovery process following physiological disturbance during exercise, which suggests that neuromuscular function immediately decreases after fatiguing exercise, which recovers towards baseline within hours post-exercise, and then decreases again before returning to baseline around four to eight days after the fatiguing exercise (Komi, 2000; Nicol et al., 2006).

Changes to the ground reaction force profile during a physical task in response to neuromuscular fatigue is yet to be fully understood. Gathercole et al. (2015b) recommended that practitioners should assess a full battery of countermovement jump variables to assess neuromuscular fatigue, due to significant individual variability observed in the response to fatigue and subsequent recovery profile in response to fatigue. However, quick decisions are required to be made to help the coaches make informed decisions on player training availability. Ultimately, for practical use the analysis of neuromuscular function needs to show sensitivity to fatigue and be time-efficient to allow for a whole squad to be monitoring over regular time periods. Therefore, further clarity is required in determining whether and which jump metrics are sensitive to fatigue as a result of a competitive football match, and whether individual differences exist in the response of a jump variable to the physical load on the player.

1.2 Aims

Much research has focussed on determining key variables within the force-time curve of the countermovement jump test to inform on player readiness and fatigue. Jump height is a commonly used variable to inform on player readiness or fatigue due to its time-efficiency and practicality to use with large numbers in a squad and low physiological cost. In addition, it replicates the stretch-shortening action apparent in the high-intensity actions performed in a football match and may therefore be useful to inform on the detriments in physical performance associated with neuromuscular fatigue. However, previous literature has reported that the use of jump height during a countermovement jump test may not be a sensitive measure of fatigue status, as well-trained athletes can alter their jump mechanics to maintain the same output. There is controversy in the literature regarding which variables of the force-time curve is best representative of fatigue. There is some evidence that suggest technique variables in the downward countermovement or ‘eccentric’ phase of the countermovement jump might be more sensitive to neuromuscular fatigue (Gathercole et al., 2015b).

Practitioners and researchers are interested in identifying the countermovement jump variables which are the most sensitive index of fatigue following a competitive football match. To this end, in the current study jump variables obtained from the vertical ground reaction force of a countermovement jump were measured before and after a match to determine the magnitude of the change induced by a match. It was hypothesised that a greater physical load during a football match would induce a greater neuromuscular fatigue and cause a player to alter their jump mechanics to obtain the same jump height. Therefore, the aim of this study was to determine which jump variables are most sensitive to changes in match load following a competitive football match.

1.3 Organisation of the thesis

Chapter one outlines the overview of the thesis, introducing the specific aims to the research question and the motivations for why the answer to this question will add value to the current body of research and in practice. Chapter two forms the theoretical review of the literature. It will provide more detail for the rationale behind the study, assessing and critiquing the current research to understand why this research question fills a current gap in the literature. Chapter two will aim to provide the evidence on current fatigue monitoring tools, why they are used and the potential inefficiencies in the current methodology. Chapters three and four will outline the experimental procedures and analysis used to answer the research questions and report the results of the analysis. Chapters 5 and 6 conclude the thesis by discussing the results in relation to previous research and providing future direction on the research topic.

Chapter 2: Literature Review

2.1 Importance of neuromuscular testing in team sports

Team field sports such as football follow a schedule which comprises a nine-month season with matches usually being played at intervals of five to seven days. During training and matches there is significant stress placed upon the neuromuscular system from the metabolic disturbances and substrate utilisation associated with high-intensity exercise during training and competition (Bangsbo et al., 2006). The muscle soreness experienced by team sports players following high-intensity explosive actions with a rapid stretch-shortening cycle and eccentric muscular contractions, causes a substantial amount of neuromuscular fatigue and may lead to physical performance impairments that last several days (Barnett, 2006). Players are often subject to these repeated fatiguing exercise bouts which can result in functional overreaching and elicit super-compensatory mechanisms that improve physical performance (Osgnach et al., 2010). Experiencing fatigue may be a goal to drive adaptation, but repeated or excessive fatigue may lead to a state of non-functional overreaching. Non-functional overreaching is characterised by an imbalance between stress and recovery resulting in persistent decrements in performance lasting from weeks to months and contributing to long-term debilitating effects such as exercise-induced muscle injury (Matos et al., 2011; Nimmo and Ekblom, 2007). Therefore, given the high number of matches and busy game and training schedules of leading teams, the debilitating effects of fatigue on performance associated with overtraining and injury should be avoided.

2.2 Neuromuscular fatigue mechanisms

Fatigue is considered as a negative consequence following demanding physical exercise, and can manifest itself in physiological, perceptual and functional performance outcomes (Nédélec et al., 2012). Previous literature has reported significant underperformance in physical tests as a result of neuromuscular fatigue, including a reduction in maximum voluntary contraction, countermovement jump height and linear sprint speed that persist for up to 96 hours after exercise (Boullosa et al., 2011; Rodacki et al., 2002). Decrements in neuromuscular function may be indicative of marked changes in biochemical factors resulting from exercise-induced muscle damage. Fatigue is a complex phenomenon and has been subject to many different definitions within the scientific literature. Abbiss and Laursen (2007) suggested that the term fatigue is interpreted differently according to which discipline of sport science the research question is aimed at. These authors give an example of how fatigue may be defined within biomechanics, suggesting that fatigue is a reduction in the task efficiency and force output of a muscle group. Psychologists may interpret fatigue as a perception of fatigue and tiredness and a decrease in mental capacity and function. In addition, the physiology literature interpret fatigue as a limitation to a physical process or system, and neurology may see fatigue as a reduced motor drive or neural activation. Much of the literature surrounding neuromuscular fatigue in elite sport has discussed fatigue as the inability to complete a given task or performance output and has attempted to understand the response to exercise on a peripheral and central level.

2.3 Peripheral fatigue mechanisms

Peripheral fatigue reflects impairments in skeletal muscle function. Competitive match-play requires players to perform explosive actions such as sprinting, changing direction, jumping, kicking, decelerating and accelerating which can cause significant physiological disturbance (de Hoyo et al., 2016). These high-intensity actions demand muscular contractions that require ATP to be produced from non-aerobic fuel sources, and the subsequent acidosis seems to cause peripheral fatigue. However, recent studies have demonstrated that the accumulation of hydrogen ions and acidosis probably do not play a major role in fatigue (Cheng et al., 2018). The key mechanism is reported to be an inhibition of the sarcoplasmic reticulum release channels in releasing calcium ions, which reduces the force production capabilities of the cross-bridges. Key mechanisms reported for this inhibition include an accumulation of phosphate, a reduction in ATP coupled with an increase in ADP, and an accumulation of extracellular potassium reducing the excitability of the sarcolemma (Cheng et al., 2018; Keeton & Binder-Macleod, 2006). The accumulation of these fatigue mechanisms negatively influences the function of skeletal muscle and physical performance in the days after exercise. Football involves many high-intensity actions which often are required to be repeated and may occur in sequence, for example, a sprint into a quick deceleration, a change of direction and a subsequent re-acceleration into another sprint is often performed during the pressing movements to close down opposition attackers. At the peripheral level the discussed metabolic cost of this form of exercise causes changes in the musculature which can accumulate fatigue and inhibit performance up to 48 hours after fatiguing exercise (Cheng et al., 2018).

However, it seems that changes to the musculature as a result of the mechanical stress associated with eccentric contractions may be the key determinant of exercise-induced muscle damage (Peake et al., 2012). Eccentric contraction causes an over-stretching of the muscle sarcomeres causing sarcomere ‘popping’. Morgan (1990) characterised this ‘popping’ as an uncontrolled lengthening of the sarcomeres. As the muscle actively lengthens during eccentric contraction the sarcomeres extend to long lengths and the function of some of these overstretched sarcomeres significantly reduces, and as a result repeated eccentric action puts additional tension on neighbouring myofibrils causing significant disruption to the sarcomeres (Morgan, 1990). Sarcomere ‘popping’ has been reported to reduce muscle force production as a result of a loss in calcium ion homeostasis and excitation-coupling dysfunction, and a shift in active and passive tension properties associated with disruption of the sarcomeres. These are key peripheral mechanisms associated with muscle damage in the days following fatiguing exercise (Taylor et al., 2012a). The damage to the sarcomeres is at its greatest between one and three days following eccentric exercise and can still be elevated for eight days (Friden et al., 1983; Yu et al., 2004). The delayed recovery of peripheral mechanisms related to fatigue is reflected in the literature reporting that low frequency fatigue has long lasting effect on muscle force production, and seems to be affected in the hours and days following fatiguing exercise to a greater extent when compared to following a fatiguing intervention of simulated high frequency contractions (Edwards et al., 1977; Taylor et al., 2012b). In addition, low frequency fatigue is also characterised by a reduction in neural drive and heightened sense of effort during muscular contractions (Taylor et al., 2012b). It seems that low frequency fatigue may occur from the repeated eccentric actions performed during a competitive match and the mechanical stress on the contractile elements causes a reduction in force production which is apparent in the days following exercise.

2.4 Central fatigue mechanisms

Some of the scientific literature has questioned the importance of central mechanisms when discussing fatigue, suggesting that a reduction in muscular force output is a manifestation of physiological fatigue mechanisms within the musculature itself (Thomas et al., 2017). However, much of the previous fatigue research reports central and peripheral mechanisms to be at play, and it is likely that muscle performance declines as a result of the likely integration of both pathways (Knicker et al., 2011; Meeusen & Rowlands, 2018). It is suggested that muscle performance may become impaired due to an inhibited motor drive and a failure of the central nervous system to recruit motor units (central fatigue), with the build-up of metabolites within the muscle cell causing a reduction in muscular force output (peripheral fatigue; Knicker et al., 2011). The greater demand peripherally and higher central nervous system inputs create a sensation of fatigue, which increases the perception of effort during exercise (Keeton & Binder-Macleod, 2006). Several fatigue symptoms contribute to a decline in performance and these central and peripheral symptoms all occur simultaneously and interact. Nine processes have been reported to reduce muscle function during fatiguing exercise; reduced primary motor cortex activation, a reduction in central nervous system drive to the motor neurons, impairments in motor unit function, neuromuscular propagation, inhibited excitation-contraction coupling, reduced availability of metabolic substrates, an inefficiency in the intracellular milieu, impairment in the contractile apparatus and reduced muscle blood flow (Enoka, 2008; Taylor, 2012b). Therefore, it is proposed that fatigue is best explained globally from both central and peripheral viewpoints as a reduction in exercise and muscle performance.

2.5 Effects on performance

Neuromuscular fatigue involves many neurophysiological processes which contribute to changes in physical performance. It is best described as a reduction in maximal force capabilities of a muscle or a muscle group as a response to strenuous exercise, regardless of whether or not a given task can be maintained. Neuromuscular fatigue can impair the ability to produce maximal intensity actions specific to football, such us high-speed running, sprinting, accelerating and decelerating. Cormack et al. (2013) reported that neuromuscular fatigue results in more running at steady states or at lower speeds. This is as a result of a reduction in vertical acceleration, which is required for high-speed runs and quick changes of direction. Furthermore, the inability to maintain vertical acceleration can contribute to a change in running mechanics and style, which may reduce the efficiency of movement and elevate the metabolic demand for a given speed (McMahon et al., 1987). Cormack et al. (2013) also suggested that players in a fatigued state may adopt the ‘Groucho’ running pattern. This is characterised by an increase in knee flexion, where peak vertical ground reaction force is not modified. However, the inability of the neuromuscular system to maintain vertical stiffness and modifications to the spring mass system cause changes in the vertical displacement of the centre of mass and slower stride frequencies, thus reducing repeated sprint ability and the ability to accelerate and decelerate at speed (Girard et al., 2011a). Therefore, neuromuscular fatigue seems to manifest itself in modifications to optimal running style and vertical stiffness, which results in impaired physical outputs in a fatigued condition such as less high-speed running, less frequent changes of direction (Girard et al., 2011a; 2011b; Hobara et al., 2010), and an elevated oxygen cost associated with an inefficient running style (McMahon et al., 1987). This provides support for the concept that neuromuscular fatigue, either directly or indirectly, results in a decrement to physical performance. Therefore, the monitoring of fatigue and the implementation of suitable recovery strategies are essential to optimize the training stimulus, minimize unplanned fatigue and avoid maladaptation to avoid impairments in performance and reduce the risk of athletic injury (Cormack et al., 2013; Kellmann, 2010; Montgomery et al., 2010; Thorpe et al., 2017).

2.6 Neuromuscular testing

Many sports practitioners conduct daily tests to determine a player’s fatigue status objectively and subjectively (McGuigan, 2017). As previously discussed, neuromuscular fatigue can have a significant impact on subsequent physical performance and may also play a role in injury risk following strenuous exercise. In order to monitor neuromuscular fatigue, it is important to consider the processes of recovery and the time course in which they occur in order to set specific recovery programmes. Immediately after fatiguing exercise there is an observed decrease in performance, which recovers close to baseline after a few hours and then has a secondary decline in neuromuscular performance which returns to baseline within a few days. This response to neuromuscular fatigue is termed bi-phasic recovery (Komi, 2000; Nicol et al., 2006). This secondary decline is thought to be mediated by an inflammatory response to mechanical damage, which allows a return to pre-exercise levels of physiological markers or supercompensation, dependant on the type of exercise performed, within 48-72 hours (De Hoyo et al., 2016). Following simulated soccer match play, Howatson and Goodall's research group observed significant neuromuscular fatigue characterised by a significantly reduced maximal voluntary contraction during an isometric knee extensor task, which was still present at 72 hours after exercise (Brownstein et al., 2017; Thomas et al., 2017). The fatigue symptoms present were both central and peripheral in origin. During the recovery process, central fatigue, as determined by the recovery in voluntary activation of the quadriceps, contributed to a significant amount of neuromuscular fatigue immediately after exercise and the initial recovery of neuromuscular function in the hours post-exercise. However, the resolution of muscle function and force producing capabilities can persist for up to 72 hours after exercise. Therefore, the greater magnitude of peripheral fatigue and the longer period of recovery suggest that the neurophysiological processes associated with recovery from neuromuscular fatigue are primarily explained by peripheral mechanisms. The premise that neuromuscular fatigue in the days following fatiguing exercise is predominantly explained by the recovery of peripheral mechanisms has been substantiated in the literature (Fowles, 2006). However, Taylor (2012b) reported that changes in countermovement jump performance did not coincide with low frequency peripheral fatigue measures, and therefore, fatigue is best considered as a reduction in functional performance that occurs as a result of numerous neurophysiological mechanisms.

As discussed, the concept of exercise-induced fatigue is difficult to define, which makes the assessment of fatigue status and readiness to train also challenging (Abbiss & Laursen, 2007; Enoka & Duchateau, 2016; Taylor et al., 2012a). In practice, the operational definition of fatigue is often reported as if an athlete or player cannot sustain expected levels of physical, technical, decision making and psychological processes resulting in impaired performance (Knicker et al., 2011). Fatigue is and known to be task dependent with intensity and duration of contraction, speed of movement and type of muscle contraction in accordance with the demands of the sport and all influencing the magnitude and type of fatigued experienced (Enoka, 1992; Gathercole et al., 2015a). Effective monitoring requires valid, reliable and sufficiently sensitive tests to discern the functional changes that will impact performance. Therefore, the neuromuscular screening protocols should reflect the functional characteristics of the task completed (Kennedy & Drake 2017).

Knicker et al. (2011) suggested that fatigue can be assessed at three different levels (Figure 1). The model shows that the assessment of the specific sporting event or task provides the best indication of the result, with the result being whether a player is experiencing competition performance symptoms as a result of fatigue. Performance in the activity itself has been suggested to be the most sport-specific indicator of neuromuscular performance readiness. However, its longitudinal assessment can be impractical and may impede adaptation from undue fatigue (Gathercole 2015a). In addition, coaches require information on fatigue status prior to competition and games. Therefore, it suggests that in a team sport setting where squads of players need to be monitored on a daily basis, the assessments of the performance during sport event itself may be inefficient and impractical. As a result, coaches require variables which can provide an index of fatigue prior to competition, to inform on the potential presence of competition performance symptoms which may negatively effect the result or outcome of the sport event.

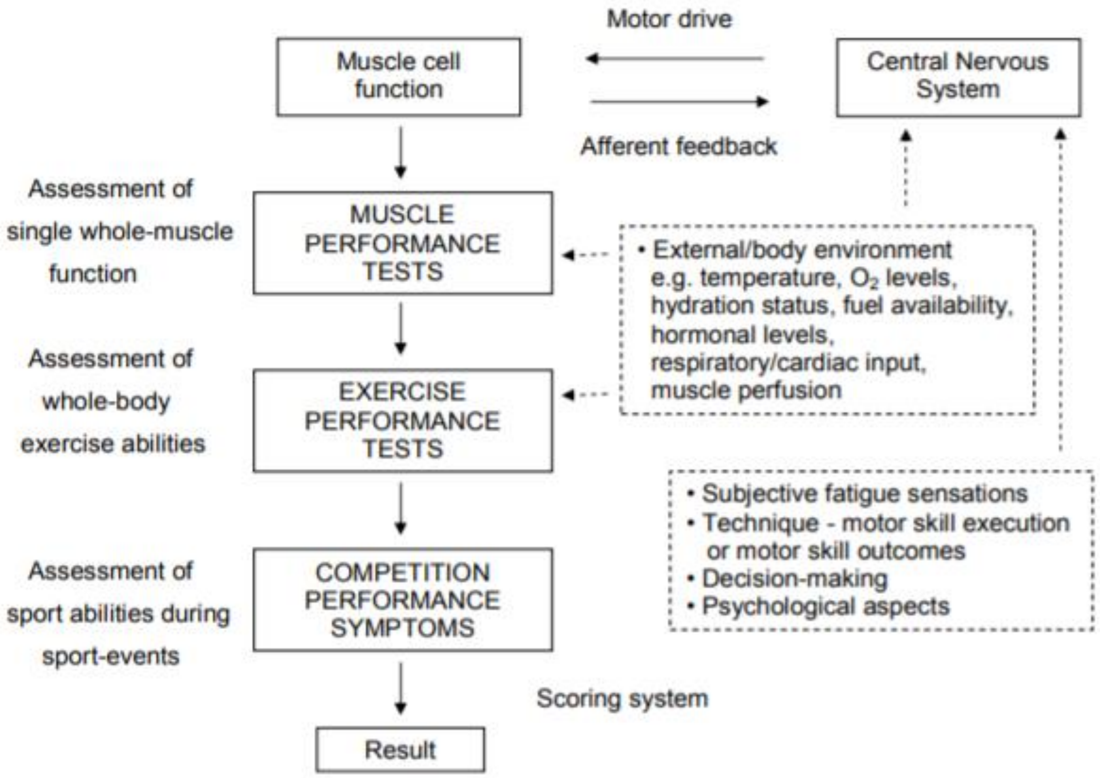


Figure 1. Taken from Knicker et al. (2011). The three levels of fatigue assessment.

The first level in the model is the assessment of single muscle function. This represents a reduction in single whole muscle function and performance as a result of a simultaneous deterioration in the force and power capabilities of several single muscle cells or motor units. Although this level of assessment gives a specific indication on the functionality and performance of a particular muscle, many practitioners question the relation to the output given in sport performance and require more understanding beyond the ‘reductionist approach’ of assessing isolated muscles (Bigland-Ritchie et al., 1986; Cairns et al., 2005). In addition, although isolated forms of muscle action have commonly been used because of the perception that high levels of repeatability can be achieved, these measures do not reflect the natural occurring stretch-shortening cycle used within most sports. Therefore, the use of exercise performance tests may be more appropriate.

A measure of stretch-shortening cycle function, such as a countermovement jump, may potentially provide a more suitable method to investigate neuromuscular function (Kennedy & Drake, 2017). The countermovement jump is easy to administer and causes little additional fatigue (Cormack et al 2013). Neuromuscular performance qualities of muscles have been shown to be similar in the vertical jump and running. Andersson et al. (2008) reported that following an elite women’s football match jump performance took the longest to recover back to pre-match baseline values (>69 hours), when compared with other neuromuscular fatigue markers, namely sprint performance (5h), quadriceps strength (27h) and hamstring strength (51h). Therefore, countermovement jump performance may be highly relevant for assessing various parameters important in sport where running is the chief component and practically important to assess fatigue to inform on complete recovery in the days after strenuous exercise (Cormack et al., 2008a).

2.7 Jump testing as a time-efficient practical assessment

Sports scientists and coaches require detailed information on readiness to train to inform on the most suitable training stimulus for each individual player in the days after a match. For example, the information from a neuromuscular function screening battery can be obtained to determine whether it is appropriate for the player to return to training or whether a player needs a modification in volume and/or intensity to their training programme in the days after a match in order to optimize their preparation of the next match.

Isoinertial testing, defined as the movement of a constant gravitational load, is considered one of the more valid forms of neuromuscular testing. A common method of monitoring fatigue status is the height achieved in a countermovement jump (Claudino 2017). For use in team sports, a countermovement jump is seen as a functional test as it involves the stretch-shortening cycle of the lower limbs similar to that in the running, cutting, and jumping actions required in football. In addition, a countermovement jump test can be administered in only a few minutes so a coach or trainer can test a whole squad in a relatively short time. A player’s jump height can be obtained with a force platform, jump mat, accelerometer, linear position transducer, optoelectronic device, jump-and-reach device, or video camera (McMahon 2018). The most accurate estimate of jump performance is obtained from the application of the impulse-momentum relation to the force-time data from a force platform (Linthorne 2001). A force platform is relatively expensive, but the force-time data obtained can be used to calculate the acceleration, velocity, and position of the jumper's centre of mass. Traces of many combinations of jump variables can then be generated and several other methods of estimating jump height can be calculated (Gathercole et al., 2015b; Meylan et al., 2011). A valid marker of recovery should be sensitive to variability in training and to match load. Consequently, research to date has evaluated the sensitivity of monitoring tools in response to changes in training load over an extended period of time (Thorpe et al., 2015). Previous literature has reported acceptable variation for numerous variables recorded during a countermovement jump performed on a force platform. Good overall reliability has been demonstrated in the countermovement jump flight time (CV; 1.9%), jump height (4%), peak power (6.1%), peak force (4%), mean force (2%), flight time: contraction time (8%) and eccentric duration (8%) (Cormack et al., 2008a; Edwards et al., 2018; Lombard et al., 2017; Mooney et al., 2013; Thorpe et al., 2015). Therefore, the use of the countermovement jump to monitor neuromuscular fatigue has been shown to produce reliable data to aid in informing individual player management.

The countermovement jump has been used in both acute settings (Cormack et al., 2008a; Gathercole et al., 2014; 2014b; McLellan et al., 2011) and chronic settings (Cormack et al., 2013; Cormack et al., 2008b; Coutts et al., 2008; McLean et al., 2010; Mooney et al., 2013) to infer on the response to training and fatigue-induced neuromuscular changes (Delextrat, Trochym & Calleja-Gonzalez, 2012; Gathercole et al., 2015a; Kennedy & Drake, 2017; Loturco et al., 2017; Nakamura et al., 2016a; Wiewelhove et al., 2015). Furthermore, countermovement jump testing is sensitive to detecting fatigue in team sport athletes immediately following a match, in the days after a match and during a competitive season (Cormack et al., 2008a; Cormack et al., 2008b; Johnston et al., 2013; McLean et al., 2010; McLellan et al., 2011). Measures of countermovement jump, reactive strength index from a drop jump and wellbeing were all sensitive to detecting post-match fatigue. However, countermovement jump height was sensitive to detecting accumulated fatigue over a seven-week period, whereas RSI and wellbeing were not (Oliver et al., 2015). Furthermore, studies have reported significant changes in jump height following a competitive football match and a simulated fatiguing protocol to replicate the neuromuscular load of a football match (Andersson et al., 2008; Hoffman et al., 2003; Oliver et al., 2008). From these studies it could be inferred that monitoring neuromuscular performance via the height achieved during a countermovement jump plays a critical role in maintaining and improving athletic performance. However, a lack of correlation between countermovement jump flight time measurement and physical match demands has been reported (Thorpe et al., 2015). In addition, Krustrup et al. (2010) observed no changes in jump height following a competitive football match, and Gathercole et al., (2015b) reported that changes in jump height following a fatiguing protocol were not greater than the observed error, suggesting that jump height is not recommended as an index of fatigue. Despite considerations that this may be due to weak association between vertical jumping and horizontal running performance (Shalfawi et al., 2011), and limitations to some of the above studies using a jump mat to collect data, other studies have shown the strong relationships between training and match load and countermovement jump performance and used force plates which provide more comprehensive understanding of neuromuscular function (Oxendale et al., 2016).

Interestingly, the inconsistency in the literature regarding jump height may be explained by the idea that low frequency fatigue may only account for small changes in jump height (Taylor et al., 2012b). Comparing the literature, Andersson et al., (2008) observed significant changes in neuromuscular (20-m sprint time, countermovement jump height, knee flexion and extension torque and muscle soreness) and biochemical measures (creatine kinase, UREA and uric acid) following a football match. In contrast, Gathercole et al., 2015b) observed significant changes greater than their error in five of the 22 variables monitored from a countermovement jump induced by a fatiguing protocol, with jump height remaining unchanged. It could be speculated that the competitive football match induced a significant amount of neuromuscular fatigue to significantly change jump height and all of the other neuromuscular and biochemical markers, whereas the protocol used by Gathercole et al. (2015b) may not have induced significant neuromuscular fatigue to significantly change jump height, and may have induced low frequency neuromuscular fatigue often observed following fatiguing exercise involving repeated eccentric actions, which can be present up to 72 hours post-exercise and may not a significant contributor for changing jump height (Taylor et al., 2012b). Therefore, it seems that jump height may be insensitive to low frequency neuromuscular fatigue monitoring. However, the observed changes in the five variables observed by Gathercole et al. (2015b) may be of interest as it may be reflective of the sensitivity of certain variables to low frequency fatigue. Given the importance of monitoring low frequency fatigue in the days following a competitive football match, monitoring alternative variables which are sensitive to low frequency fatigue may be of significant importance.

2.8 Alternative neuromuscular assessments

However, discrete force time variables represent just one instantaneous force data point amongst hundreds that are collected between jump initiation and take off. Consequently, these discrete variables do not explain how the countermovement jump force-time curves obtained for the entire jump (which combines the unweighting, braking, and propulsion phases) change between testing occasions or between populations. The increasing popularity of jump tests may be attributed to the ability of force plate hardware and software systems to give detailed kinetic and kinematic variables to provide insight into biomechanical and neuromuscular changes associated with fatigue (Gathercole et al., 2015a). An alternative approach, sometimes termed waveform analysis or Temporal Phase Analysis (TPA), involves the time normalization of individual countermovement jump force time curves (i.e. the expression of the time between jump initiation and take off as a percentage rather than as an absolute value), followed by a statistical comparison of the time-normalized force curves. This approach has gained popularity with it being suggested that it overcomes the previously stated issues of the discrete data analysis alone (Lake & McMahon, 2018). Thus, combining TPA and discrete methods can lead to a clearer understanding of biomechanical changes (or lack of) in countermovement jump strategy following certain training regimes, or difference between specific sporting cohorts.

Measurement of physical capability via various jump tests is widely employed within team sports and may provide a surrogate assessment of neuromuscular function. The countermovement jump is a popular assessment due to the transition from eccentric to concentric muscular contraction in the stretch-shortening cycle. However, it is unclear whether traditional metrics obtained from the countermovement jump such as vertical jump height and peak power are the most sensitive markers of physical readiness or fatigue. The countermovement jump represents a simple neuromuscular task and as a result highly trained athletes can modify their movement strategy to maintain the task output and jump height when fatigued (Gathercole et al., 2008; Oliver et al., 2015). Recent studies investigating the performance of a countermovement jump on force platforms in games players (Cormie et al., 2009; 2010) have observed the eccentric phase of the stretch-shortening cycle to lengthen following either an acute fatiguing exercise challenge or during the course of a competitive season in the absence of significant changes in jump height or peak power. Such observations seem reasonable if the important role eccentric contraction plays in the stretch-shortening cycle is taken into consideration. It is plausible that if a performer is experiencing transient or chronic neuromuscular fatigue the contractile capabilities of their muscular system will be reduced. However, if the length of time spent contracting eccentrically is manipulated to provide a longer period from which to store elastic energy and generate force (McBride & Snyder, 2012), a similar impulse and concentric contraction as to that generated in a non-fatigued state may be elicited, resulting in the maintenance of jump height. Such modification of jump mechanics potentially compromises performance in fast-paced sports as a longer period of time is required to produce a forceful action. Furthermore, impaired eccentric contraction may impact on neuromuscular control during changes of direction and rapid decelerations tasks, increasing the chance of injury (McLean et al., 2010). Consequently, changes to the eccentric phase of the jump may be a more sensitive marker of physical readiness than jump height alone. As a result, variables relating to the force profile of the eccentric portion of the jump may be of interest for assessment. Variables obtained from the force-time curve representing the eccentric or braking phase of the countermovement jump may represent the alterations in the jumping technique as a result of neuromuscular fatigue.

This is supported by literature observing the strength of the relationships between ground reaction force variables from a countermovement jump and jump height. Barker et al. (2018) reported a significant and large correlation between jump height and variables relating to the concentric phase of the jump (concentric work and concentric displacement). This supports the previously discussed idea that experienced performer's may be able to modify their jump strategy by manipulating the force, time and/or velocity produced in the eccentric phase of the jump to produce a similar amount of concentric work and maintain jump height. Therefore, given the potential maintenance of jump height in the presence of neuromuscular fatigue, it may be of interest to observe changes in variables not directly related to jump height. Variables such as eccentric work, jump time and force at zero velocity have been reported to show trivial correlations with jump height (Barker et al., 2018).

Eccentric work was defined as the force produced in the eccentric phase of the countermovement jump multiplied by the eccentric displacement (Barker et al., 2018). The amplitude of the countermovement during a countermovement jump has also been of interest within contemporary research. Taylor et al. (2012b) reported that elevated levels of muscle soreness and subjective perceptions of fatigue coincided with a reduction in eccentric displacement during a countermovement jump during periods of high physical training loads. This change in countermovement has been attributed to a reduction in hip and knee angle during take-off (Augustsson et al., 2006). Rodacki et al., (2002) observed the depth of the countermovement to decrease by 20% following a fatiguing protocol. This has been attributed to a significant reduction in lower limb joint angle, predominantly as a result of decreased knee and hip flexion. The reduction in lower limb joint angles and subsequent reduction in countermovement depth has been associated with a subconscious strategy to protect the musculature of the lower limb from further muscle damage and/or maximise performance in a fatigued condition (Kipp et al., 2020). Rodacki et al. (2002) reported the decrease in eccentric displacement to be a mechanism to maximise performance. These authors suggested that the increase in joint stiffness and greater resistance to the applied load, in this instance gravity, may prevent the muscular tendon units being in a lengthened state when concentric recruitment of muscle and the production of upward force occurs. This causes the amortisation phase to be shorter in duration and therefore maximises the use of the stretch-shortening cycle, which is of great importance for an athlete to maintain or maximise performance in a fatigued state. Furthermore, stiffening the lower limbs earlier in the negative phase will prevent sarcomere ‘popping’ and reduced performance, which may be apparent in the presence of low frequency fatigue from the disruption to contractile elements in the musculature and sarcomeres following the excessive myofibrillar slipping that may occur during repeated fatiguing eccentric actions (Taylor et al., 2012b; Kipp et al., 2020). Therefore, it seems that the countermovement depth used during a countermovement jump may provide practitioners with a sensitive marker to monitor neuromuscular fatigue.

In addition, eccentric force production during a countermovement jump may be of interest. Many researchers have reported that determining the eccentric loading behaviours of individuals during a countermovement jump in the presence of fatigue may have greater sensitivity to neuromuscular fatigue than commonly used output variables such as jump height (Gathercole et al., 2015b; Cormack et al., 2008a). Furthermore, given the speculation that the force produced in the eccentric phase may not be closely correlated with jump height, it’s inclusion may provide insight into variables which are sensitive to low frequency fatigue when jump height is unchanged.

Another variable which has been reported in the literature to be sensitive to fatigue is force at zero velocity. As discussed previously, Barker et al. (2018) reported amortisation force to have a trivial correlation with jump height. Kennedy and Drake (2017) reported force at zero velocity to be impaired by the greatest magnitude following a fatiguing protocol, and this was substantiated by Gathercole et al. (2015b) who reported that out of the 22 variables they assessed, force at zero velocity was one of the few variables to change greater than it's error.

Flight time:contraction time has recently been used as a measure of neuromuscular fatigue. Previous research has suggested that a change in flight time:contraction time of greater than 5% (Gathercole et al., 2015c) or 8% (Cormack et al., 2008a) are indicative of neuromuscular fatigue and this variable can be adopted by sport scientists as a sensitive measure of fatigue status. Furthermore, Taylor et al. (2012b) observed a clear reduction in flight time: contraction time during an overload phase of resistance training. However, it was less sensitive to fatigue compared with other variables used in the study. These authors concluded that different variables relating to a countermovement jump task are exercise specific, and flight time:contraction time may be more suitable for team sport activities that include a large numbers of accelerations, decelerations, maximal sprinting efforts and high velocity SSC and eccentric muscle actions.

Some previous studies of neuromuscular fatigue in field sports only reported jump variables for which the coefficient of variation was less than 10% (a common threshold for designation as 'reliable'). However, the most sensitive variables for monitoring neuromuscular fatigue are not necessarily the most reliable (Cormack et al., 2008b; Heishman et al., 2018). Rather, it is the signal-to-noise ratio that determines the sensitivity of a jump variable (Kennedy & Drake, 2018). That is, the most sensitive variables are those that show a large induced change relative to the inter-trial variability. In the present study, the countermovement jump variables were selected according to previous studies that demonstrated high sensitivity to changes in daily training load and physical match load (Thorpe et al., 2015), and according to the supposed practical importance of the variable.

As discussed, performance in the activity itself has been suggested to be the most sport-specific indicator of neuromuscular performance readiness. However, its longitudinal assessment can be impractical. Therefore, research has determined various methodology to provide an index of fatigue. These methodologies are assessed for their construct validity, which is the extent to which the construct and a similar measure are related, and the results from a valid measure will actually reflect the theoretical trait it says it does (Ginty, 2013). It is likely that a valid test measure will also show sensitivity. A sensitive test measure is one which correctly identifies the tests for which the construct is present, and the smaller the stimulus needed to identify the intended outcomes, the more sensitive the measure is. Variables from a countermovement jump have been reported to be a valid measure, and sensitive to neuromuscular fatigue (Gathercole et al., 2015a). In the current study, selected countermovement jump variables will be plotted against the physical load from a competitive football match to inform on their sensitivity to changes in match load. In addition, changes in match load can cause significant neuromuscular fatigue (Russell et al., 2016), and may also cause significant alterations in countermovement jump variables post-match. Therefore, the current study aims to determine the construct validity of the countermovement jump variables in response to changes in match load to inform on neuromuscular fatigue..

2.9 Physical load on a player

Many studies have reported that the physical load of a football match can cause significant changes to neuromuscular function as a result of the repeated high-intensity actions causing fatigue (Nédélec et al., 2012; 2014; Reilly et al., 2008). As discussed previously, competitive football involves key physical actions which have been linked to successful performance, such as maximal acceleration, sprinting, deceleration, change of direction, and subsequent re-acceleration and sprinting, in addition to repetitive jumping and kicking. These high-intensity actions can cause a significant amount of fatigue (de Hoyo et al., 2016).

Most player monitoring systems report a measure of external load on the player to reflect the training load or match load. The external load is the work performed by a player, and is usually quantified by a distance, the number of efforts, or a speed variable (Halson, 2014). Video time-motion analysis and global positioning systems (GPS) are frequently used to monitor the external load on a player in team sports. The sampling rate, velocity, and duration of the task can influence the reliability of GPS monitoring; however, the current market-leading technology uses a sampling rate of 10 Hz (Aughey, 2011). Computerised video monitoring systems (such as ProZone TM) give valid and reliable measures of a player’s motion during football match play. In addition, due to some restraints of the use of GPS in the Premier League for example, camera operating systems and GPS can be used interchangeably (Taberner et al., 2020), however this is not a common observation (Dallaway, 2014). Also, the use of camera operating systems is often costly and not viable for many sport teams. Therefore, GPS seem to be a less expensive method of monitoring the load on a player, and the reported reliability and validity allows for valid and reliable data to be collected. There is some question regarding the validity and reliability of GPS variables to assess movement of high or varying intensity/speed and over short distances (Jennings et al., 2010). However, GPS variables have shown good reliability within team sports (Boyd et al., 2011; Jennings et al., 2010). In addition, increasing the sampling rate improves the reliability and validity of these measures (Jennings et al., 2010), so using the current 10 Hz sampling rate has been reported to be optimal for measurement accuracy (Johnston et al., 2014; ; Rampinini et al.,2015; Scott et al., 2016).

The total distance covered by the player when running at very high speed is believed to be an important measure of the external load during training and matches (Coutts & Duffield, 2010; Thorpe et al., 2015). A recent review reported large correlation between high-speed running and muscle damage markers, with the absence of such findings for total distance covered. Running distance at high-speed seems to be the most sensitive external load monitoring variable to inform on subsequent fatigue related neuromuscular and biochemical disturbance (Hader et al., 2019). However, this variable (high-speed running distance) does not reflect the external load associated with accelerations and decelerations. The repeated eccentric muscular contractions performed whilst stopping and changing direction in a match can produce significant muscular damage and neuromuscular fatigue. Therefore, the monitoring of high intensity decelerations also has significant importance in representing the neuromuscular cost of the mach. Interestingly the review by Hader et al. (2019) suggested further research is needed to determine the strength of associations between markers of neuromuscular fatigue and both very high-speed running (> 7 m.s^{-1}) and deceleration variables. This is reported due to the lack of evidence using higher speed thresholds, and also the small number of studies that could be included in the review for comparison due to the changing technology over recent years. Much of the research using high-speed running has used a threshold of 4-5.5 ms-1 (Russel et al., 2016; Thorpe et al., 2012), however it could be speculated that given the significant increase in the force production of the contributing muscles running at higher running speeds (Dorn et al., 2012), assessing the distance covered at very high speed thresholds may be significantly associated with neuromuscular fatigue.

2.10 Causal relationship between match load and match fatigue

In the current study the ‘match load’ is taken as the physical output of the player in each football match and quantified by the high-speed running distance and the number of high-intensity decelerations measured by the GPS. The ‘match fatigue’ is quantified by the change in the jump metric induced by a football match. More precisely, it is the difference between the jump value measured on the day before the game and two days after the game. A cause-effect relationship was expected between the match load (causal factor) and the match fatigue (effect variables), where an increase in match load will cause greater match fatigue.

In order to determine which jump variables are most sensitive to delayed neuromuscular fatigue, match fatigue can be plotted against match load and linear regression used to calculate the gradient of the line of best fit. The uncertainty in the gradient of the line determines the signal-to-noise ratio of the gradient. The most sensitive countermovement jump variables are those with the greatest signal-to-noise ratio. The signal-to-noise ratio can be calculated using:

$$\text{signal} - \text{to} - \text{noise ratio (SNR)} = \frac{|\text{gradient}|}{95\%\ \text{confident interval of the gradient}}$$

In a plot of match fatigue against match load, the greater the gradient of the line of best fit the greater the signal-to-noise ratio. Likewise, the lesser the 95% confidence interval of the gradient, the greater the signal-to-noise ratio. Factors that influence the 95% confidence interval of the gradient include the variability in the jump variable, the range in match load and the number of matches that have been played. The influence of these factors are presented in plots of simulated data (Figures 2–6).

In each plot a straight line can be fitted to the data. If the confidence interval does not include zero, the gradient of the line is deemed as significantly different to zero, which indicates a clear effect of the match load variable on the match fatigue jump variable. A gradient that is significantly different to zero is equivalent to saying that the signal-to-noise ratio is greater than ± 1.0. This analysis assumes that there is a linear relationship between the match load variable and the match fatigue variable. In addition, it is assumed that the data are accurate and reliable measures of the match load variable and the match fatigue variable. That is, the uncertainties in the match load and match fatigue values are assumed to be less than the changes induced by the match.

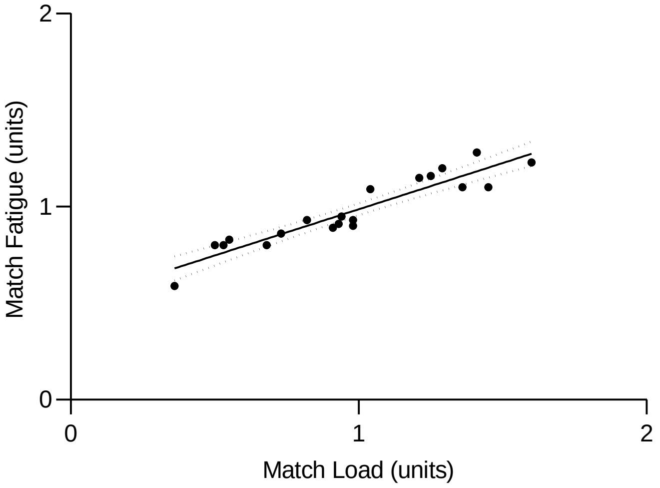


Figure 2. Plot of match fatigue against match load (simulated data). Values used to generate the simulated data: gradient = 0.5; standard deviation in the jump variable = 0.05; standard deviation in the match load = 0.3; number of matches = 20. Equation of the line of best fit: Y = 0.48x + 0.51. R^2 = 0.88. Gradient 95% confidence interval = 0.09. Signal-to-noise ratio of the gradient = 5.6.

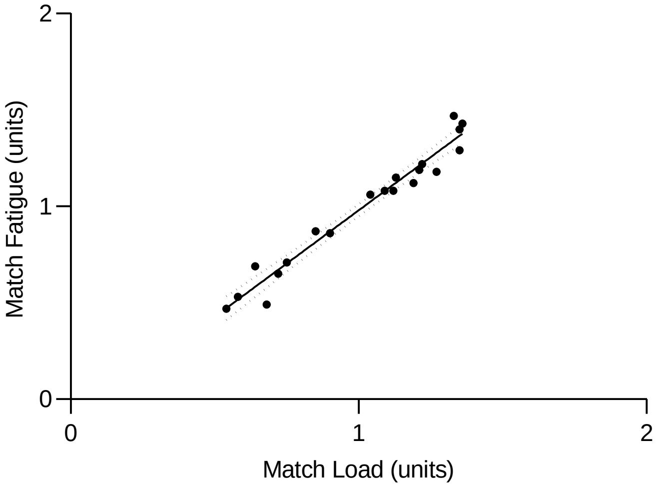


Figure 3. Plot of match fatigue against match load (simulated data). Values used to generate the simulated data are the same as in Figure 2 except: gradient = 1.0. Equation of the line of best fit: Y = 1.10X - 0.12. R^2 = 0.96. Gradient 95% confidence interval = 0.11. Signal-to-noise ratio of gradient = 9.1.

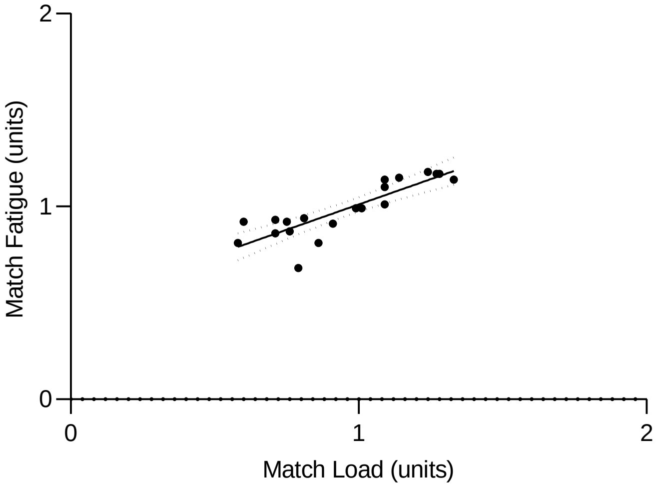


Figure 4. Plot of match fatigue against match load (simulated data). Values used to generate the simulated data are the same as in Figure 2 except: standard deviation in the jump variable = 0.10. Equation of the line of best fit: Y = 0.52X + 0.49. R^2 = 0.72. Gradient 95% confidence interval = 0.16. Signal-to-noise ratio of gradient = 3.3.

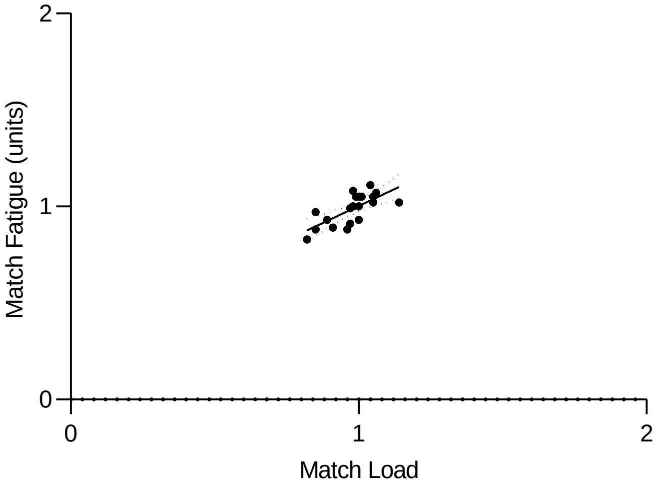


Figure 5. Plot of match fatigue against match load (simulated data). Values used to generate the simulated data are the same as in Figure 2 except: standard deviation in the match load = 0.1. Equation of the line of best fit: Y = 0.70X + 0.29. R^2 = 0.50. Gradient 95% confidence interval = 0.35. Signal-to-noise ratio of gradient = 2.0.

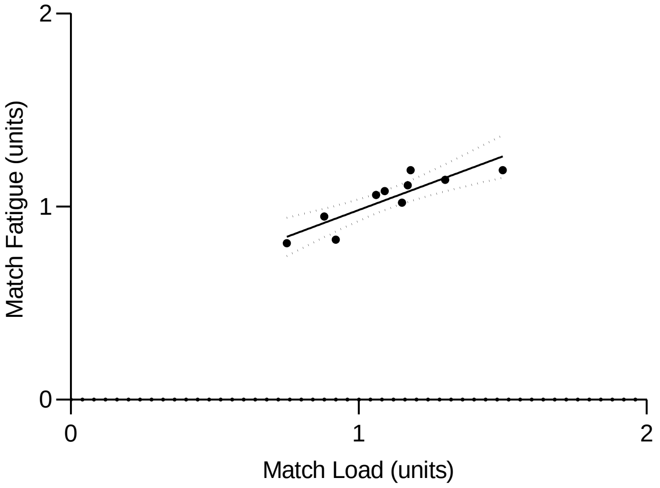


Figure 6. Plot of match fatigue against match load (simulated data). Values used to generate the simulated data are the same as in Figure 2 except: number of matches = 10. Equation of the line of best fit: Y = 0.56X + 0.43. R^2 = 0.77. Gradient 95% confidence interval = 0.25. Signal-to-noise ratio of gradient = 2.3.

2.11 Experimental approach to the problem

In the present study the strength of the relationship between match load and the change in a jump variable was investigated using an analysis of each participant separately and an analysis of grouped data from all the participants. Group statistics are often used to compare the outcome of groups of individuals in response to an intervention. However, an intervention can produce considerable inter-individual differences in outcomes due to differences in biological make-up (Puthucheary et al., 2011). Also, when investigating sports performance the coach is usually more concerned with the individual case rather than with the group outcome. A recent study by Kipp et al. (2020) found significant individual differences in lower limb kinematics during a countermovement jump, and performers used individual joint-specific jump strategies when performing a maximal countermovement jump effort. In this study the single-subject analysis provided an insight which was in contrast to the group analysis and was practically important for prescribing individual exercise programmes to optimise training adaptations. Therefore, in the present study there was an individual analysis of the strength of the relationships between match load and the jump variables for each participant, in addition to a group analysis.

The present study used a quasi-experimental design. This is a quantitative research process which aims to approximate control features of a typical true experiment to help researchers make an informed decision on what effect the intervention or treatment in question has had in solving the research problem (Carr, 1994; Cozby, 1997). This form of experimental design is typically used when evaluating and observing the effect of a programme on a population and attempts to show causality between an intervention and the associated outcome (Padgett & Reid, 2002). Bärnighausen et al. (2017) defined a quasi-experiment as “an observational study with an exogenous explanatory variable that the investigator does not control”. This is in contrast to a true experiment where a researcher systematically and deliberately manipulates the independent variable to determine an effect. In the current study the independent variable is the physical load experienced by each player during a match, which is determined by various variables outside of the researcher’s control. This type of design is often termed an ‘observational analysis’ and has been cited as particularly useful in ‘real world’ research. As a result it has high external validity and is very effective when the answer to a particular research question may be constrained by normal operations, politics and ethics, and when using an active research or randomised control trial may be impractical or impossible (Bärnighausen et al., 2017; Eliopoulos et al., 2004). Further strengths of quasi-experiments include the fact that this form of research process can provide sufficient information about the relationship between the variables under investigation to enable prediction and control over future outcomes (Carr et al., 1994). The present research project is most suited to a quasi-experimental design as it enables the researcher to collect causal evidence with a high degree of external validity in a ‘real-world’ setting and to determine which countermovement jump variables are most suitable for use when assessing neuromuscular fatigue in a group of elite academy footballers.

The type of quasi-experiment used in the present study is the one group pre-test – post-test design. Eliopoulos and colleagues (2004) reported a hierarchy of designs when using a quasi-experiment and suggested that the use of a non-equivalent dependent variable that includes multiple dependent variables which have similar confounding variables and some collinearity, with the exception of the effect the independent variable and intervention has on them, strengthen the value of the interpretation of the results. For example, previous research has shown that the depth to which an individual drops their centre of mass during a countermovement jump will have an effect on the jump height achieved (Domire & Challis, 2007; Mandic et al., 2015; Markovic et al., 2014). However, as previously discussed, in the presence of neuromuscular fatigue the monitoring of jump height has been reported to be insensitive, due to experienced performers being able to alter their jump mechanics to achieve the same jump height when in fatigued states and other variables which reflect a change in jump strategy. For example, countermovement depth may be more sensitive to neuromuscular fatigue and show a greater magnitude of change. Furthermore, the same researchers suggested that a quasi-experimental design would produce more convincing results if the presence of the intervention caused the opposing effect to the absence of the intervention. In the context of the current research, if a selected countermovement jump variable was to significantly increase from pre-match to post-match testing when the magnitude of the physical output in the match was large, and the same countermovement jump variable showed trivial changes or decreased in response to a smaller magnitude of physical output, the inferences made from the study would be more convincing.

In the present study, a group analysis was used to attempt to understand a phenomena, by calculating a mean value for all countermovement jump variables for group comparison between pre- and post-match and to determine associations with changes in physical output from a football match. This analysis approach is commonplace in the majority of previous literature and studies reporting on the use of jump analysis to determine neuromuscular fatigue. However, in addition to establishing a phenomena, it is important in practice to be able use the findings from the current research within the real world for athlete monitoring. Practitioners are guided by information on fatigue status and required to make informed decisions on athlete development and programming on an individual level (McGuigan, 2017). This requirement to monitor athletes on an individual level stems from substantial inter-individual differences that occur in recovery profiles and in determining neuromuscular fatigue in response to a training or match stimulus (Gathercole et al., 2014). Differences in genetic make up, fitness levels, age, gender, responses to physical training loads, player position and tactics employed during a match also needs to be considered.

The secondary analysis for this study was consistent with methods used in a single subject design. This design represents an alternative to traditional normothetic designs (group-based analyses) and can provide several benefits (Nourbakhsh & Ottenbacher et al., 1994). Common methods of approach to analyse single subject designs are visual inspection of the data and quantitative procedures. Previous literature has reported visual analysis to be advantageous for a researcher in reporting large treatment effects and remain insensitive to small or weak treatment effects (Brossart et al., 2006; Nourbakhsh & Ottenbacher, 1994). However, there are inefficiencies from observed researcher bias in visual analysis. For example, there a no formal rules or rigorous statistical methods for researchers to consistently interpret the data. Many researchers have reported inconsistent and unreliable data from this form of analysis (intraclass correlation coefficients [ICC] = 0.52-0.66; Furlong & Wampold, 1981; Gibson & Ottenbacher, 1988; Harbst et al, 1991). Therefore, many researchers recommend the use of an integrated approach of visual and statistical analysis (Franklin et al., 1997; 2004; Huitema, 1986; White et al. 1987). Therefore, the present research used the two methods, visual analysis and quantitative analysis to examine the relationship between the selected countermovement jump metrics and physical output variables obtained during a competitive match. Combining these methods in this order increases the confidence that the results are meaningful (Sands, 2019).

2.12 Aims

The aim of the present study was to identify the countermovement jump variables that were the most sensitive to changes in physical match load for potential use as indicators of full recovery from the neuromuscular fatigue induced by a football match. Previous research has reported the insensitivity of jump height as an indicator of neuromuscular fatigue, and so alternative jump metrics obtained from a countermovement jump test were sought.

2.13 Hypotheses

1. Jump height will not show a strong relationship with the change in the jump variable as an index of neuromuscular fatigue (match fatigue) and the physical load on the player due to the match (match load). That is, the signal-to-noise ratio of the gradient will be less than 1.0.

2. The variables associated with jumping technique, especially in the eccentric phase of the jump, will show a strong relationship between the change in jump variable as an index of neuromuscular fatigue and the physical loads on the player due to the match. That is, the signal-to-noise ratio of the gradients will be greater than 1.0.

3. There will be substantial individual differences among the participants in which jump variables show a strong relationship between the change in the jump variable as an index of neuromuscular fatigue and the physical load on the player due to the match.

Chapter 3: Methods

3.1 Participants

Twenty professional under 18 and under 23 male football players from an elite football academy participated in the study (age, 17.9 ± 1.2 years; body mass, 77.3 ± 6.7 kg; height, 1.79 ± 0.08 m). Participants were recruited from an English football academy and participated in the study on a voluntary basis. The participants were all healthy and played in common positions on the field. Following exclusion criteria, data from eight participants were used for the data analysis. The study was conducted in accordance with the Declaration of Helsinki and the protocol was approved by the Ethics Committee of Brunel University London (project reference 11030-MHR, Appendix A). The participants were informed of the procedures and inherent risks prior to their involvement in the study and their written informed consent was obtained. Parental consent was obtained for those participants aged under 18 years.

3.2 Study Design

This study used a quasi-experiment design with a linear regression analysis. The football matches were an interrupted time-series with multiple pre-match and post-match observations, and the participants were their own controls. The outcome (dependent) variable was the change in the countermovement jump variable due to the match, and the predictor (independent) variable was the physical load on the player during the match. Each of the outcome variables was plotted against the predictor variables and a straight line was fitted to the data in the plot. The gradient of the line and the signal-to-noise ratio indicates the strength of relationship between the physical load on the player and the jump variable. The best countermovement jump variables for monitoring neuromuscular fatigue in football players would be those that showed the highest signal-to-noise ratio between the change in the jump variable and the physical load on the player.

A countermovement jump test was selected as measure of neuromuscular function. Jump assessments were performed the day before each match (pre-match) and the second day after the match (post-match) following a rest day. All participants were familiar with performing a countermovement jump test as they had performed many jump tests as part of their regular monitoring in previous seasons. The tests were conducted at the same time each day, between 9:00 and 10:00 a.m., to minimise the effect of any daily fluctuations in countermovement jump performance (Heishman et al, 2017; Taylor, 2012b).

3.3 Procedures

The typical weekly schedule for an academy player was prescribed by the coaching staff. The competitive match schedule for the academy team was prescribed by the Premier League, and team selection for the matches and the duration of play in a match was determined by the coaching staff. The day immediately following a match was always a rest day with no scheduled training and between matches the players followed a training schedule that was prescribed by the coaching staff. There were usually two training sessions per day consisting of a pitch-based football session in the morning and a one-hour gym-based weight training session in the afternoon.

Over the period of the study the participants took part in skills sessions, tactical sessions and physical conditioning sessions, which were prescribed by the football coaching staff and the strength and conditioning staff.

3.3.1 Countermovement jump test

The countermovement jump tests were performed on a 37 × 37 cm portable force platform (PS-2142, PASCO, Pasport PS-2142, Roseville, USA) fixed to the floor of an indoor gymnasium. The force platform uses strain gauges at each corner of the platform to measure the resultant vertical ground reaction force, and the sampling rate was set to 1000 Hz. In the jump test the participant’s arm movement was constrained by gripping a lightweight wooden dowel, which was positioned across the upper shoulders and back between the superior portion of the scapula and the C7 vertebra. The participant stood upright and stationary on the force platform with the feet placed within 15 cm of the lateral portion of the deltoid muscle. After about two seconds the participant initiated a jump using a downward countermovement to a self-selected depth, followed immediately by a maximal-effort upwards jump. The participant was instructed to keep constant downward pressure on the dowel throughout the jump and to aim for maximum height in the flight phase of the jump. The participant landed back on the force platform and remained stationary for at least two seconds after landing. Five trials were recorded with at least one minute’s rest between each jump. Prior to performing the jump test the participant performed three practice jump trials. The participants wore lightweight sports clothing and sports footwear.

ForceDecks software (ForceDecks, London, United Kingdom) was used to generate the jump variable data. The force–time data was not filtered and the gravitational acceleration in the software was set to the local value (9.812 m/s^2). In this software acceleration–time data is obtained by dividing the ground reaction force–time data by body mass and then subtracting the local gravitational acceleration. Velocity–time data is obtained by numerical integration of the acceleration–time data and position–time data is obtained by further numerical integration of the velocity–time data (Linthorne, 2001). Power–time data is obtained by multiplying the ground reaction force data and the velocity data.

The jump variables selected for analysis are part of the *Forcedecks* software default output (Table 1). This output is calculated automatically using algorithms that detect key events in the force trace, including the start of the jump, the start of the upward phase, the instant of take-off and the instant of landing. The start of the jump is taken as the time when the force drops by 20 N below the participant's body weight, and the start of the upward phase of the jump is taken as the first sample for which the velocity has a positive value. The instant of take-off is taken as the first sample for which the force falls below 20 N and the instant of landing is taken as the first sample after take-off for which the force rises above 20 N.

Table 1. Definitions of the countermovement jump variables.

Jump Variable	*Definition*
Jump Height	Vertical distance travelled by the jumper's centre of mass between take-off and the peak of the jump Jump Height = g $(\text{Flight Time})^2/8$ Flight Time is time between the instant of take-off and the instant of landing
Countermovement Depth	Vertical distance travelled by the jumper's centre of mass between standing upright and the bottom of the countermovement
Flight Time: Contraction Time	Ratio of flight time to contraction time (Time between take-off and landing:

	Time between start of the movement and take-off)
Eccentric Mean Braking Force	Mean force during the eccentric braking phase (the time between the minimum vertical force and the start of the concentric phase)
Force at Zero Velocity	Vertical force at the instant of zero velocity during the countermovement
Force at Peak Power	Vertical force at the instant of peak power
Eccentric: Concentric Mean Force Ratio	Ratio of the eccentric mean force and the concentric mean force, expressed as a percentage

The countermovement jump data was checked visually and obvious erroneous data arising from the misidentification of key events by the *Forcedecks* software were removed. The mean of the remaining jump trials was calculated for each of the jump variables, and the differences between the pre-match and post-match scores were calculated.

3.3.2 Physical load on a participant during a match ('match load')

The physical load on a participant during a match was quantified using data from a Global Positioning System (GPS) athlete tracking device (Optimeye X4, Catapult Innovations, Scoresby, Victoria). This device uses a very precise 10 Hz GPS engine to generate position, velocity and acceleration data. The device also uses a three-axis 100 Hz accelerometer to measure linear motion, impact forces, acceleration and deceleration. Similar athlete tracking devices have demonstrated high validity and reliability.

The GPS athlete tracking device was attached to the participant's upper back using a custom-made vest that was supplied by the manufacturer (Figure 7). The antenna of the device was exposed to allow clear satellite reception. The device was turned on about 30 minutes before the match in order to obtain a clear and stable satellite connection. During the match the device was always able to connect to between 9 and 11 satellites. Velocity and acceleration dwell time was set at 0.4 seconds. A custom-built GPS receiver and software application (Catapult Innovations, Scoresby, Victoria) was used to time-code each match. After the match, the data from the GPS athlete tracking device was downloaded using the manufacturer’s software package (Openfield Operator Console, Catapult, Scoresby, Victoria).

Figure 7. Example image of the position of the GPS tracking device on a participant. Image taken from https://performbetter.co.uk/product/catapult-vests/.

The eccentric actions arising from high-speed runs and sudden decelerations are believed to induce neuromuscular fatigue in a football player. In the present study, two variables were used to quantify the physical load on the participant during the match:

1) Distance of very high-speed running, which was defined as the total distance covered (in metres) whilst running at a speed greater than 6.5 m/s.

2) Number of high-intensity decelerations, which was defined as the number of movements in which the deceleration was greater than 3 m/s^2.

Only the match load data for participants who played the full 90 minutes of the match were included for analysis. This removed the confounding effect of the duration of match play on the response of a jump variable to the match load.

3.4 Data Analysis

3.4.1 Check of data quality and overview

A period in the competition season from January to August 2018 was selected for data analysis. The data collection period was initially set for January 2018 to May 2020 as so to include an entire competition football season. However, after eight months (six of which were in the competition season) there was a hardware failure in the force platform that ended data collection.

Data was analysed for eight of the twenty participants. A participant was included in the analysis if he played 90 minutes or more in at least six matches (and also performed both the pre-match jump test and the post-match jump test for the match). Table 2 shows the matches in which participants played at least 90 minutes and competed the pre-match and post-match countermovement jump testing. Six matches were chosen as the threshold to limit the uncertainty when fitting a line of best fit to a small number of data points. Of the eight participants selected for analysis, three were defenders, two were central midfielders, and three were forwards.

Table 2. Number of datapoints for each participant over the data collection period, where the participant played over 90 minutes, and completed the pre-match and post-match jump assessments.

Participant	Week																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Number of datapoints
1					●	●		●	●		●		●		●		●	●	●	●	11
2				●		●		●	●		●		●		●			●		●	9
3	●	●	●		●		●			●		●		●		●					9
4						●		●					●		●			●	●	●	7
5				●		●		●	●		●		●		●						7
6	●	●	●		●					●		●									6
7						●	●	●	●		●				●						6
8			●		●		●			●		●				●					6
9				●		●		●			●		●								5
10				●							●							●	●	●	5
11													●				●	●	●		4
12											●		●		●						3
13						●		●									●				3
14								●			●										2
15				●													●				2
16	●																				1
17																		●			1
18				●																	1
19								●													1
20																	●				1

One potential confounding factor in this study is that a participant might not return to their baseline level before performing the pre-match jump test in the subsequent week. All matches were 5-7 days apart. A recovery period of 72 hours (3 days) is believed to be sufficient for neuromuscular function to return to baseline as long as any microtrauma to the muscle fibres is not severe (De Hoyo et al 2016; Komi, 2000). Plots of the pre-match jump variables did not show clear evidence of a decreasing time trend, which indicates the recovery period was sufficient for a return to baseline (Appendix B; Table 3).

Table 3. Descriptive statistics for the pre-match data for jump height (*n* = 8) over the 20 weeks of the study. Mean, standard deviation (SD) and coefficient of variation (CV).

Participant	Mean (cm)	SD (cm)	CV
1	34.9	1.6	4.7
2	32.9	2.0	6.1
3	39.1	3.4	8.8
4	31.6	2.4	7.5
5	38.3	0.5	1.4
6	40.1	1.7	4.2
7	32.3	1.6	5.1
8	34.3	2.3	6.6

3.4.2 Group analysis

For the group analysis the data from the eight selected participants was analysed. Jump variables and match load data from the eight participants were tested for normality using the Kolmogorov-Smirnov test. Where data satisfied normality, data was presented as a mean ± standard deviation. Skewed or heteroscedastic data was analysed using a non-parametric equivalent, the Wilcoxon test, and presented as a median ± IQR. A paired t-test was conducted using statistical software package SPSS (IBM, SPSS Statistics, Version 25, Armonk, NY) to determine the statistical difference of the jump variables between pre-match and post-match. Statistical significance was accepted at $p<0.05$. Cohens *d* effect sizes (ES) and 95% confidence intervals (CI) were calculated to determine the meaningfulness of the differences between the pre-match and post-match values. The effect size was classified as trivial (0.0–0.2), small (0.2–0.5), moderate (0.5–0.8) and large (> 0.8). Furthermore, the effect size was deemed clear if the ± 95% confidence intervals in the observed value spanned two categories or fewer, and unclear if the ± 95% confidence intervals spanned more than two categories. Pearson's correlations were performed to determine associations between the magnitude of change between pre- and post-match for each match for all countermovement jump variables and match load. Spearman's rank correlation coefficient was calculated for non-normal data. Inferences made based on the strength of the correlation were defined from trivial to almost perfect following the criteria: 0-0.1, trivial; 0.1-

0.3, small; 0.3-0.5, moderate; 0.5-0.7, large; 0.7-0.9 very large; 0.9-1.0, almost perfect. If the 90% confidence intervals overlapped positive and negative values the magnitude was deemed unclear (Batterham & Hopkins, 2006; Hopkins et al., 2009). The coefficient of variation (CV) was calculated for each variable to determine the between-trial variability (Table 4).

The relationship between the physical load variables and the jump variables was also determined by plotting each of the seven jump variables against each of the two match load variables (for 14 plots in total) using GraphPad Prism (GraphPad Software Inc, v5, La Jolla, CA, USA). Each plot was inspected visually to confirm that a straight line was the best choice of fit to the data. (With a low number of data points, it is unlikely that a non-linear fit would be a clearly better fit than a straight line). In each plot, a straight line was fitted to the data using linear regression, and the gradient of the line, its 95% confidence interval and the signal-to-noise ratio was calculated. The calculation used to calculate signal-to-noise ratio is:

$$\mathrm{signal-to-noise\ ratio\ (SNR)} = \frac{|\mathrm{gradient}|}{95\%\ \mathrm{confident\ interval\ of\ the\ gradient}}$$

If the signal-to-noise ratio was greater than one, this was deemed as a significant relationship. Moreover, if the confidence interval included zero, the gradient was deemed to be not significantly different from zero, thus indicating no clear effect of the match load variable on the jump variable. If the confidence interval did not include zero, the gradient was deemed to be significantly different from zero, thus indicating a clear effect of the match load variable on the jump variable. A jump variable with a signal-to-noise ratio greater than 1.0 and a gradient which was significantly different from zero was considered to be potentially suitable for monitoring neuromuscular fatigue. The coefficient of determination (r^2) was recorded to give an indication of the percentage of the total variation in the change in jump variable which can be explained by the change in the match load variable. Although both r^2 and the signal-to-noise ratio have been used interchangeably for linear regression models, they are calculated slightly differently (Czanner et al., 2015). In the current study, the r^2 value is used to measure the goodness of fit in the regression analysis and the SNR is analysed to determine the strength of signal in relation to the associated noise.

A power analysis using statistical software package GPower (GPower 3.1, Heinrich-Heine-Universität, Düsseldorf, Germany) was used to compute the required sample size.

The input parameters included a two-tailed test, an effect size of 0.5, an alpha level of 0.05 and to achieve an acceptable power of 0.8. The total sample size required was 18. Although 20 participants were recruited for the study, as a result of exclusion criteria, eight participants were selected for the analysis. The actual power of the study therefore was calculated at 0.39.

Table 4. Coefficient of variation (CV) and smallest worthwhile change (SWC) for all jump variables.

Variable	CV (%)	SWC
Jump Height (cm)	7	0.5
Countermovement Depth (cm)	11	0.7
Flight Time: Contraction Time	18	0.02
Eccentric Mean Braking Force (N)	8	14.5
Force at Zero Velocity (N)	8	26
Force at Peak Power (N)	7	22
Eccentric: Concentric Mean Force Ratio	8	0.8

3.4.3 Individual analysis

For the individual analysis, data from each of the eight selected participants was analysed separately. For each participant, each of the seven jump variables was plotted against each of the two match load variables (for 112 plots in total) using GraphPad Prism (GraphPad Software Inc, v5, La Jolla, CA, USA). Again, the relationship between the physical load variable and the jump variable was determined by plotting the variables using GraphPad Prism. Each plot was inspected visually to confirm that a straight line was the best choice of fit to the data. (With a low number of data points, it is unlikely that a non-linear fit would be a clearly better fit than a straight line). In each plot, a straight line was fitted to the data using linear regression, and the gradient of the gradient of the line, its 95% confidence interval and the signal-to-noise ratio was calculated. The calculation used to calculate signal-to-noise ratio is:

$$\text{signal} - \text{to} - \text{noise ratio (SNR)} = \frac{|\text{gradient}|}{95\% \text{ confident interval of the gradient}}$$

If the signal-to-noise ratio was greater than one, this was deemed as a significant relationship. Moreover, if the confidence interval included zero, the gradient was deemed to be not significantly different from zero, thus indicating no clear effect of the match load variable on the jump variable. If the confidence interval did not include zero, the gradient was deemed to be significantly different from zero, thus indicating a clear effect of the match load variable on the jump variable. A jump variable with a signal-to-noise ratio greater than 1.0 and a gradient which was significantly different from zero was considered to be potentially suitable for monitoring neuromuscular fatigue. The coefficient of determination (r^2) was recorded to give an indication of the percentage of the total variation in the change in jump variable which can be explained by the change in the match load variable.

Chapter 4: Results

4.1 Group analysis

Data was collected from eight participants, who all performed countermovement jump testing pre- and post-match. Average physical match load in the competitive matches for each participant are displayed in Table 5.

Table 5. Mean ± SD for very high-speed running distance and high-intensity decelerations for each participant over the 20-week data collection period.

Participant	Very High-Speed Running (m)	High-Intensity Decelerations (no.)
1	169 ± 76	25 ± 9
2	220 ± 62	42 ± 13
3	118 ± 41	37 ± 7
4	207 ± 80	32 ± 5
5	231 ± 95	24 ± 10
6	308 ± 125	60 ± 8
7	125 ± 37	20 ± 7
8	206 ± 92	42 ± 8

The statistical analysis of the group data showed no significant changes in jump height (Figure 9), or any of the alternative jump variables as a result of a match from pre-match to post-match (Table 6).

Table 6. Data from the t-tests showing the change between pre-match and post-match.

Jump Variable	t-statistic	Degrees of freedom	p-value
Jump Height (cm)	1.08	7	0.3
Countermovement Depth (cm)	-2.06	7	0.08
Flight Time: Contraction Time	0.1	7	0.9
Eccentric Mean Braking Force (N)	-0.04	7	1.0
Force at Zero Velocity (N)	0.3	7	0.7
Force at Peak Power (N)	-1.1	7	0.3
Eccentric: Concentric Mean Force Ratio	0.4	7	0.7

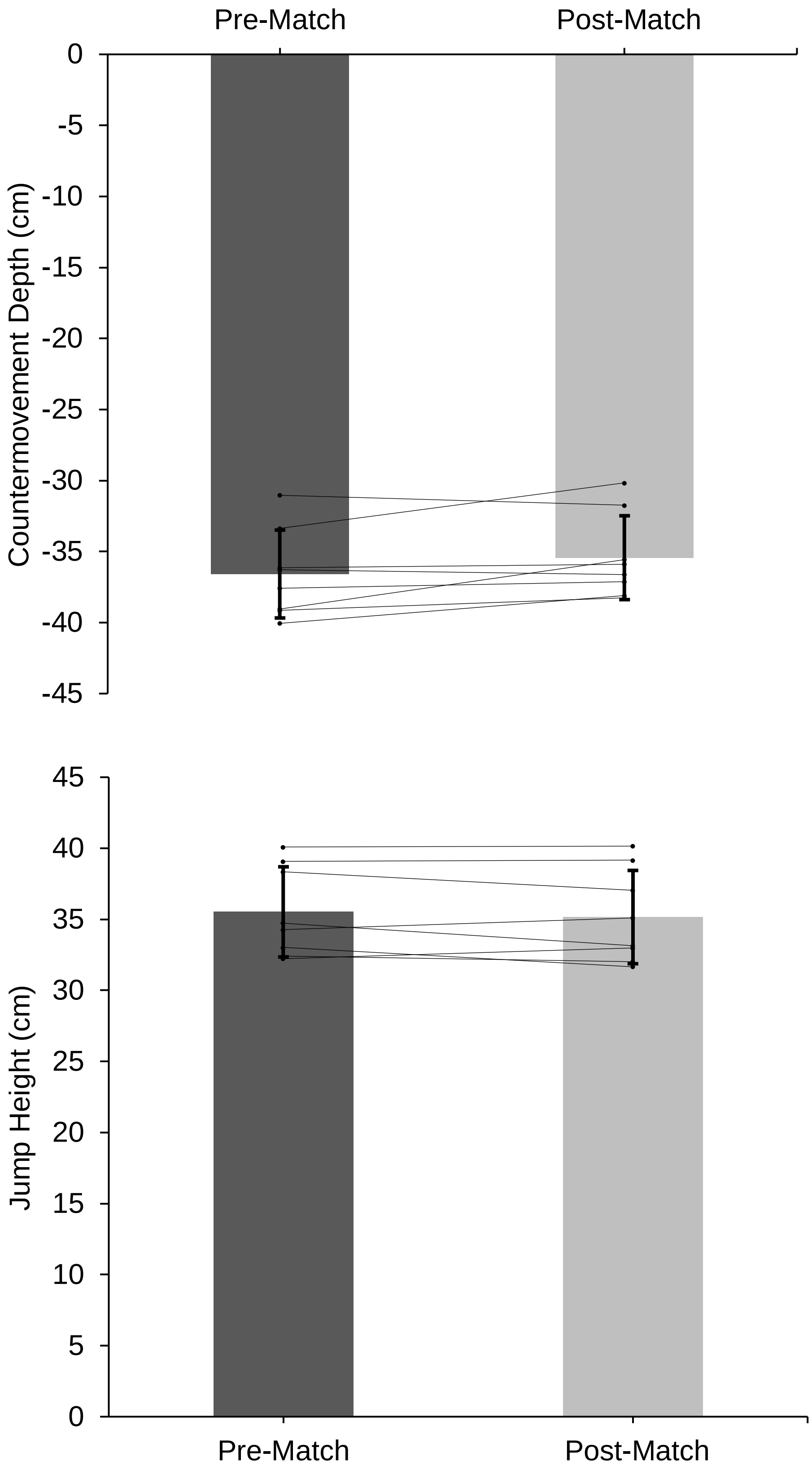


Figure 9. Magnitude of change from pre-match and post-match (mean and standard deviation) for countermovement depth (top) and jump height (bottom). Black lines represent the responses from each participant (n=8).

The largest effect was observed in countermovement depth when comparing this variable before and after a match (Pre, -36.6 ± 3.1; Post, -35.4 ± 3.0 cm; ES = -0.38 ± 0.41). However, only trivial and small effects were shown for all other countermovement jump variables comparing pre-match to post-match, and the high variability within the data meant this was not a ‘clear’ meaningful effect (Figure 10).

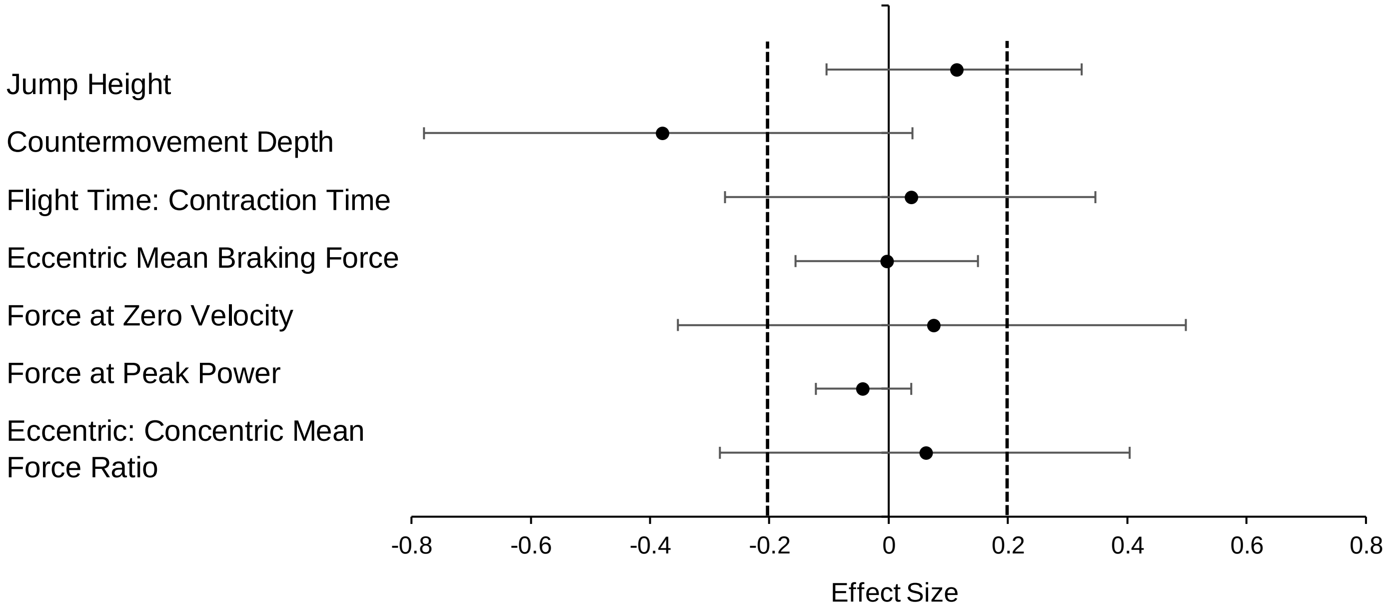


Figure 10. Cohen’s *d* effect size (with 95% confidence interval) for all countermovement jump variables between pre-match and post-match results. Small effect size thresholds are represented as dashed lines.

No significant correlations were observed when assessing the relationship between the match load and match fatigue for all the jump variables. Furthermore, the results of the graphical representation between the physical load variables and jump variables showed no meaningful relationships between the physical match load metrics and all jump variables (Figure 11)

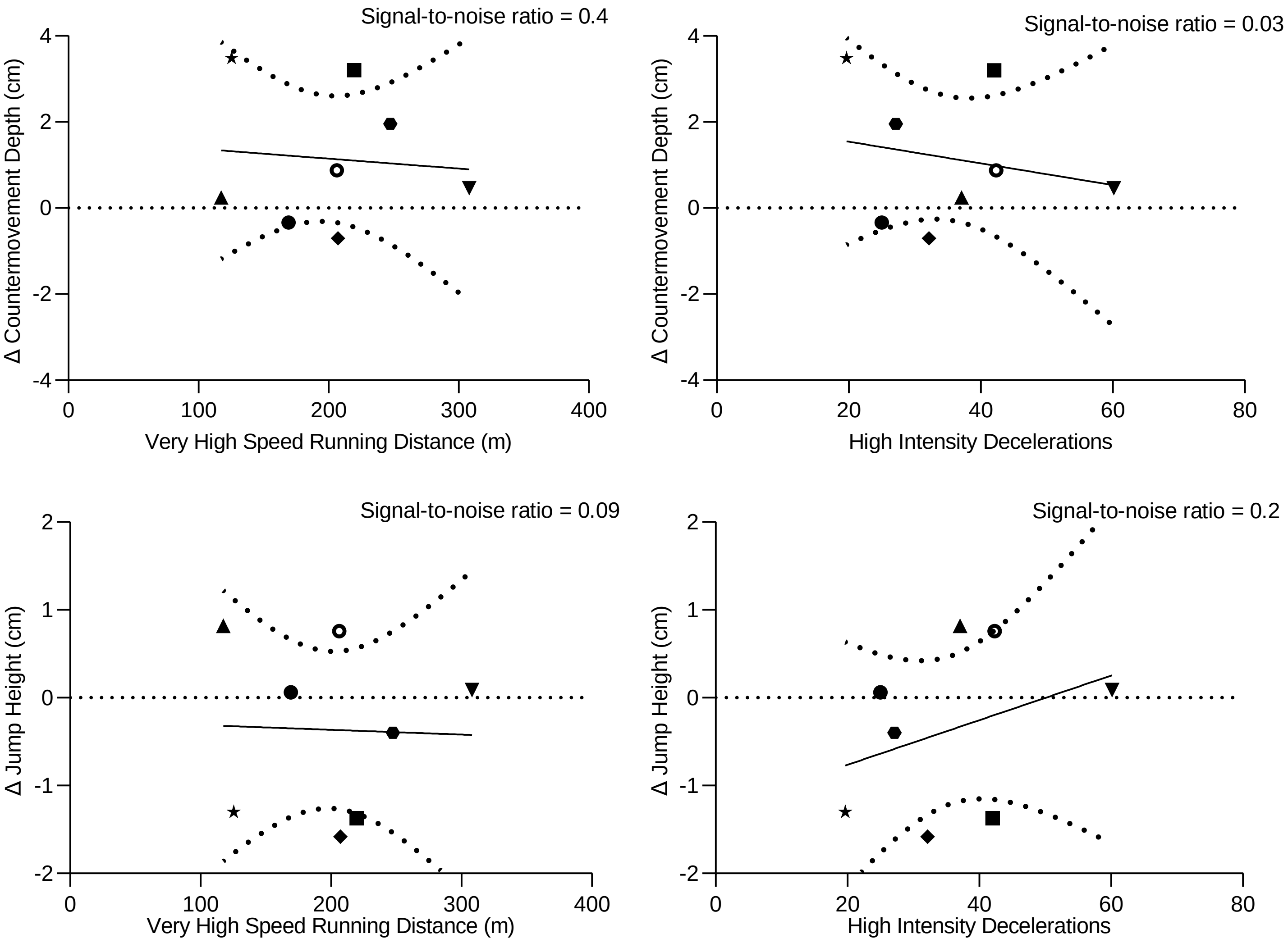


Figure 11. Graphical representation of the relationship between change in countermovement depth and jump height plotted against both physical match load variables. Each graph shows a line of best fit and 95% confidence intervals (dotted lines). Signal-to-noise ratio is shown on the graph. Each data point represents a participant (n=8).

Table 7 displays the results from the graphical analysis performed to determine the relationships between the physical load variables and jump variables. For all relationships the signal-to-noise ratio was less than 1.0. In addition, the confidence intervals for the gradient of the line of best fit value spanned through zero, and therefore the line does not have a significant deviation from zero indicating no clear effect of the match load variable on the jump variable representing match fatigue.

Table 7. The results from the graphical analysis performed to determine the relationships between the physical load and jump variables

Physical Load Variable	Jump Variable	Gradient	95% Confidence Intervals	R^2	p	Difference from zero	Signal-to-noise ratio
Very High-Speed Running	Jump Height (cm)	-0.0005	-0.0157 to 0.0146	0.0013	0.93	Not Significant	0.4
	Countermovement Depth (cm)	-0.002	-0.027 to 0.023	0.009	0.83	Not Significant	0.09
	Flight Time: Contraction Time	0.0000	-0.0005 to 0.0005	0.00006	0.98	Not Significant	0.008
	Eccentric Mean Braking Force (N)	-0.1	-0.3 to 0.1	0.2	0.28	Not Significant	0.5
	Force at Zero Velocity (N)	0.1	-1.1 to 1.4	0.009	0.83	Not Significant	0.09
	Force at Peak Power (N)	-0.06	-0.49 to 0.37	0.02	0.75	Not Significant	0.1
	Eccentric: Concentric Mean Force Ratio	0.00	-0.01 to 0.01	0.00	1.00	Not Significant	0.0006
High-intensity Decelerations	Jump Height (cm)	0.03	-0.05 to 0.10	0.11	0.41	Not Significant	0.03
	Countermovement Depth (cm)	-0.03	-0.15 to 0.10	0.04	0.63	Not Significant	0.2
	Flight Time: Contraction Time	0.001	-0.002 to 0.003	0.06	0.57	Not Significant	0.2
	Eccentric Mean Braking Force (N)	-0.3	-1.4 to 0.8	0.07	0.52	Not Significant	0.3
	Force at Zero Velocity (N)	1.8	-4.0 to 7.6	0.09	0.48	Not Significant	0.3
	Force at Peak Power (N)	-0.6	-2.6 to 1.5	0.07	0.53	Not Significant	0.3
	Eccentric: Concentric Mean Force Ratio	-0.01	-0.09 to 0.06	0.03	0.67	Not Significant	0.2

4.2 Individual Analysis

Some isolated statistically significant changes were observed when assessing the individual response to the change in countermovement depth and jump height from pre-match to post-match (Figure 9). However, the direction of the change was not consistent with some data showing change which could be indicative of improved neuromuscular function. Some players showed marked changes in the alternative countermovement jump variables from pre-match to post-match. The results observed between countermovement jump variables and physical load experienced during competitive match play in the present study highlighted some consistencies (Table 7). An example of the objective data collected and visual representation of the relationships for each individual are shown below (Table 8; Figure 12). A visual analysis of the graphs showed a clear relationship and quantitatively meaningful relationship was demonstrated between high-intensity decelerations and countermovement depth in four of the eight participants (Figure 13). Interestingly, consistent in three participants was a negative gradient of slope and therefore inverse relationship between the variables. However, in one participant a positive gradient reflected a reduction in countermovement depth following competitive match play with a greater number of high-intensity decelerations. Furthermore, eccentric mean braking force seemed to have a significant relationship with match load variables also in four participants (Figure 13). However, the direction of the relationship varied between participants.

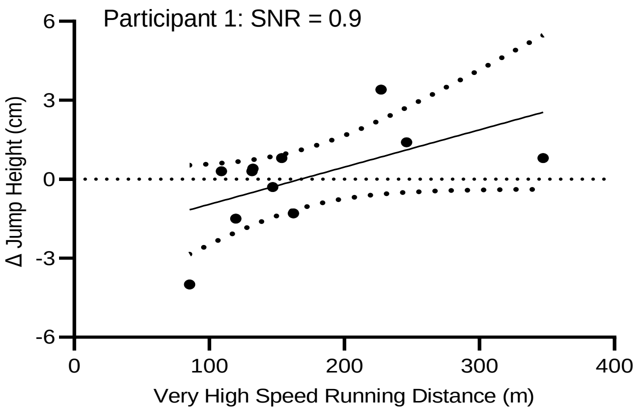
Table 8. Signal-to-noise ratio for the gradient of the relationship between a jump variable and a physical load variable (very high-speed running distance and high-intensity decelerations). Signal-to-noise ratio values greater than 1.0 are in bold.

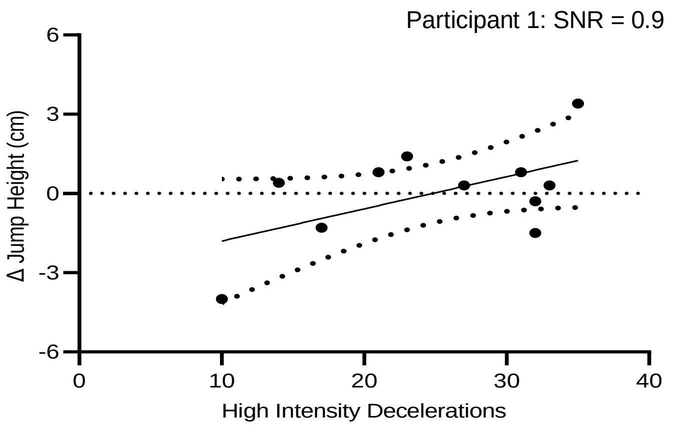
Participant	Very high-speed running distance						
	Jump Height	Countermovement Depth	Flight Time: Contraction Time	Eccentric Mean Braking Force	Force at Zero Velocity	Force at Peak Power	Eccentric: Concentric Mean Force Ratio
1	0.9	0.2	0.06	0.03	0.3	0.7	0.03
2	0.08	0.4	0.1	0.4	0.4	0.1	0.2
3	0.08	0.5	0.3	**1.0**	0.4	**1.2**	0.6
4	0.5	0.7	0.2	0.4	0.2	0.9	0.1
5	0.6	0.5	0.3	0.4	0.1	0.9	0.4
6	**1.1**	0.4	0.02	**1.1**	**3.5**	0.3	0.06
7	0.2	0.4	0.3	0.4	0.04	0.5	0.3
8	0.3	0.7	**1.4**	0.5	0.2	0.9	**1.5**

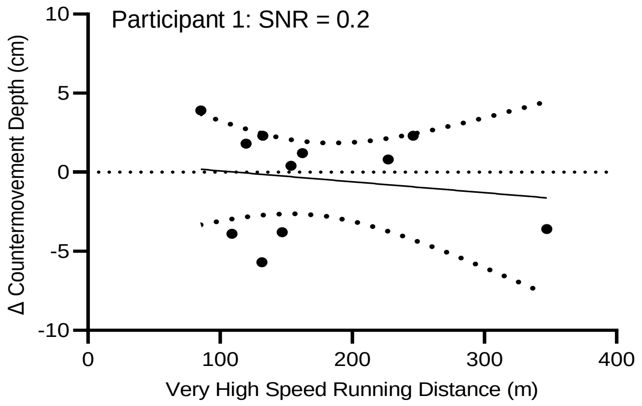
Participant	High-intensity decelerations						
	Jump Height	Countermovement Depth	Flight Time: Contraction Time	Eccentric Mean Braking Force	Force at Zero Velocity	Force at Peak Power	Eccentric: Concentric Mean Force Ratio
1	0.9	**1.1**	0.04	0.6	0.09	0.7	0.3
2	0.1	**2.2**	0.5	**1.3**	0.6	0.01	0.05
3	0.08	0.1	**1.0**	0.2	0.2	0.8	0.2
4	0.3	0.4	0.5	0.3	0.4	0.1	0.3
5	0.5	**1.6**	0.2	**1.1**	0.2	0.5	0.1
6	0.5	0.5	0.1	0.5	0.6	0.09	0.09
7	0.05	**1.4**	0.3	0.4	0.1	0.7	0.6
8	0.7	0.2	0.9	0.9	0.5	0.8	**1.3**

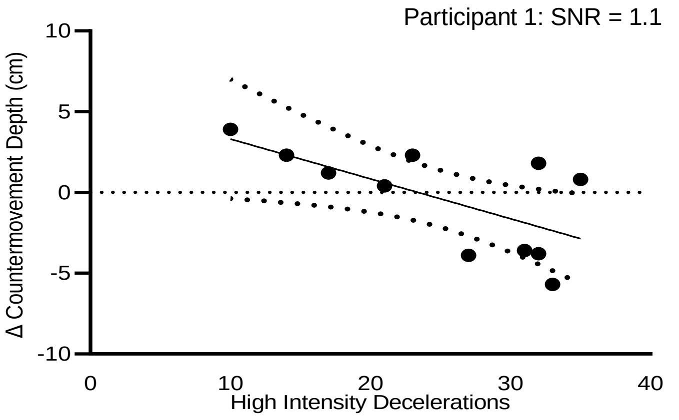
Table 9. Data from the relationships between the physical load and jump variables for participant 1.

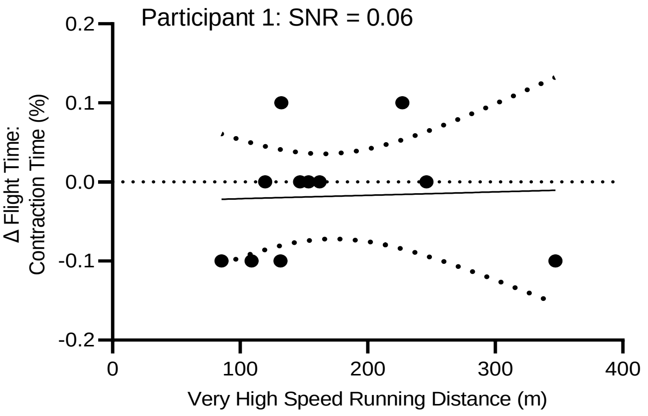
Physical Load Variable	Jump Variable	Gradient	95% Confidence Intervals	R^2	p	Difference from zero	Signal-to-noise ratio
Very High-Speed Running	Jump Height (cm)	0.014	-0.001 to 0.029	0.3	0.07	Not Significant	0.9
	Countermovement Depth (cm)	-0.01	-0.04 to 0.02	0.02	0.63	Not Significant	0.2
	Flight Time: Contraction Time	0.0000	-0.0007 to 0.0008	0.0019	0.90	Not Significant	0.06
	Eccentric Mean Braking Force (N)	0.0	-0.3 to 0.3	0.0004	0.95	Not Significant	0.03
	Force at Zero Velocity (N)	-0.3	-0.2 to 0.9	0.04	0.55	Not Significant	0.3
	Force at Peak Power (N)	0.2	-0.1 to 0.6	0.2	0.17	Not Significant	0.7
	Eccentric: Concentric Mean Force Ratio	0.00	-0.02 to 0.02	0.0006	0.94	Not Significant	0.03
High-intensity Decelerations	Jump Height (cm)	0.1	-0.0 to 0.3	0.3	0.08	Not Significant	0.9
	Countermovement Depth (cm)	-0.2	-0.5 to -0.0	0.4	0.03	Significant	1.1
	Flight Time: Contraction Time	-0.000	-0.007 to 0.006	0.0009	0.93	Not Significant	0.04
	Eccentric Mean Braking Force (N)	-1.5	-3.9 to 0.9	0.2	0.21	Not Significant	0.6
	Force at Zero Velocity (N)	1	-10 to 12	0.004	0.85	Not Significant	0.09
	Force at Peak Power (N)	-2	-5 to 1	0.2	0.17	Not Significant	0.7
	Eccentric: Concentric Mean Force Ratio	0.1	-0.1 to 0.2	0.05	0.51	Not Significant	0.3

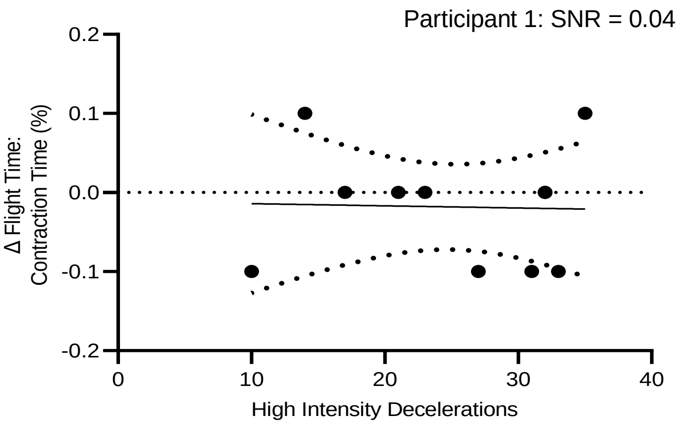

Participant 1: SNR = 0.9
Δ Jump Height (cm)
6
3
0
-3
-6
0
100
200
300
400
Very High Speed Running Distance (m)

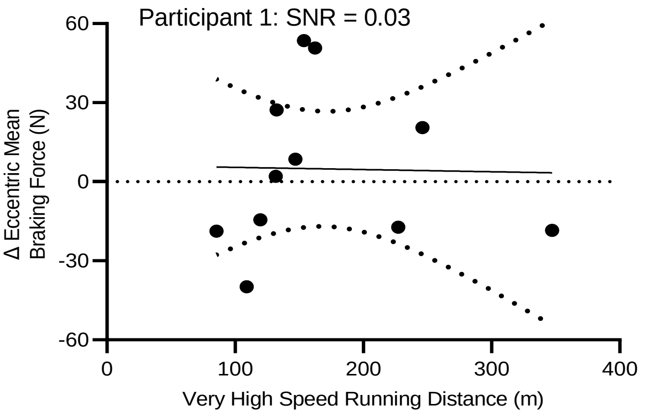

Participant 1: SNR = 0.9
Δ Jump Height (cm)
6
3
0
-3
-6
0
10
20
30
40
High Intensity Decelerations

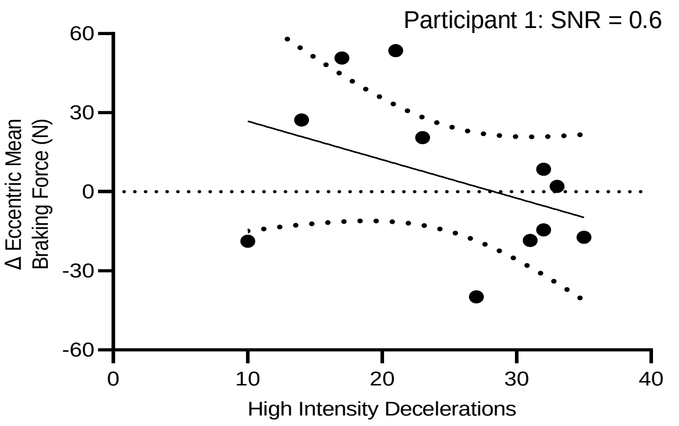

Participant 1: SNR = 0.2
Δ Countermovement Depth (cm)
10
5
0
-5
-10
0
100
200
300
400
Very High Speed Running Distance (m)


Participant 1: SNR = 1.1
Δ Countermovement Depth (cm)
10
5
0
-5
-10
0
10
20
30
40
High Intensity Decelerations


Participant 1: SNR = 0.06
Δ Flight Time:
Contraction Time (%)
0.2
0.1
0.0
-0.1
-0.2
0
100
200
300
400
Very High Speed Running Distance (m)


Participant 1: SNR = 0.04
Δ Flight Time:
Contraction Time (%)
0.2
0.1
0.0
-0.1
-0.2
0
10
20
30
40
High Intensity Decelerations


Participant 1: SNR = 0.03
Δ Eccentric Mean
Braking Force (N)
60
30
0
-30
-60
0
100
200
300
400
Very High Speed Running Distance (m)


Participant 1: SNR = 0.6
Δ Eccentric Mean
Braking Force (N)
60
30
0
-30
-60
0
10
20
30
40
High Intensity Decelerations

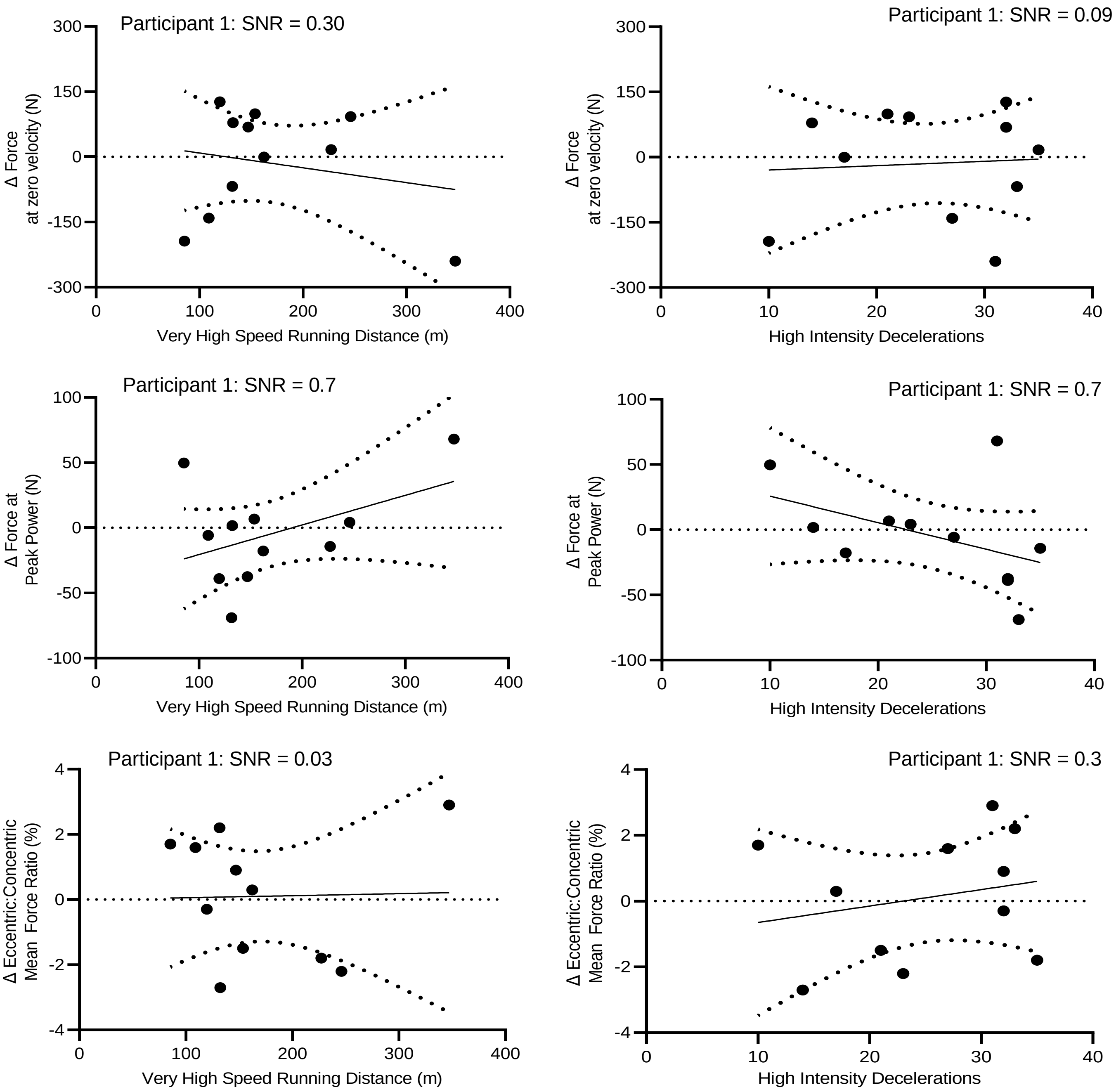


Figure 12. Participant 1: Plots of all relationships between the physical load variables and the countermovement jump variables. The solid line is a linear regression fit and the dashed lines show the 95% confidence intervals. Only the relationship between countermovement depth and high intensity decelerations had a signal-to-noise ratio (SNR) of greater than 1.0.

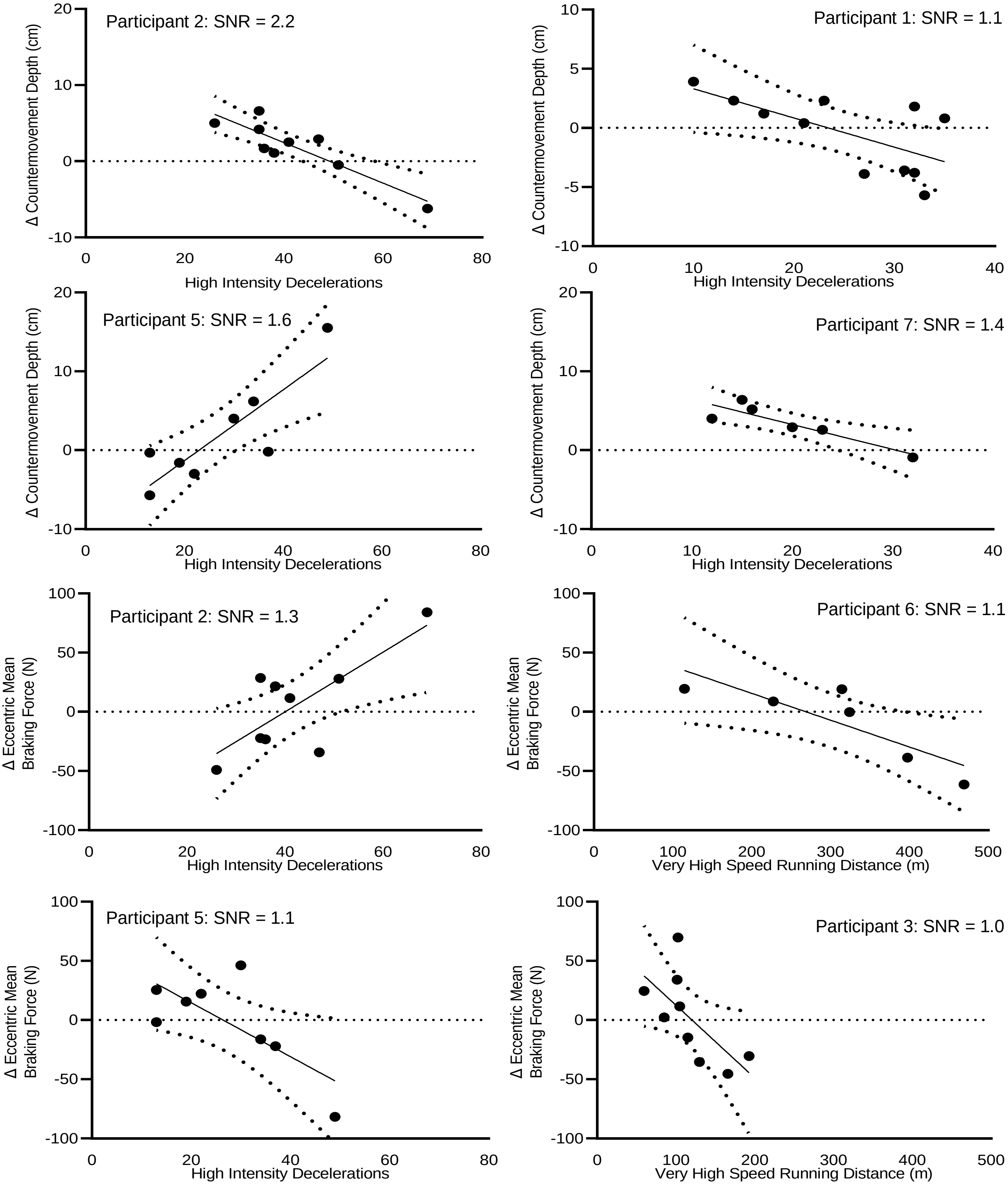


Figure 13. All participants: Plots for relationships between a match load variable and countermovement depth and eccentric mean braking force in which the signal-to-noise ratio was greater than 1.0. The solid line is a linear regression fit and the dashed lines show the 95% confidence intervals.

Chapter 5: Discussion

5.1 Key findings

The purpose of this study was to determine the countermovement jump variables that are the most sensitive to changes in the physical match load on a player in a competitive football match. The most sensitive jump variables could then be used by the coach to monitor neuromuscular fatigue. The key finding from the study is that there was no significant change in jump height from pre-match to post-match. The results from the current study suggest that jump height may not be a good marker of neuromuscular fatigue in professional players. Furthermore, during the 20-week analysis period in this study, there were no universally consistent relationships between the change in a jump variable due to a match and the physical load on a player. A significant relationship between countermovement depth and the number of high-intensity decelerations was observed in four of the eight participants and other significant relationships were observed in individual participants, but these were specific to the individual participant. These results suggest that force-time variables from a countermovement jump test may not be sensitive to the change in the match load.

5.2 Countermovement depth

A key finding of the current study was that there was no significant change in countermovement depth as a result of a match, and no significant relationships were observed with match load. On an individual level, four of the eight participants showed a significant relationship between the number of high-intensity decelerations in a match and the change in countermovement depth. However, the direction of the relationship was not the same in all participants. Three of the four participants had a negative relationship, whereas one participant had a positive relationship. Therefore, the absence of universally consistent findings relating to the change in the countermovement depth of a jump suggest that it may be too individualised to be meaningful to generalise to other populations for use in fatigue monitoring. However, the reasons for the differences in the direction of the relationship between individuals may be explained by the contrasting literature relating to the altered movement strategies adopted when fatigued, to maintain jump height during a countermovement jump.

The reasons why an individual in a fatigued state may increase their countermovement depth are unclear. Gathercole et al. (2015b) reported that many structural and neural processes are responsible for the changes that occur during stretch-shortening cycle activities when fatigued. They speculated that changes in the neuromuscular reflex sensitivity may account for the changes in physical performance, and this mechanism is used to protect the musculature from further damage when exercise-induced fatigue is present. This mechanism is substantiated in the literature. Avela et al. (1999) reported that following a marathon run impairments in exercise involving stretch-shortening muscle actions were still present six days after exercise completion. The impairments in exercise performance were thought to be as a result of reduced reflex sensitivity, and a significant decrease in the stretch-resisting force of the muscle was detected. It was suggested that this reduction in force production was due to disfacilitation and presynaptic inhibition and was accompanied by increases in markers of muscle damage, including creatine kinase and troponin 1. Although not discerned in the current study, a greater countermovement depth may have been as a result of a decreased reflex sensitivity following fatiguing exercise involving a large amount of stretch-shortening cycle actions. The study by Avela et al. (1999) was in marathon runners, however it can be speculated that the high number and intensity of repeated stretch-shortening cycle muscle actions to perform high-speed running, sprinting and rapid changes of direction during a football match can cause significant neuromuscular disturbance. The results from the current study need to be interpreted with caution as the small sample size reduces the statistical power of inferences made. However, given that the individual analysis revealed some meaningful relationships, it seems that countermovement depth may be sensitive to subtle changes in muscle function and may therefore be used for individualised monitoring of neuromuscular fatigue.

Previous literature has reported other alternative neuromuscular movement strategies apparent during a countermovement jump, which may cause different changes in countermovement depth following a fatiguing stimulus and highlights the complexity of neuromuscular fatigue. It has been suggested that a reduction in eccentric displacement during a countermovement jump is also a commonly used strategy to maximise performance output whilst in a fatigued state (Rodacki et al., 2002). Augusston et al. (2006) observed significant decreases in hip and knee flexion during the take-off phase of a hopping task in a fatigued condition compared with the non-fatigued condition, which coincided with reduced knee and ankle joint power and ground reaction force during take-off. The study required participants to repeatedly hop for maximal distance and reported on horizontal propulsion and antero-posterior horizontal ground reaction force, which was therefore reflecting a different movement skill to that of the current study. Despite the differences in methodology, the current study and other studies employing vertical countermovement jump testing have reported findings consistent with those reported by Augusston et al. (2006). Rodacki et al. (2002) observed significantly reduced eccentric displacement for participants completing the countermovement jump protocol in a fatigued state compared to non-fatigued. Although joint angles at all three lower limb joints showed changes indicative of a reduced eccentric displacement (ankle: 94.1 ± 7.0 vs. 97.7 ± 7.6; knee: 89.5 ± 12.4 vs. 97.1 ± 12.2; hip: 68.6 ± 13.5 vs. 69.9 ± 12.3 degrees; non-fatigued vs. fatigued respectively), the authors observed the change in knee angle to be the most significant change effecting countermovement depth during the countermovement jump protocol. However, the fatiguing protocol in the study was a knee flexion and extension task to failure, therefore fatiguing the musculature specific to movement of the knee joint. Given the multi-joint movement of a countermovement jump, muscles around the hip such as the gluteus maximus and adductor magnus, are powerful hip extensors during a countermovement jump and were not fatigued within the used protocol. However, the reduction in countermovement depth and the significance of knee joint kinetics when jumping whilst fatigued has been supported by Kippo et al. (2020), who observed that knee joint kinetics have the strongest correlations with countermovement jump height.

The reduction in eccentric displacement may also be a subconscious strategy to avoid further muscle damage in a fatigued condition. If the musculo-tendinous units are required to endure greater eccentric contraction and become relatively more stretched, sarcomere slipping may occur and result in myofibrillar disruption and poorer performance output (Kippo et al., 2020). Furthermore, these authors reported that the increase in leg stiffness in a fatigued state maintains the elasticity and efficiency of the stretch-shortening cycle to maintain performance output. This provides a possible explanation to support the idea that experienced performers can change their jump technique to maintain jump output. This may also be apparent in the current study, which observed some significant changes in countermovement depth in response to changes in physical match load in some individual participants, while no such changes were evident when assessing jump height. In addition, although in the current study lower limb angles were not recorded, participants who alter their movement strategy in a fatigue state by performing a vertical jump with a shallower countermovement depth could be the result of this sub-conscious strategy performers use to reduce the eccentric 'stretch' of the musculature and maintain performance output.

These results are only indicative of some significant relationships between countermovement depth and high-intensity decelerations observed in the current study, and therefore the limitations to generalising these findings are apparent. However there was significant individual variation in the current study. For example, individual relationships were observed between the physical load variables and countermovement depth of varying magnitudes and direction. Therefore it seems possible that individuals may perform the countermovement jump testing with different compensatory mechanisms while fatigued so as to alter their movement pattern and attempt to maintain jump output. The reasons explaining why fatigued individuals may adopt different compensatory movement strategies during a countermovement jump are unclear. However, fatigue is a multi-factorial and complex phenomenon that consists of many processes and mechanisms which form the fatigue-related responses to exercise. As a result, there are large individual differences in the response to exercise and the recovery from fatigue in the days following exercise (Taylor, 2012b). Therefore fatigue monitoring testing batteries need to be individualised to cater for these differences. In the current study differences in countermovement depth after the match may be as a result of some players needing more time and a greater amplitude in countermovement displacement to produce more force eccentrically to maintain jump height. Others may sub-consciously avoid dropping into a greater eccentric 'stretch' due to the high level of eccentric muscle damage incurred. However, both strategies may be representative of neuromuscular fatigue. The countermovement jump monitoring strategies should be tailored to the individual, and sports practitioners need to be able to determine how each player responds to fatigue and be able to set individual fatigue detection thresholds (Gathercole et al., 2014). Therefore, this may indicate that practitioners should design neuromuscular screening batteries bespoke to each individual and based upon the identification of which variables may be sensitive to fatigue and which subsequent compensatory strategies individuals may commonly use to maintain performance output during countermovement jump testing.

5.3 Jump height

Observations from the current study show no significant changes in jump height as a result of a competitive football match. Moreover, only one significant relationship was observed between jump height and match load from the individual analysis. These results could agree with previous literature suggesting that participants are able to modify their jumping strategy to maintain jump height even in the presence of neuromuscular fatigue. However, the lack of consistent significant relationships when assessing the other countermovement jump variables with physical match load suggests this is unlikely to be the case. Furthermore, the non-significant changes in jump height contrasts with previous literature reporting a decrease in countermovement jump performance immediately, and at 72 hours following a football match within similar populations (Ispirlidis et al., 2008; Magalhaes et al., 2010; Nédélec et al., 2014; 2012; Rampinini et al., 2011; Thomas et al., 2017). Therefore, it could be speculated that in the current study the muscle damage induced by the football matches may not have been enough to cause the participants to alter countermovement jump height. In addition, the post-match countermovement jump assessment was performed at one timepoint, two days following a football match, and therefore the participants may have been sufficiently recovered. As a result, future research should include more countermovement jump assessment timepoints to observe and gain further clarity on the time-course of recovery in jump height following a competitive football match.

In the current study, one participant had a significant relationship between very high-speed running distance and the change in jump height following a match, reflecting an association between an increase in very high-speed running and reductions in countermovement jump height. Interestingly, this participant also had the highest average match load (very high-speed running distance: 308.1 ± 125.1; high-intensity decelerations: 60.2 ± 8.0). Thorpe and colleagues (2017) reported that the slope of regression model they used indicated that every ~400m increase in high-speed running distance led to a one unit decrease in the player's perceived rating of fatigue. In the current study participant six was the only participant who recorded a very high-speed running distance of over 400m in a match, and therefore may be the only participant who performed enough high-speed running distance to elicit neuromuscular disturbance and changes in jump height as a result of fatigue. Despite differences in the velocity threshold set by Thorpe and authors for high-speed running distance compared to that of the current study (14.4 vs. 23.4 km/h, respectively), it could be suggested that the very high-speed running distance covered required to affect jump height may be greater than 400m. This may suggest that measuring jump height and task output may only be sensitive to significant neuromuscular disturbance following a large amount of eccentric and stretch-shortening actions. However, practitioners and coaches are required to determine more subtle changes in neuromuscular fatigue to prevent the negative outcomes associated with accumulated neuromuscular fatigue on performance output and injury risk. The use of jump height as a marker of neuromuscular fatigue may therefore be insensitive to small changes in fatigue status and highly variable for use on a group level and for all players within a squad.

The results from the current study suggest that jump height may not be useful to inform on a player's fatigue status. However, the use of jump height to inform on neuromuscular fatigue may become important based upon a player's individual physical playing profile. Wingers and forwards have been shown to cover the highest amount of high-speed running distance during football match play (Buchheit et al., 2010). Furthermore, high-speed running requires high muscle tendon tension and significant muscle fibre recruitment at high force to perform, which causes a large amount of neuromuscular strain (Laursen & Buchheit, 2019). In the current study the individual who covered the highest average very-high speed running distance and high-intensity decelerations showed a significant association between an increase in match load and a decrement in jump height. Therefore, it could be speculated that the use of jump height may be dependent on playing position and sensitive to fatigue for wingers and forwards who perform large amounts of high-speed and high-intensity movements in a match, and elicit a large amount of neuromuscular fatigue. However, further research is required to substantiate these speculations.

The absence of significant changes in jump height highlights its limited use in detecting neuromuscular fatigue. This finding is consistent with previous research reporting an absence in change in jump height following fatiguing exercise (Cormack et al., 2008a; Gathercole et al., 2014). Thorpe et al. (2017) performed countermovement jump testing on 12 days of a 17-day football training period (which included all post-match timepoints 24, 48 and 72 hours), and observed no significant correlations between jump height and the total amount of high-speed running distance. Although not reported, these observations may be consistent with the idea that experienced performers can alter their jumping mechanics to maintain jump height. Alternative jump variables have been reported to be more sensitive to accumulated fatigue. However, jump height may still be an important performance marker when assessing an athlete's readiness to train as it is considered to be a key movement in sports performance. Jump performance can be modified dependent on numerous neuromuscular mechanisms, and therefore, jump height should be assessed alongside other alternative mechanical variables associated altered jump technique as a result of fatigue.

The validity of the use of the flight time calculation to determine jump height has also been questioned (Gathercole et al., 2015d). The use of flight time calculations to determine jump height from force plate data is the simplest method to use when compared with other methods involving calculations of vertical displacement of the centre of mass and jump velocity data (Moir, 2008a). However the mathematical assumptions associated with indirect calculations of jump height make the variable prone to error and possibly insensitive to changes in neuromuscular function. The equations used to measure jump height include assumptions of uniform acceleration and no change in the vertical displacement of the centre of mass between take-off and landing (Moir et al., 2008b). Therefore it assumes that jumpers do not 'tuck' their legs or 'push' their legs backwards, changing their posture during the jump and over-estimating jump height. Although in the current study the researchers attempted to control for this by cueing the jumpers, subtle changes in posture during flight may have impacted the calculation and resulted in erroneous values. The use of jump height has been reported as a sensitive measure to detect neuromuscular fatigue and the external validity with team sports performance renders jump height an important performance measure for practitioners to be aware of when assessing readiness to train. However, the contrasting literature relating to the use of jump height highlights the need for practitioners to assess this output variable with caution and use jump height in combination with alternative jump variables to gain greater clarity on an individual's neuromuscular function.

5.4 Flight time: contraction time

Some isolated significant changes occurred when assessing flight time: contraction time for individuals. However there were no consistent relationships between the change in flight time: contraction time with either of the physical match load variables. Therefore, when assessing the group analysis, the change in flight time: contraction time was not influenced by the physical load of the match. This is consistent with previous literature reporting that flight time: contraction time only had a small decrease immediately post-game, before returning to baseline after 24 hours (Gathercole et al., 2014). This may suggest that the use of flight time: contraction time to monitor fatigue in team sports following a schedule which includes a rest day immediately after the day of a match and the next training session two days after the match (~48 hours) is not required. This may be because the physical mechanisms which cause subtle acute decrements in flight time and contraction time following a fatiguing stimulus have recovered enough to produce the same performance output as baseline by 48 hours. Moreover Cormack et al. (2008b) reported that fight time: contraction time could be important for detecting neuromuscular impairments from longer periods of deliberate non-functional over-training, as opposed to acute low frequency fatigue. As a result, given that in the current study the players followed a typical weekly schedule and countermovement jump testing was completed 48 hours after a single match, it could be speculated from these results that this variable is not sensitive to acute fatigue mechanisms which last more than 24 hours and may not be appropriate to use for player fatigue monitoring to inform on post-match recovery and readiness to train.

In contrast, previous research has reported that neuromuscular function may not be restored until four days after a team sports match. Mclean et al. (2010) performed countermovement jump testing one day and four days after a rugby league match. They observed flight time to be reduced at 24 hours post-game and remained reduced until returning to baseline at four days, which suggests that neuromuscular fatigue measures may take up to four days to return to baseline following a rugby league match. However measurements were not recorded at 48 hours and 72 hours after the match to determine the recovery profile over the days following the match. Cormack et al. (2008a) observed flight time, mean power, mean force and flight time: contraction time from a countermovement jump to all be substantially diminished at 24 hours following an Australian rules match, with all variables returning to baseline between 72-96 hours. However, like the research by McLean et al. (2010), these authors did not record measures of neuromuscular function at 48 hours post-match. This is substantiated in the literature reporting flight time: contraction time and other time-related alternative countermovement jump variables to show a trend towards recovery at 24 hours, and a further decline to 72 hours. The absence of significant findings relating to flight time: contraction time in the current study is contradictory to the research reporting the variables importance in neuromuscular fatigue monitoring. However, given the timing of the testing in the current study, including assessment time-points at 24 hours and 72 hours after the match may have provided a greater understating of an individual’s recovery profile following neuromuscular fatigue incurred during a match.

The marked differences in the literature regarding the use of flight time: contraction time for neuromuscular fatigue monitoring may be reflective of the variables reported limitations. For example, when assessing countermovement jump variables which inform on an individual’s altered movement strategy or technique to perform the countermovement jump, the proposed ‘alternative’ jump variables have a high degree of co-linearity. As a ratio variable flight time: contraction time has multiple contributory variables. As a result, reporting flight time: contraction time on its own may be inefficient. Previous work has observed significant changes in flight time: contraction time and not reported whether this change represented an increase in contraction time as a result of a decrease in musculo-tendon stiffness of the lower limbs when fatigued or a change in flight time commonly used to determine jump height output. More recently authors have reported the change in flight time: contraction time alongside changes in flight time, contact/contraction time and total duration, and the change in flight time: contraction time has been reported to be primarily as a result of the change in contraction time (Cormack et al., 2008a; Gathercole et al., 2014). These authors reported significant changes in flight time: contraction time (-7.7 and -7.8%) with small changes in flight time (-0.8 to -0.7%) and large changes in total duration (7.6%), speculating that the latter changes must therefore be reflective of an increase in contact/contraction time. This research supports the use of alternative jump variables relating to the mechanics of the jump, such as contraction time, to be more sensitive to change in neuromuscular state than commonly used output variables such as jump height and flight time. Therefore the use of contraction time in isolation may provide a clearer understanding of the movement strategy used to maintain jump output in a fatigued state as opposed to flight time: contraction time.

The absence of significant changes in the current study may also reflect the insensitivity of contraction time to fully assess altered movement strategy. The contraction time variable is defined as the start of the movement to take off. Therefore, incorporating the eccentric and concentric phase of the countermovement jump. Research has reported that the eccentric phase of the countermovement jump may be affected following fatiguing team sports performance, due to the large number of eccentric and stretch-shortening cycle actions required for performance. Gathercole et al., (2015b) observed an increase in eccentric duration following fatiguing exercise. These authors also noted a greater magnitude of negative velocity during the eccentric phase. Therefore, given that both duration and velocity of the eccentric phase was greater, although not reported, it can be deduced that eccentric displacement would have also been increased. This is in agreement with previous work observing an increase in eccentric displacement during a countermovement jump following fatiguing exercise (Avela et al., 1999). The increase in velocity, duration and/or depth in the eccentric phase of the jump may limit performance decrement in the concentric phase of the jump in the presence of neuromuscular fatigue (Gathercole et al., 2015b). Therefore, it can also be argued that fatigue-related changes in the eccentric phase may be masked by changes in the concentric phase to maintain performance. For example, an increase in the length of the muscle-tendon units during the eccentric phase is followed by a greater efficiency and more work done in the concentric phase of stretch-shortening cycle activity (Kubo et al., 1999). Assessing the influence of the phases on one another in the presence of fatigue requires further research. However, when assessing contraction time, which incorporates both the eccentric and concentric phase together, changes in the eccentric or concentric phase may act to maintain performance output in a countermovement jump to account for fatigue-induced inefficiencies in the opposing phase. As a result, practitioners should assess changes in both the eccentric and concentric phase separately to gain greater clarity and avoid using variables which combine the eccentric and concentric phases of the jump which may mask any fatigue-related neuromuscular changes present.

There were large individual differences apparent in flight time: contraction time when assessing the results from the current study. Considerable individual differences were also observed in previous work (Gathercole et al, 2014). Individuals may exhibit large individual variability in their recovery profile following fatigue, and this is reflected in neuromuscular fatigue monitoring. Therefore, this supports an individual approach to screening and monitoring for neuromuscular fatigue and may also support the idea that each individual may need a tailored monitoring battery which encompasses multiple testing procedures which have been shown to be sensitive to fatigue for each individual. Although the time-efficiency and effectiveness of this approach may be questioned, the results from the current study further highlight the importance of individual fatigue monitoring.

5.5 Eccentric mean braking force

There was no significant relationship between eccentric mean braking force and physical march load in the current study. However, the single-subject analysis revealed four participants had significant relationships between eccentric mean braking force and the physical match load variables. Previous work attempting to determine neuromuscular status from a countermovement jump have commonly used jump height and peak power. However, as previously discussed, experienced performers may be able to alter the mechanics of the jump to maintain the same output. As a result, other mechanical variables are of interest. Changes in the eccentric phase of the jump have been reported as indicative of neuromuscular fatigue following fatiguing exercise (Cormack et al., 2008a; Gathercole et al., 2015b; Kennedy & Drake, 2017). Despite eccentric muscular contraction being a fundamental component to neuromuscular function and stretch-shortening cycle movements which are apparent in sports performance, the assessment of eccentric function during a countermovement jump to inform on fatigue status is often overlooked (Gathercole et al., 2015b).

Variables relating to the eccentric phase of the countermovement jump have previously been reported to have an acceptable reliability (CV < 5%; Cormie et al., 2009; 2010, McMahon et al., 2019). In the current study the CV of eccentric mean braking force was also indicative of a reliable test measure. The results from the group analysis revealed no significant changes as a result of a competitive football match, and no significant relationships were observed with the physical match load variables. These results suggest that the force produced during the eccentric braking phase of the jump may be insensitive to changes in exercise-induced neuromuscular fatigue. In non-fatigued subjects Aboordarda et al. (2013) observed that adding an additional elastic force to the eccentric phase of the countermovement jump improved jump performance. The use of the downward tensile force increased peak eccentric ground reaction force. The increase in force production in the eccentric phase and greater stretch in the muscle-tendon units caused a greater build up and recovery of stored elastic energy and enhanced vertical ground reaction force in the concentric phase, power output, net impulse and jump height. This phenomenon has been substantiated by Kubo et al. (1999) who as previously mentioned, implied that an enhanced lengthening of the muscle-tendon-complex resulted in significantly more work performed in the subsequent concentric phase of the stretch-shortening cycle activity. Given the previously reported literature suggesting that athletes modify their jumping technique to maintain jump height in a fatigued state and the reported importance of eccentric force production in jump height performance, it could be speculated that the insensitivity in jump height to changes in neuromuscular fatigue may also be apparent in eccentric force production variables.

Time and velocity-based variables relating to how the force is produced may be more of interest in assessing subtle changes in fatigue status. For example, the current study shows some consistencies relating to changes in countermovement depth and the physical match load in certain individuals. Moreover studies have reported that increasing segment velocity during the eccentric phase rapidly shortens the unweighting phase and allows the development of ground reaction forces earlier in the phase while the quadriceps continue to lengthen. The faster eccentric loading enhances the active state of the actin-myosin cross-bridge formation in preparation for the concentric phase to improve peak power output (Sheppard et al., 2007). Gathercole et al. (2015b) reported that at 72 hours after fatiguing exercise minimum velocity was improved, which may suggest that fatigued athletes can increase eccentric velocity to maintain task output in spite of a decrement in concentric muscular function. In addition, in a fatigued state when micro-traumas to muscle contractile units cause an inefficiency in force production, this phase may require more time in order to allow the eccentric force to be produced and result in the maintenance of jump height and performance outcome (Gathercole et al., 2015b). As a result eccentric velocity and duration may be better predictors of neuromuscular fatigue. However it seems that an individual approach is required in order to determine the specific altered movement strategy used to prevent a reduction in countermovement jump performance.

The results from the current study revealed that four participants had a significant relationship between physical match load metrics and eccentric mean braking force, with three of these participants having an inverse relationship. This demonstrated that an increase in match load was evident with a subsequent reduction in eccentric mean braking force. The difference between subjects in any significant findings may be as a result of differences in eccentric strength profiling which will result in differences in how many eccentric actions a player will perform, the physiological cost and fatigue response of these actions and the recovery and restoration of eccentric function after fatiguing exercise. Furthermore, there are positional differences observed in physical loading during a football match. It is commonly reported that attackers perform the highest number of high-intensity actions during a match, while central defenders perform the lowest (Buchheit et al., 2010). Wingers, wide attackers and full-backs have been reported to perform the greatest frequency of high-intensity bouts compared with other positional roles because of the positions' usual role to perform repeated sprints to get away from defenders into space and generate goal scoring opportunities and their need to sprint on transition to get forward to join an attack or perform recovery runs to mark the winger and help in defence (Buchhde eit et al., 2010; Carling et al., 2012; Di Salvo et al., 2009). Furthermore, the recovery time between high-intensity efforts and the intensity of the work performed during this recovery time significantly varied between positions (Carling et al., 2012). Therefore, it could be speculated that individuals who play in positions who perform a greater volume, intensity or density of high-intensity efforts and eccentric, stretch-shortening cycle actions may experience greater changes in eccentric force production while fatigued. However, this trend was not apparent in the current study as the four participants who showed a significant relationship between eccentric mean braking force and physical load variables included one central defender, two central midfielders and one attacker. Interestingly, of these four participants, three had the highest volume of very high-speed running and three also had the highest number of high-intensity decelerations from the matches played. Therefore, this could reflect that there may not have been enough muscle damage in the other athletes to significantly change eccentric mean braking force during a countermovement jump. However, the current study did not directly measure muscle damage and therefore further research is required to substantiate this speculation.

One methodological limitation reported by Carling et al. (2012) was that their study recruited a small number of participants from one professional football club. Similar to the current study, the results may only be a reflection on that particular team. Despite contradictory reports, it seems that given the importance of eccentric contraction in the stretch-shortening cycle and high-intensity actions performed during a match, and the reported importance of these eccentric variables in determining jump height during a countermovement jump, the assessment of eccentric time, velocity and force production variables during a countermovement jump task may be an effective measure of neuromuscular fatigue for certain individuals. However, it is evident that individual attention is required when determining whether eccentric variables are sensitive to neuromuscular fatigue.

5.6 Force at zero velocity

Force at zero velocity has been shown to display changes indicative of altered neuromuscular function during a high-intensity and high-volume rugby training programme (Gathercole et al., 2015b; Kennedy & Drake, 2017). These authors reported a large magnitude of change at 24 hours and 48 hours after baseline testing, in addition to a meaningful correlation between force at zero velocity and the answers to a subjective wellness questionnaire. Despite reports of the limitations of false or deceiving responses to subjective wellness questions, this type of survey is the most commonly used and practically efficient means of monitoring a squad of athletes (Saw et al., 2016). In addition to the validity of using force at zero velocity as a measure of neuromuscular fatigue, a good level of reliability has also been reported (Gathercole et al., 2015b). In the current study there were no significant associations between force at zero velocity and very high-speed running distance or number of high-intensity decelerations when analysing group average data. Moreover, only one significant relationship was observed from the single-subject analysis. Previous work reporting that force at zero velocity may be a good indicator of neuromuscular fatigue has also reported it alongside significant changes in countermovement jump output variables such a jump height and peak power following fatiguing exercise, which is supported in the current study which observed no significant findings relating to the changes in jump height or force at zero velocity. As previously discussed, experienced performers can maintain jump output by altering their jump strategy, and therefore variables which have greater sensitivity to low intensity fatigue to show changes indicative of diminished neuromuscular function with an absence in change in countermovement jump output variables may be of greater importance.

5.7 Physical Load Variables

Very high-speed running distance has been commonly used to reflect training load. It has been shown to have a strong correlation with other training load variables which have also been cited as very good indicators of training load, such as ratings of perceived exertion (RPE; Rago et al., 2019). Interestingly, Thorpe et al. (2015) observed a positive correlation between high-intensity running distance and countermovement jump height, which they speculated to be as a result of a priming potentiation effect of a large amount of high-intensity running distance on the neuromuscular system. However, this study was only performed over a 17-day assessment period with a relatively small sample size and a large variance in high-speed running load (235-1528 metres). Despite positive reports for the use of high-speed running distance to quantify training loads incurred by the players, this variable will underestimate the total training load experienced as it does not reflect the repeated accelerations and decelerations experienced and the cardiovascular response to the training load. This limitation is also apparent when using high-intensity decelerations as a single variable to reflect training load, as it only captures a snapshot of the training demand. In addition, the current study used an absolute speed threshold to determine the speed at which a high-speed run and a high-intensity deceleration were recorded for the participants. This does not account for differences in maximum velocity capabilities and maximal aerobic speed thresholds, which will for example, influence the physiological fatigue responses to a given high-speed running volume. Therefore high-speed running distance may be a good indicator of total physical load, however the use of individual speed thresholds may provide a variable which can account for individual differences. In addition, successful football performance has a large cognitive as well as physical demand and external load variables do not account for the significant mental fatigue present during a football match, which may increase the perception of effort of physical actions performed during a match (Thomas et al., 2017). Therefore, other training load variables such as RPE may provide a greater all-round understanding of the match load.

5.8 Strengths of the Study

In the author's opinion there were some strengths in the study which could be used for future research. Firstly, the study design allowed access to elite academy footballers over a large period of time. Studies have recruited elite academy footballers over a short period of time (Oliver et al., 2008; Thorpe et al., 2015), and performed countermovement jump assessments over the course of a competitive season in rugby league and Aussie rules (Cormack et al., 2008b; McLean et al., 2010). However, implementing countermovement jump testing around competitive football matches and within normal training and match schedule, with the intention to do so over the course of a whole season, would have been the first within elite academy footballers. This provides information for practitioners working with this population.

Furthermore, the selection of countermovement jump and physical match load variables was novel to this research area. Using a combination of scientific and practical knowledge provided some novel rationale for the use of the selected variables. This study attempted to introduce some new variables from the ground reaction force of a countermovement jump to indicate fatigue, and also used some previously used variables to allow for support or refute of their use within neuromuscular fatigue monitoring. Also, using multiple measures of match load provides greater insight into the most appropriate variables to use.

Finally, the analysis technique provided an alternative method for analysing relationships between match fatigue and match load variables. Combining a natural experiment with a single-subject analysis and applying a linear regression to determine the signal-to-noise ratio of the observed relationships may provide a greater meaningfulness of the associations.

5.9 Methodological Limitations

There were some known methodological limitations to the study design used. The use of a randomised control trial is gold standard in research. The current study could have used a study design where investigators manipulated match load. Protocols designed to replicate football match load, such as the Loughborough Intermittent Shuttle Test have been used and shown to replicate some physical demands of football match play (Magalhaes et al., 2010). However, in an elite football setting with elite athletes, it would be difficult to arrange repeat testing over a long period of time to collect a suitable number of datapoints.

There are numerous logistical constraints to performing such research with elite athletes. The current study recruited elite academy footballers, who were required to carry out the technical and tactical plans set out by academy coaches and management. As a result the participants performed their regular training routines and there were some confounding variables which could not be controlled due to the real-world environment in which the study was performed. For example, changes in the training schedule as prescribed by coaching staff and team selection for each match. In a controlled study the investigators may wish to control playing conditions. Confounding variables in the current study may include environmental conditions (temperature, wind, humidity, precipitation and solar energy), whether it was a home or away match, the type of travel to games and the time of day, the physical condition of the pitch and changes in participant activity between the match and the post-match countermovement jump measurement (Giersch et al., 2019; Leite, 2017). The effect of some of these confounding variables may be negligible, however future research should investigate the effect of these on the match load variables during the match.

As discussed previously, a limitation to this study was the relatively small sample size. This limits the statistical power of the analyses, and also limits the generalisability of the results of the current study. These eight participants were all male academy footballers of a similar age and drawn from a homogenous population. Therefore, the relative inter-individual differences were expected to be small. However, given the highly individual responses shown when performing a countermovement jump in a fatigued condition, the current results are expected to only reflect those of the participants in the study. A similar study with more participants is needed to explore the possible range of responses between match load and match fatigue in elite male academy footballers.

In the current study, competitive matches over the course of the testing period in-season were viewed as a time-series of multiple datapoints with pre-test and post-test observations spaced at almost equal amounts of time in between. This study design of quasi-experiment is ‘highly rated’ in terms of establishing causality from a quasi-experimental design (Harris et al., 2006). In this study, only six to eleven matches (datapoints) were included within the data analysis from eight participants. The statistical power of the study to detect causality between match load and match fatigue would have been greater if data were analysed from matches across a full competitive season. For example, over the course of a season a team may be scheduled to play ~30-40 matches, therefore increasing the number of data pairs for each participants would have reduced the 95% confidence intervals in the gradient of the regression analysis and increased the signal-to-noise ratio (Hughes & Hase, 2010). Future research should aim to maximise the number of observations by using data from a whole season. The use of more participants and more datapoints would allow for interpretation of a wide range of possible relationships between different match load and match fatigue variables.

A number of the analyses resulted in no significant changes or relationships when comparing before and after a match and between physical load variables and jump variables. In addition, some of the changes seem to contradict what may be expected when a player has accumulated fatigue and impaired muscle function. There are a few confounding variables present which may explain these findings. For example, as discussed, the countermovement jump testing was conducted two days (~48 hours) after a match, which may be when players return to baseline neuromuscular function. As a result, measuring countermovement jump variables at multiple timepoints after the game (~24, 48 and 72 hours) may be better, as previous research has shown changes in countermovement jump variables up to 72-96 hours post-match (Cormack et al., 2008a; McLean et al., 2010) and well-conditioned players may have recovered by ~48 hours following a match (Hader et al., 2019). Therefore, the high training level of elite academy footballers may contribute to the absence of changes in some of the countermovement jump variables. Furthermore although standardisation procedures were put in place regarding the ability for players to perform a maximal effort in the days following a match, players are sometimes reluctant to perform explosive actions whilst fatigued.

5.10 Recommendations for Future Research

The novel analysis techniques used in this study could provide an alternative way to determine which countermovement jump variables are the most sensitive to change in physical match load and could therefore be used as an index of fatigue. Calculating the strength of associations and signal from the linear regression in relation to the noise provides a meaningful data which could be used in research of this nature moving forward.

Future research could attempt to gain a better understanding and definitive evidence of which countermovement jump variables are sensitive measures of match fatigue. The use of a controlled study where match load is manipulated may help determine which countermovement jump variables are most sensitive to changes in physical load. However, this type of testing is difficult to arrange with athletes because it would require a study with repeat intervention and testing over a long period outside of their normal routine.

To increase the number of data points collected and power of the data, researchers may look to employ a similar study design to the current study by collecting data over a longer period of time. This would allow for the supposed variety of individual responses to be observed.

Moreover, this study may benefit from including a criterion measure of fatigue. Including additional neuromuscular and biochemical markers of fatigue will provide more information on the validity of the countermovement jump variables for use as a marker of neuromuscular fatigue.

5.11 Practical application

In practice neuromuscular fatigue results in an inability to perform frequent high-intensity accelerations and decelerations and high-speed running effort and sprints (Cormack et al., 2008a). As a result players with a significant amount of fatigue perform more running at slower speeds and fewer high-speed running metres per minute. A reduction in vertical stiffness is the probable cause of these impairments in physical performance, especially that requiring a high number of eccentric and stretch-shortening cycle actions such as football. Although the performance output from a task such as the jump height from a countermovement jump is commonly used to determine fatigue status, the current study suggests that the use of a countermovement jump for neuromuscular fatigue monitoring may not be sensitive enough to changes in match load to give an indication on fatigue status following a match. However, given that some individual relationships were shown reflecting significant changes in countermovement jump variables following a match, it could be concluded that the current study concurs with other research suggesting that experienced and skilled performers can change their jump technique to maintain the same output. Sport scientists and coaches seeking means of monitoring neuromuscular fatigue to inform on individual player management should use alternative countermovement jump variables to jump height. Therefore in team sports, where sporting success is dependent not only on the performance output, but also on the timing and speed of this output (Gathercole et al., 2015b), practitioners should assess movement strategy in addition to task output to inform on neuromuscular fatigue.

Countermovement depth showed some strong relationships with changes in physical load within certain individuals from the single-subject analysis. In addition, the variable has shown a high level of reproducibility, suggesting that it can be used as a reliable measure to inform on fatigue status. However, it is evident from the inconsistencies in the data that there are substantial individual differences in the neuromuscular response and recovery from fatiguing exercise. In addition, these inconsistencies reflect differences in the neuromuscular movement strategy used to perform a countermovement jump in a fatigued condition. Practically, individual neuromuscular profiling using a countermovement jump is required to determine which variables best reflect any individual changes to jumping technique and potential changes in countermovement jump output. Once these variables are determined, this information has the potential to be used to inform on modifications to an individuals training programme to best prepare the individual for the following match.

Chapter 6: Conclusion

6.1 Conclusion

This study used novel analysis techniques to determine which variables from a countermovement jump were most sensitive to neuromuscular fatigue from a football match. Using both statistical and visual techniques in a group analysis and subsequent single-subject analysis allows for initial understanding of any phenomena relating to the change in jump variables in response to different physical loads during competitive matches, as well as more detailed individual analysis to understand the individual differences and trends that occur as a result of the differential responses to neuromuscular fatigue during a countermovement jump. This is apparent in the current study, with the single-subject analysis showing some findings which may be of statistical and practical significance. Both countermovement depth and eccentric mean braking force show some promise for assessing fatigue status on an individual level. Although the main finding from the study was the observation that there were no significant differences between pre and post-match for any of the countermovement jump variables and no universally consistent relationships, a key finding from the current study was that there were substantial individual differences present in the movement strategies used when performing a countermovement jump in a fatigued state. Therefore the countermovement jump variables used to inform on neuromuscular fatigue and readiness to train should either be tailored for each individual or practitioners should assess a full countermovement jump variable battery, which incorporates countermovement jump output and jump technique variables to account for markedly different neuromuscular fatigue responses to physical load.

Chapter 7: References

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Chapter 8. Appendices

8.1 Appendix A – Ethical approval

College of Health and Life Sciences Research Ethics Committee (DLS)
Brunel University London
Kingston Lane
Uxbridge
UB8 3PH
United Kingdom

www.brunel.ac.uk

9 November 2018

LETTER OF APPROVAL

Applicant: MR BEN MALE

Project Title: Jump biomechanics as an indicator of fatigue status in footballers

Reference: 11030-MHR-Nov/2018- 14704-2

Dear MR BEN MALE

The Research Ethics Committee has considered the above application recently submitted by you.

The Chair, acting under delegated authority has agreed that there is no objection on ethical grounds to the proposed study. Approval is given on the understanding that the conditions of approval set out below are followed:

- Risk Assessment - Please comment whether CMJ will be completed barefoot or shod. In the latter condition landing with football boots on a force plate not covered with artificial turf or other appropriate material may lead to slip and injury. The situation and the possibility of risk due to slip should be acknowledged and appropriate measures to reduce the risk should be considered.
- The agreed protocol must be followed. Any changes to the protocol will require prior approval from the Committee by way of an application for an amendment.

Please note that:

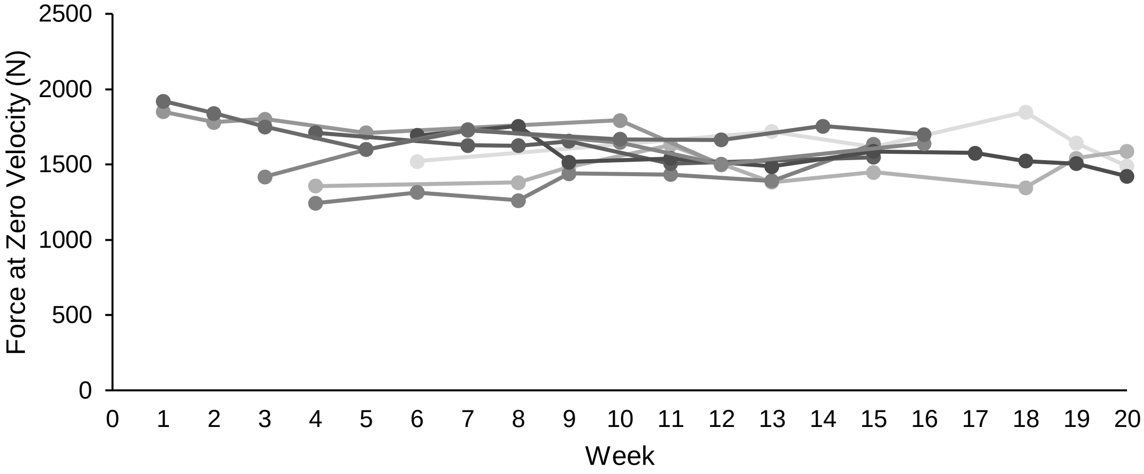
- Research Participant Information Sheets and (where relevant) flyers, posters, and consent forms should include a clear statement that research ethics approval has been obtained from the relevant Research Ethics Committee.
- The Research Participant Information Sheets should include a clear statement that queries should be directed, in the first instance, to the Supervisor (where relevant), or the researcher. Complaints, on the other hand, should be directed, in the first instance, to the Chair of the relevant Research Ethics Committee.
- The Research Ethics Committee reserves the right to sample and review documentation, including raw data, relevant to the study.
- You may not undertake any research activity if you are not a registered student of Brunel University or if you cease to become registered, including abeyance or temporary withdrawal. As a deregistered student you would not be insured to undertake research activity. Research activity includes the recruitment of participants, undertaking consent procedures and collection of data. Breach of this requirement constitutes research misconduct and is a disciplinary offence.

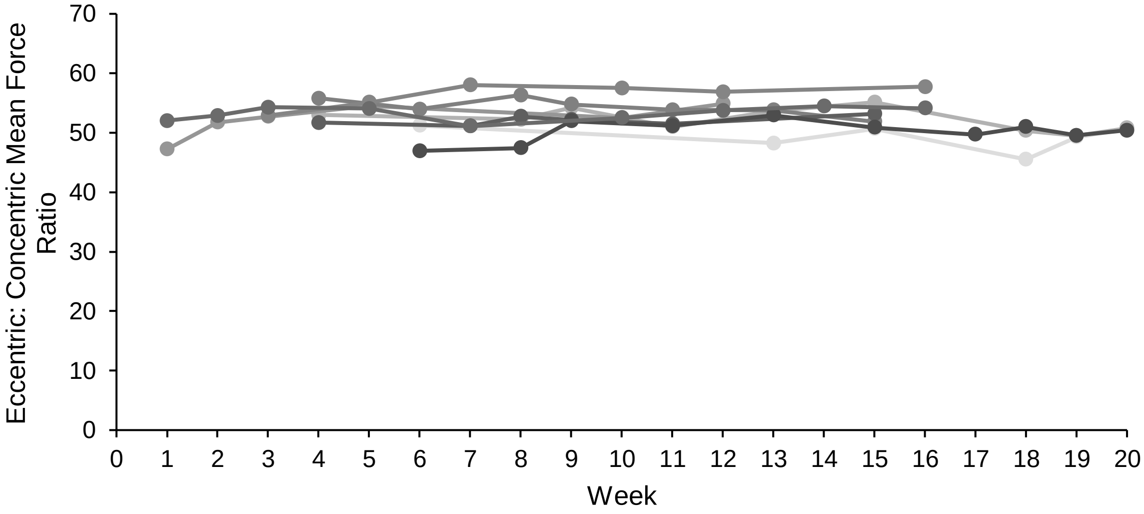
Professor Christina Victor

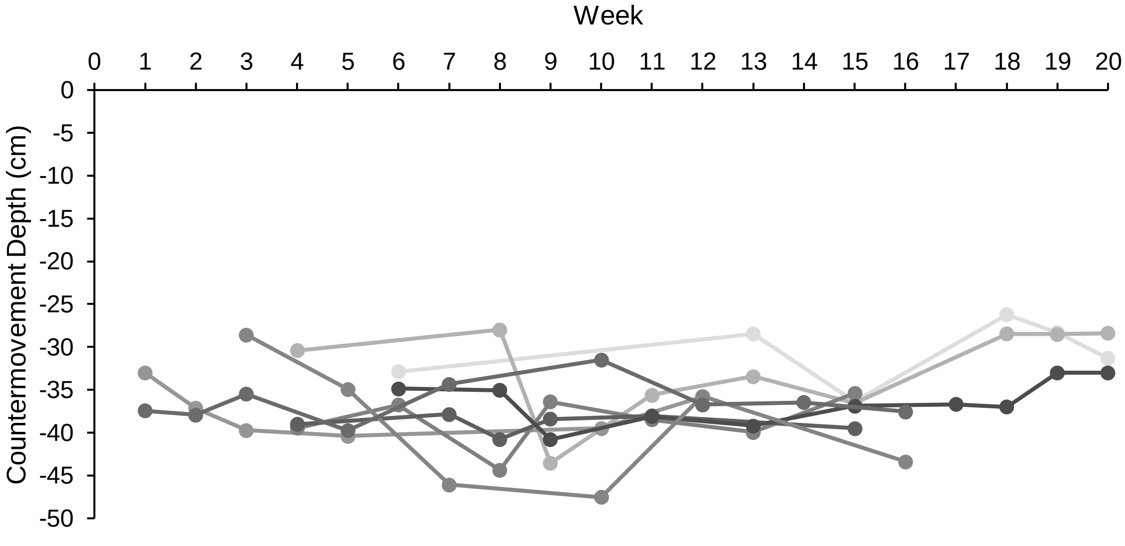
Chair

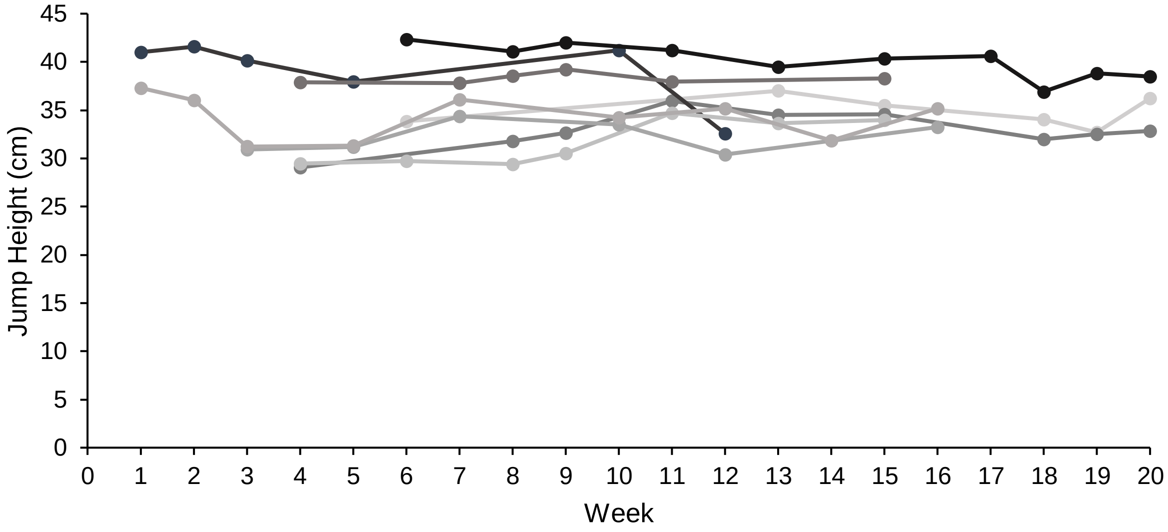
College of Health and Life Sciences Research Ethics Committee (DLS)
Brunel University London

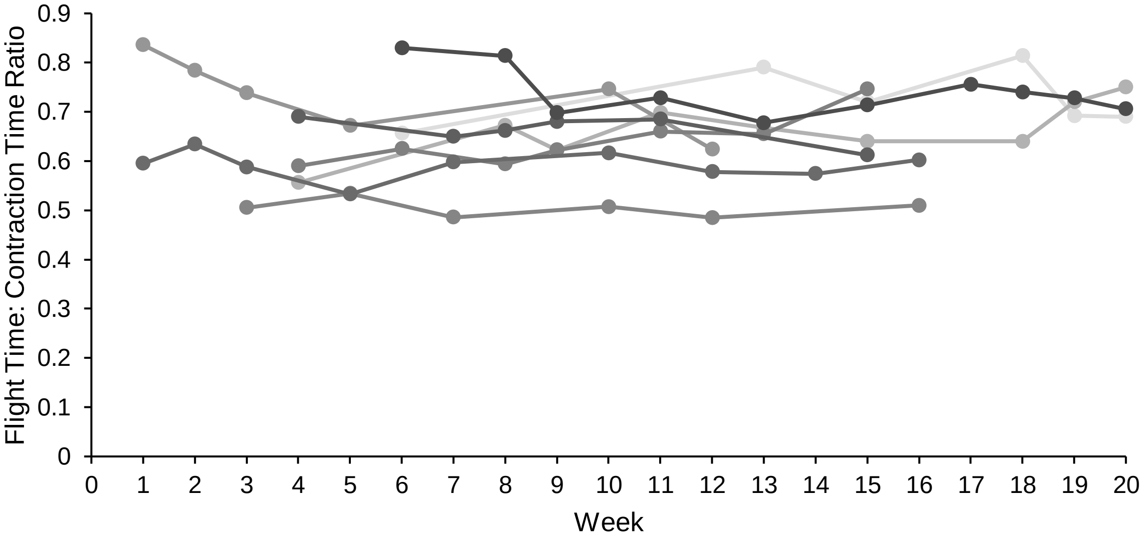
8.2 Appendix B. Pre-match data for all participants (n=8) over 20 weeks.

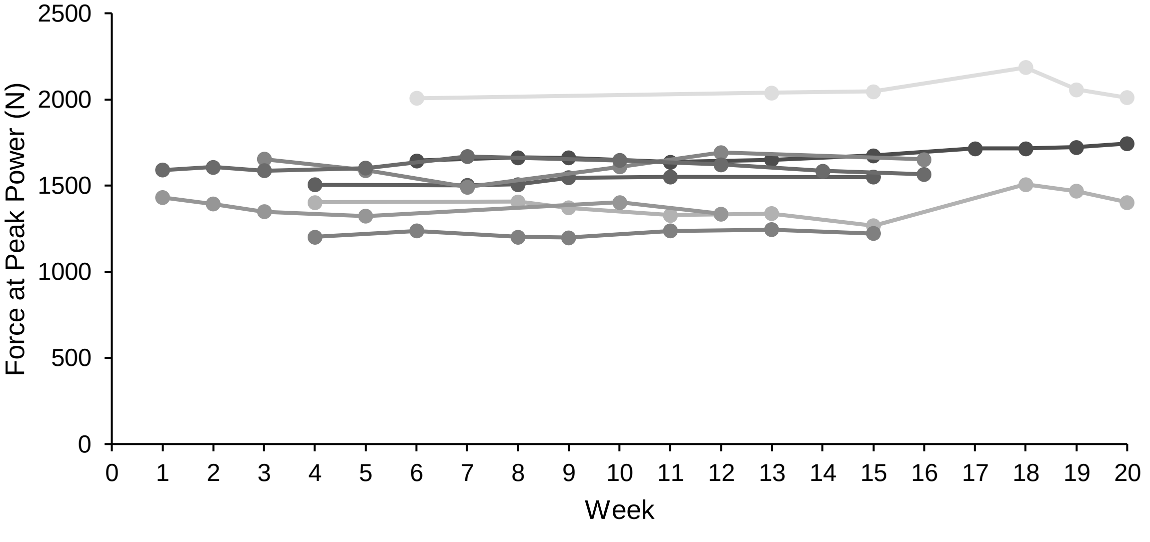


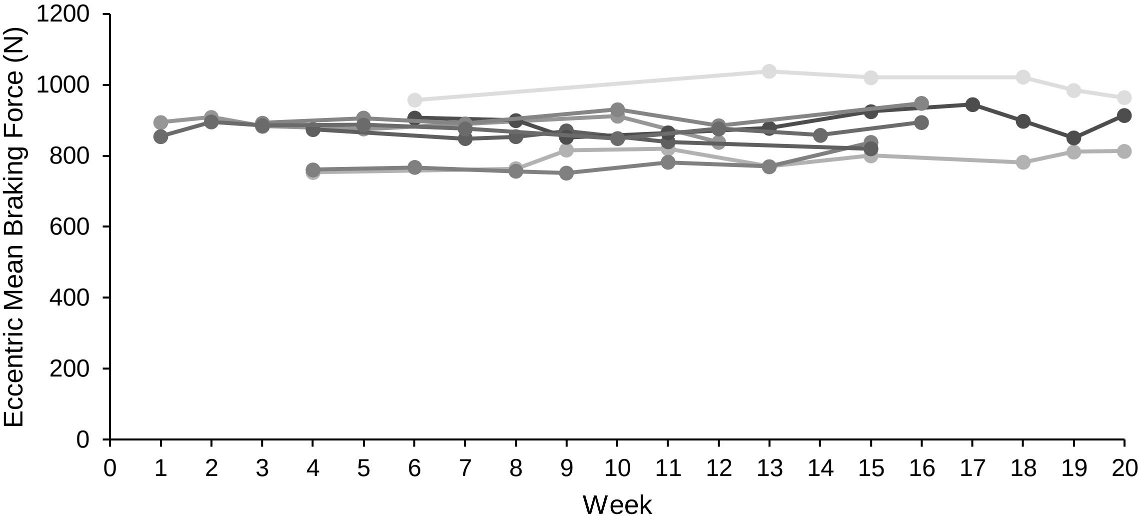





Jump Height (cm)
0
5
10
15
20
25
30
35
40
45
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Week


Flight Time: Contraction Time Ratio
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Week


Force at Peak Power (N)
0
500
1000
1500
2000
2500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Week


Eccentric Mean Braking Force (N)
0
200
400
600
800
1000
1200
Week
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20