Module 3. A framework and toolbox for short term load-response monitoring and evaluating chronic adaptations

Introduction

As part of “strength diagnostics”, strength and power testing are conventionally used to evaluate a range of neuromuscular performance qualities and to assess the subsequent impact of training programs on these qualities after blocks of training. However, it is increasingly recognised that higher frequency assessment of these neuromuscular qualities - testing typically at least once per week– also has a valuable role in the development and care of athletes. The high physiological and psychological demands of competition and training and need to maximise performance in elite athletes suggest that close monitoring of potential fatigue and maladaptation is critical in order to optimise the adaptive response to training, maximise competitive performance and minimise the risk of overuse injuries. Considerable scientific literature and practitioner experience supports the use of simple measures of power performance such as the jump tests and, to a lesser extent, maximal isometric strength tests, as markers of neuromuscular load-response (Cohen & Kennedy, 2021).

This section focuses on the use of jump tests and principally the CMJ in its role as a tool to detect positive and negative adaptations to competition and training load. It is important to emphasise that the bulk of the literature and the “discourse” on CMJ and other neuromuscular assessments in the context of regular monitoring examine and refer to their potential to improve the accuracy / sensitivity of the detection of neuromuscular fatigue. The use of the term load-response monitoring (LRM) instead of *fatigue-recovery monitoring* (FRM) is deliberate and acknowledges that we may also more effectively detect positive adaptations which have not manifested in other gross performance outputs. In addition, while fatigue has been defined as the reduction in the maximal ability to produce force or power induced through exercise (McLeellan, 2011), this definition reflects one aspect of fatigue and other tools are used in FRM. These include measures of function within specific systems such as autonomic nervous system (heart rate variability / recovery) or more general, subjective scales and questionnaires on athlete well-being and overall fatigue (Thorpe et al., 2017). Therefore, the practitioner should also be aware of these tools to monitor “internal load” and consider whether these are appropriate and practical for their athletes. It is recommended that at a minimum regular (ideally daily) subjective monitoring is implemented.

Hence, regular neuromuscular monitoring using jump or isometric assessments is widely adopted in professional team sports with long and dense competitive seasons to evaluate the fatigue recovery cycle or identify week to week negative trends. In this context assessments have the potential to provide information to performance and medical staff that would inform adjustments of an athlete's training load and or recovery strategies within a micro-cycle. In some teams, this data might also influence selection/deployment of players – player rotation, alterations in time on pitch. As such neuromuscular monitoring aspires to support the parallel objectives of optimising athlete performance for competition and the delivery of early indicators of the development of maladaptation to training/competition loads that may interfere with performance and potentially increase risk of musculoskeletal injuries.

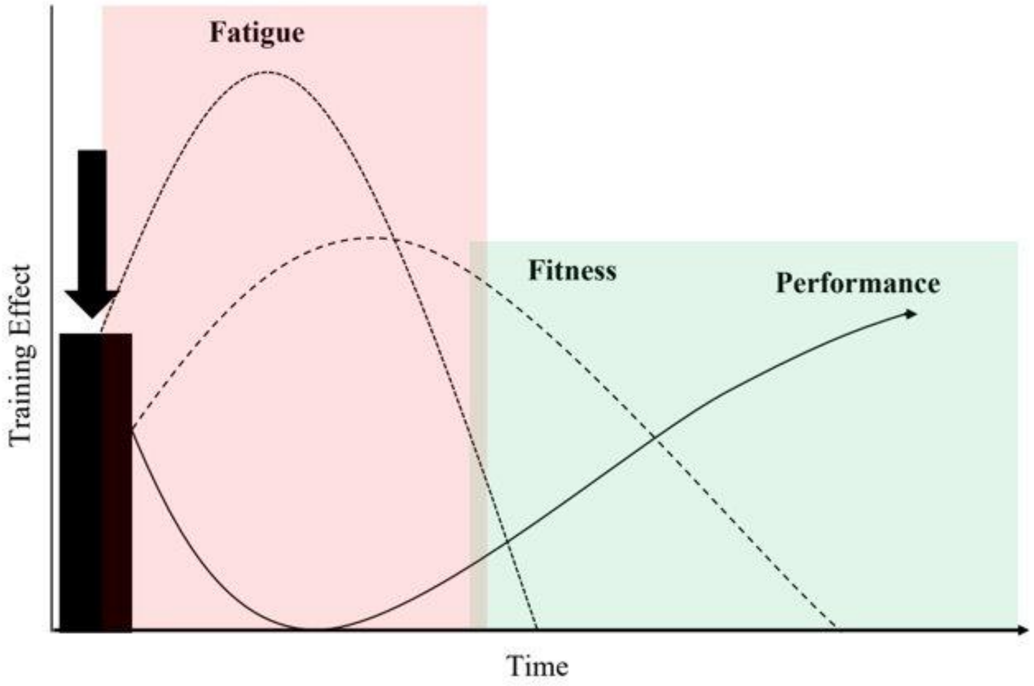
However, it may also be a tool to help coaches and physical trainers to:

- Determine the efficacy of conditioning strategies in driving adaptations in specific neuromuscular qualities in team and individual sports
- Define the efficacy and timing of tapering and recovery strategies employed prior to competition in individual athletic events

Fatigue-recovery / adaptation-maladaptation

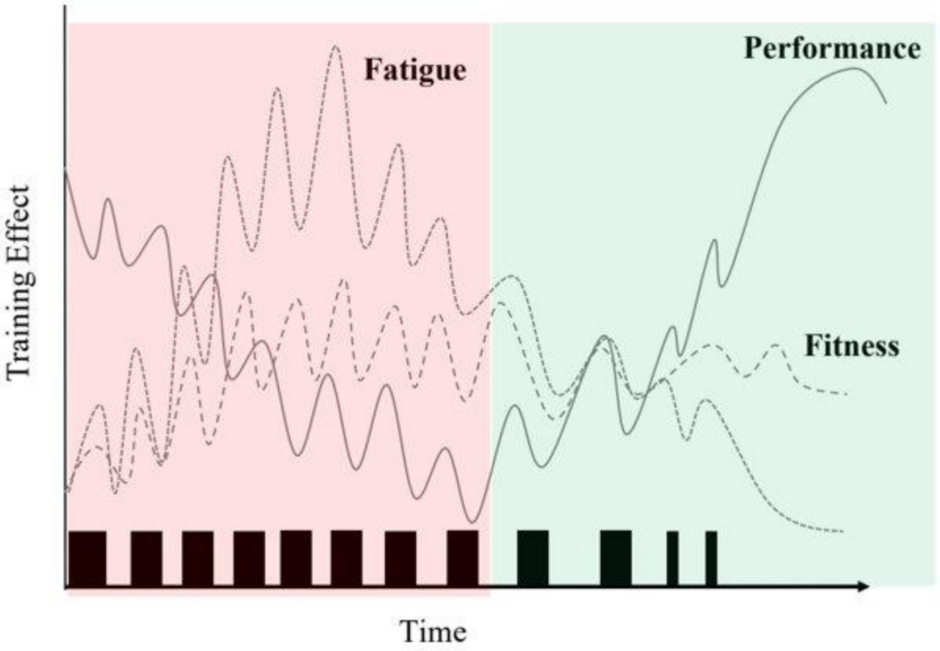
The classic model of the adaptation process represents the train-fatigue-recovery cycle of supercompensation/fitness-fatigue. This model suggests that a training stimulus which is of sufficient overload to cause fatigue causes cellular disruption and disturbances within various systems. Disruption is followed by a recovery and remodelling to improve the organism's capacity such that a future exposure to the same training stimulus will result in less disruption (Coutts et al., 2018). This enhanced capacity or "supercompensation" manifests after a sufficient period of recovery, the length of which varies according to the degree of fatigue that depends primarily on factors related to the training load – intensity, volume, and type of activity, but also on a number of intrinsic and extrinsic factors.

Figure 1: Fitness-fatigue model



Source: ‘A systems model of training for athletic performance’, by Banister E, Calvert T, Savage M, Bach T, 1975.Aust J Sports Med;7(3):57-61.

Figure 2: Fatigue, fitness, performance model



Source: Developing athlete monitoring systems:Theoretical basis and practical applications, by Coutts AJ, Crowcroft, S., & Kempton; 2018. In: Beckmann MKJ, ed. Sport, Recovery and Performance: Interdisciplinary Insights. Abingdon: Routledge; 19-32.

Recovery capacity / load response may also be influenced by an athlete's genetic profile, fibre type (Eston et al., 2003), training background (e.g., chronological and training age, competitive level) nutritional factors, and concurrent psychosocial stresses. It is evident that there is a considerable degree of interindividual variation in the time course of recovery to the same training load. For example, a study in 11 athletes– showed that, at 24 hours, three had recovered; five more at 48 hours; and two more at 72, with one still not recovered at this time point (Byrne & Eston, 2002).

Not only is there interindividual variation in athlete's rate of recovery to a given training stimulus, but also an intraindividual variability –the athlete's capacity to recover from a given training load may also vary over time in accordance not only with changes or accumulation of training load, but also these non-training load factors. It is also important to highlight that not all "load" is equal in its disruption capacity and that for example deceleration load, considered to be a component with a large disruptive capacity may not be well/reliably quantified, particularly by GPS devices (Malone et al., 2017)**.** As such, frequent, precise quantification of athlete **response,** aims to establish both the group and the individual athlete's capacity to tolerate either deliberate periodic over stress or the demands of competition at a given time-point - and for the practitioner to base decisions (i.e., to *increase/maintain/decrease***)** not on only on input but also **output** (i.e., response). Therefore, it is also worth noting that while a far less common cause of maladaptation in elite athletes, frequent LRM could potentially identify maladaptation due to consistent insufficient stimulus resulting from inadequate exposure to competition + training loads.

Many of the processes responsible for acute muscular fatigue recover soon after the cessation of high intensity activity with full recovery, taking as little as or less than 24 hours. However, metabolic, neural, and performance recovery following both long duration activity and high intensity activity may take several days, particularly with exercise repeated on consecutive days (McLean et al., 2010; Keeton & Binder-Macleod, 2006).

However, the role of LRM is not simply to identify the point of full recovery to signal that the athlete can train again: full recovery or super compensation need not be achieved before the next training stimulus is applied, and it is obvious that elite athletes will typically train and potentially compete before they have fully recovered. Indeed, the deliberate accumulation of fatigue over periods of days or weeks, resulting in delayed adaptation (Macdougall et al., 1991), forms the basis of deliberate short-term overreaching (defined as "functional overreaching"). While this is well recognised as an effective training approach, it requires careful planning and timely reductions in training load to eventually allow complete recovery and super compensation of performance (Meeusen et al., 2013) and to avoid a persistent imbalance between the training and competition load and the athlete's tolerance.

In theory therefore, frequent LRM has the potential to inform the coaching process in such a way to maximise stimulatory overload while minimising the risk of reaching a "critical point" at which an athlete's tolerance to accumulated fatigue is exceeded (Kentta & Hassmen, 1998).

Indeed, this information may not impact selection for competition, but can be used to adjust training load between games to ensure optimal training load changes (decrease/increase) for performance.

In this context, simple and rapid performance tests for monitoring of an athlete's responses to training and competition loads may be particularly relevant during intensive training cycles, during tournaments, and across the dense competitive seasons that characterise many team sports. Nonetheless, LRM begins by defining normal methodological and biological noise for a given test and metric in the non-fatigued state at the start of the pre-season (Howarth et al., 2021) or preparation phase. These measurements of typical error can then be used to calculate a "bandwidth" with which to determine how meaningful any observed change is - as discussed below.

Below we describe some of the less common examples in the literature where kinetics provides enhanced detection of positive adaptations or detraining of neuromuscular qualities. First, let's examine the use of jump test LRM as a tool to detect neuromuscular fatigue.

So, what is neuromuscular fatigue (NMF) and what does it indicate?

Studies have used various approaches to examine the capacity of neuromuscular assessments to detect NMF. Research designed to examine acute and residual fatigue typically involve the test of interest being performed pre and post the athlete or subject performing a fatiguing laboratory or field tests, which might aim to simulate the metabolic and neuromuscular patterns of competition (such as the 90 min LIST test - simulating a football match and including walking, jogging and high speed running) or shorter protocols that involve a component of the sport, such as repeated sprints/high speed running efforts. Comparing performance in a test performed minutes after completion of this fatiguing activity with pre fatiguing protocol test performance, represents a measurement of acute fatigue; i.e., < 3 h post (Hader et al., 2019). While this approach is potentially useful in furthering the understanding of "cost" of match play and effect on neuromuscular performance - the application to high-performance sport is limited - immediate post-match CMJ assessments are not implemented in these settings. Instead, measures of what has been termed the residual response - evident up to 72h post-match (Hader et al., 2019) are of more practical interest as they can transfer to high performance settings where assessments can and are implemented at such time points. This data can inform performance and medical staff on the magnitude of fatigue induced by recent competition (if matchday -1 measures are also taken) or on recent competition superimposed on the previous week's loading and recovery (if only weekly matchday + 1 or more commonly, +2 assessments are performed). A similar approach is advocated for isometric posterior chain testing (Wollin et al., 2020), as described in module 2 of this course - with which CMJ assessments are often combined (AFC SEMS conference, 2019).

Observational studies which do not control the input - i.e., the load the athlete is exposed to - have also contributed to the understanding of LRM and NMF. These studies typically assess higher level athletes, for whom participation in set “protocols” to produce fatigue is far less feasible. While observational studies do not control the load **in**; comprising the variable and chaotic loading patterns of real competition with + on and off pitch training and conditioning sessions, they do generally have control of the neuromuscular assessment protocols and the conditions under which they are performed. These studies may involve a specific period of the season, a tournament or potentially the whole season. These observational studies may also have consistent measurement of on-pitch load using GPS allowing analysis of relationships between input and response - discussed below in the tool box.

The majority of studies have assessed jump performance following high-intensity intermittent-sprint sport (HIIS) competition and training (particularly rugby, soccer, and Australian rules football). But there is also evidence showing jump performance and/or isometric strength to be sensitive to acute and or accumulated fatigue in middle-long distance events, combat sports, volleyball, tennis, and others. Furthermore, since many of the physiological and mechanical loads associated with HIIS sports are also shared by other team and individual sports, we may, with caution, extrapolate some of this data to a wide spectrum of athletic endeavours that have a significant lower body loading component, but for which there is a smaller or not evidence base. Despite technical differences between sports, there are common physiological and mechanical stresses which result in central and peripheral fatigue, including substrate depletion, hyperthermia, nervous system fatigue, mechanical muscle damage and disruption, oxidative stress, and inflammatory responses.

Mechanical stress that causes alterations in muscle biochemistry and structural damage to the muscle fibre and disruptions to the muscle membrane (Fridén et al., 1983) result in a decrease in the muscle’s ability to produce active force and power – the components of athletic performance most commonly assessed in fatigue research. However, decreases in reaction-time, proprioception (Brockett et al., 1997), range of motion and decreased efficiency of movement (increased energy cost to perform a given activity), and alterations in the pattern of muscle activation are also associated with exercise-induced muscle damage (EIMD). These changes can also independently impact on an athlete’s performance, some of which could also increase musculoskeletal injury risk in training or competition.

Secondary to EIMD, classically indicated by increased blood levels of the muscle enzymes creatine kinase (CK) and lactate dehydrogenase, inflammatory processes are initiated which may underlie sensations of (delayed onset) muscle soreness (DOMS). However, the time course of normalisation of blood markers, muscle function, and DOMS are not closely associated with each other, and coaches and athletes should be aware that the recovery from DOMS is not alone a valid or reliable marker of recovery from NMF.

Research shows that the residual response to training/competition, quantified by CK levels, is strongly related to the amount of the high intensity activity performed (Nedelec et al., 2013), with vulnerability to damage higher during lengthening contractions (Faulkner et al., 1993) and at long fibre lengths (Newham et al., 1988); on the other hand, damage to muscle fibres can occur during all types of contractions, and not only following high intensity, but also long duration exercise (Kyröläinen et al., 2000).

In addition, the magnitude of EIMD and degree of associated NMF fatigue reflected in decreased jump performance is also influenced by the characteristics and loading patterns of training/competition. Mechanical stress and EIMD are higher after running than cycling (Bell et al., 2000) and higher when the distance covered includes a larger number of changes of direction (with its associated accelerations-decelerations), compared to the same distance covered in a straight line (Oliver et al., 2008). The specific effects of deceleration load in footballers are discussed further below. Impacts with opposing players (Pointon and Duffield, 2012; McLellan and Lovell, 2012) also accentuate markers of NMF, as does mental stress associated with competition (Marcora et al., 2009).

While sampling of CK and LDH has helped our understanding of the acute response single bouts of exercise and sports activity at the cellular level, in longer term non-laboratory studies across micro-cycles or seasons, the “stress hormone” (cortisol) is a more commonly used biomarker to evaluate accumulated fatigue and recovery. A number of studies have shown that changes in jump performance may reflect the muscle damage/blood CK levels (Coutts et al., 2007) or salivary cortisol levels (Balsalobre-Fernández et al., 2014; Chatzinikolau et al., 2010).

There is also some evidence that jump performance may be a more sensitive marker, in that deficits have been reported without changes in salivary Cortisol (McLean et al., 2010) or after CK and LDH have returned to normal. This may be due to the possibility that NMF reflected in deficits in jump performance may be indicative of either peripheral (related to metabolic and structural disturbances within muscle) or central fatigue (relating to neural activation/inhibition of the muscle or as increased sensation of effort and perception of tiredness).

For example, in strength-trained athletes recovering from heavy resistance exercise, jump performance fluctuations have been observed to follow similar patterns of change as that of direct measures of muscle force production capacity (Raastad & Hallén, 2000). This is indicative of peripheral fatigue, while jump deficits have also been observed after long duration endurance exercise where no loss of muscle force production is found (Petersen et al., 2007), indicative of a decrease in central drive or muscle activation. In addition, NMF may be indicative of a need for increased energy intake. While low muscle glycogen levels are traditionally associated with deficits in endurance performance and may not be a limiting factor in the performance of short high intensity exercise, low glycogen levels can also initiate functional changes in the muscle fibre cell, which reduce muscle force production independence (Fitts, 1994).

Why jumps?

It might seem logical that the most specific measure of fluctuations in an athlete's performance throughout a training cycle would be to assess some aspect of performance within competition. However, there are a number of methodological and practical difficulties associated with this approach. In football for example, fatigue is likely to affect the amount of high speed running performed by a player within a match. However, a number of contextual factors such as tactics, opposition performance and scoreline, which are independent of the neuromuscular status of the player will also impact on that HSR volume. As such, *can a reduction in output be attributed to fatigue?* While measures of maximal sprint performance that could theoretically be obtained in training with tracking technology, radar or light gates within the training week, coaches are generally not willing to allow sports scientists to implement such tests and players are often also resistant to in-season maximal sprint testing - due to concerns that this may contribute to fatigue, as well as concerns with injury risk.

As highlighted throughout the certificate, the CMJ, particularly when performed on force platforms with the derived kinetics, rather than a jump test, is an assessment of eccentric and concentric performance and indirect kinematics in lower limb triple extension. As such, in the context of detecting fatigue during load-response monitoring, it provides an indirect evaluation of markers of fatigue induced by some combination of central, neuromuscular and / or metabolic disruption in a brief non-fatiguing maximal effort, relatively high-velocity, low-load, multi-joint movement, without further contributing to the load burden or risk exposure. Hence, these assessments are such widely applied measures of neuromuscular fatigue, with the potential to capture peripheral fatigue in the lower extremity kinetic chain, central fatigue and limb-specific trends (in force and impulse).

The countermovement- (CMJ), drop- (DJ) and squat- (SJ) jumps are the most widely investigated in the context of fatigue-recovery monitoring (Ebben et al., 2008; Cormack et al., 2008; Stephenson et al., 2011), with the largest volume of research evaluating the CMJ. Of the jump studies, a substantial proportion were conducted with contact or optical devices. Therefore, the most commonly investigated variables assessed across these jumps are jump height in the CMJ and SJ, and in the DJ also contact time, therefore also allowing the calculation of reactive strength index (RSI) (=jump height/contact time), in addition to jump height. Curiously however in the context of current knowledge, in a recent meta-analysis of acute and residual jump performance changes in response to football match play, the majority of those using force platforms still only reported concentric peak power and occasionally peak force, in addition to jump height (Hader et al., 2019).

The low time investment and ease of assessment mean minimising the disruption of training schedules. The lower technical demand and higher familiarity with the test, the higher reliability of relevant kinetic metrics compared to other jumps (Gathercole et al., 2015a), the lower perception of load amongst athletes (i.e., relative to the drop jump), mean that based on a combination of both evidence base and practical factors, the force platform CMJ is, in most environments, the optimal jump to select for regular monitoring of NMP in groups of athletes in-season.

It is also important for practitioners to communicate to coaches to and possibly to the athlete, that in the context of LRM, the CMJ is not being used to repeatedly reassess jump performance and is purposefully not sports specific -i.e., use of hands-on-hip/dowel protocol in order to minimise the contribution of the trunk and upper body and potential compensations which may mask alterations in lower extremity neuromuscular performance (Schmitz et al., 2013). Furthermore, it has been demonstrated that the value of the CMJ or other jump tests in LRM does not depend on vertical jumps or even maximal / explosive efforts being a component of an athlete's training or competition activities. These tests are an indicator of neuromuscular status during intensive overload training –which may result from accumulated volume of moderate intensity as well as high intensity activities. Decreased jump height was reported in soldiers subjected to prolonged physical effort with limited food intake and sleep (Welsh et al., 2008) despite jumps not being a major component of their activity. Similarly, jump performance has been shown to be a useful index of both acute and accumulated fatigue in elite middle-distance runners (Balsalobre-Fernández et al., 2014) and following longer distance events such as the marathon.

It should also be noted that other measures of neuromuscular performance such as assessment of maximal strength or rate of force development (RFD) in single or multiple muscle groups are also sensitive to NMF resulting from training and competition, and have a potential role in LRM. On the other hand, isokinetic dynamometry, considered the gold standard measure of dynamic strength and useful in research settings to better understand angle or speed specific changes in fatigue in specific muscle groups, is probably not a practical tool for regular monitoring. Indeed, since deficits in jump performance may (Thorlund et al., 2008) or may not (Chatzinikolau et al., 2010) parallel changes in measures of maximum isometric or isokinetic strength within specific lower body muscle groups. For example, a plyometric training session which significantly reduced SJ and CMJ performance by between 8-20% for between 24 and 72 hours post exercise led to no reduction in either isometric or isokinetic strength measures (Chatzinikolau et al., 2010). Similarly, in professional soccer players, an intermittent sprint protocol which led to significant decreases in CMJ height immediately after exercise, and 48 and 72 hours after exercise, resulted in no significant change in isometric peak force at any time point (Nedelec et al., 2013). In amateur rugby players, sleep deprivation resulted in an accentuated post-match CK response, decline in cognitive performance, and decrease in CMJ performance compared to changes observed after normal sleep. However, there was no difference in maximum isometric force in the knee extensors between the two conditions (Skein et al., 2013). In contrast, in national level players, during a 3-day tennis tournament in which significant declines in lower extremity (leg press) peak isometric force (26%) and rate of force development (38%) were observed, no significant change in CMJ height was noted (Ojala and Häkkinen, 2013). These data suggest that in some cases both jump and isometric performance monitoring may be warranted to capture specific components or sites of fatigue within the neuromuscular system.

Which jump?

The CMJ and DJ, but not the SJ, involve the stretch shortening cycle (SSC) to achieve optimal jump performance (Markovic et al., 2004) and are therefore considered the most appropriate for evaluation of FRM in sports which involve high-speed running (and/or jumping) that depend on rapid and explosive SSC movements (Maffiuletti et al., 2000; Chaouachi et al., 2014). The SSC is a combination of a high velocity eccentric muscle contraction followed immediately with a concentric contraction, which is enhanced by the preceding rapid pre-stretch (Nicol et al., 2006). Therefore, a test which includes a high velocity eccentric component such as the CMJ or DJ can be considered the most ecologically valid to movements common to most sports, particularly those associated with the greatest mechanical demand.

The SJ, which aims to eliminate the contribution of the SSC to jump performance, potentially isolating concentric power production from the contribution of the stretch reflex and elastic energy, is also sensitive to NMF. The SJ is less well researched in the context of FRM and has been found to be less sensitive to NMF when directly compared to the CMJ following repeated high intensity sprints. However, there is also some evidence that the SJ may be a better measure of fatigue following specific types of loading; fatigue induced by a large volume of dynamic lower body strength training (squats) resulted in deficits in SJ performance but not in either CMJ or DJ (Byrne and Eston, 2002). This suggests that an increased contribution of SSC by a greater countermovement in the CMJ or DJ test was able to compensate for the NMF, which was revealed in the non-SSC SJ.

Therefore, while it may not reflect the eccentric/SSC-specific fatigue/damage, the SJ should not be ruled out as a potential tool in the monitoring of NMF. It appears that rather than there being a universally superior jump type, coaches need to consider which activities they are aiming to assess from the recovery when selecting the type of jump test employed in LRM. Different movement patterns, muscle activation profiles, and forms of SSC activity within training and competition in different sports are likely to be reflected in different fatigue responses and to contribute to the observed variation in the sensitivity of these jump tests to NMF. If training/competition involves a mixture of SSC and non-SSC (in parallel or training blocks), it may be useful to implement a combination of jumps to identify and differentiate the effects of training/competition on components of NMF.

Jump height evaluation as a measure of acute fatigue

Decreases in jump-height observed after simulated or real competition or training sessions in a variety of exercises bouts and real or simulated competition suggest that it is a valid marker of acute fatigue. Post-competition decreases in CMJ height (Nedelec et al., 2014; Nedelec et al., 2013) or CMJ and SJ-height (Oliver et al., 2008) are reported in a number of HIIS sports. While the largest body of evidence comes from HIIS sports, both SJ and CMJ height are also reported after a competitive kickboxing match (Ouergui et al., 2013), 5% CMJ decreases after simulated handball (Thorlund et al., 2008), and decreased CMJ and DJ after long-distance running, amongst others.

These data are based on research designed to determine and validate jump performance as a measure of fatigue within a specific group of athletes or sport, and, in some cases, also to compare its sensitivity to that of other lab-based measures. Evaluation of acute NMF with jump (or other strength/power tests) following a training session or competitive event by testing immediately before and after the training session/event clearly does not profile the complete fatigue-recovery cycle. However, it may be useful to the coach or trainer to do the following:

- Assess the athlete's strength/power endurance by evaluating changes before and after fatiguing sports specific activity. For example, Boullosa et al (2011) recommended the evaluation of CMJ performance pre and post an incremental running test as a useful measure of muscular adaptations in endurance athletes. They also found that CMJ performance changes correlated with improvements in sprint performance, but injury risk concerns with performing sprints under fatigued conditions mean that jump testing is arguably a safer and more acceptable means to assess changes to evaluate fatigue resistance as part of performance profiling and/or following a training block.
- Evaluate and refine the efficacy of post exercise recovery strategies. In elite tennis players, CMJ height changes differed among post-training recovery interventions (cold-water immersion, compression garments, and sleep recommendations), which were reflected in differences in time in play and stroke rate in subsequent competition (Duffield et al., 2014).

Lack of change in jump height with acute fatigue

However, there are also several examples in the literature where CMJ height failed to show the decreases expected in a post-competition/ “fatiguing” training session. No changes in CMJ or SJ height was reported in college soccer players immediately after a match, although decreases in both were seen at 24 hours (Hoffman et al., 2003). In elite soccer players, Mohr and Krustrup (2013) found no decrease in CMJ height after a competitive soccer match played in temperate conditions, but did after the same players competed in a hot environment - reporting a significant (6%) decrease. In professional Australian rules footballers, CMJ height did not show meaningful declines after a match (Cormack et al., 2008); and in amateur soccer players, a significant decrease in SJ height but not CMJ height was noted after a simulated soccer match (Robineau et al., 2012). While, as discussed below, CMJ height may indeed not be a consistently valid marker of fatigue, it is also important to consider that the lack of expected decrease following fatiguing activity could also be due to the following:

- An inadequate warm-up preceding the pre-exercise jump test, such that the increased muscle temperature generated by the exercise bout leads to enhanced muscle shortening velocity and maximal jump performance after “fatiguing” training or competition.
- Enhanced post-exercise jump performance due to post activation potentiation (PAP), fatigue induced reduction in force production, manifesting as a transient post-exercise increase in CMJ (Boullosa et al., 2011), also observed in DJ performance (Comyns et al., 2011).

Due to these factors, when applying or experimenting with the use of jump testing for acute monitoring, coaches should take into consideration:

- The window associated with PAP post-exercise if jump testing is being used to evaluate acute fatigue (rather than PAP), immediately following training or competition. Indeed, in a case series of two EPL players who performed CMJ assessments pre and post a competitive match, substantial improvements not only in jump height but also in a range of kinetic variables were observed (Stevenson, 2022).
- Adequate warm-up prior to the pre-exercise jump tests, is critical for the assessment of true maximal power, particularly if conducted in the morning when muscle temperature and power output is substantially lower. For example, a dynamic warm up may increase CMJ height by 4.7 cm (~14%) (Schmitz et al., 2013).

Jump testing to quantify residual accumulated fatigue/recovery

SSC fatigue is a biphasic process and can be so since it is divided into two recovery phases:

> 1) The acute decrement in SSC function immediately post exercise, which recovers within 1-2 hours.
>
> 2) Transient recovery causing an SSC decrease at around 2 days, which takes a further 4-8 days for recovery (Komi, 2000; McLellan, 2011; Gathercole et al., 2014).

CMJ performance parameters return to baseline values at varying rates following competition/simulated competition or intense training sessions with most "normalised" at 96 hours (McLean et al., 2010).

Thus, jump testing as part of LRM is in practice usually implemented between 2-4 days after competition as a means to assess NMF/recovery and readiness for subsequent training/competition. There is also substantial evidence that CMJ height is a sensitive indicator of the second phase of recovery, and possibly more so than other functional tests. Decreases are reported 48 hours after match in professional rugby players (McLean et al., 2010). Following a 4 x 4 min high intensity interval training session, the CMJ height of soccer players was depressed for 48 hours while 20 m sprint time, a 5 hop for distance test, and HR response recovered within 24 hours (Sjökvist et al., 2011). Significant reductions in CMJ height are also reported during tournaments with more frequent competition or intense training camps (Rogaland et al., 2005).

There is also good evidence that CMJ height changes are relevant in LRM over longer-term periods, such as training phases and seasons. In semi-professional rugby players, CMJ height increases were noted during a post-overreaching tapering phase, paralleling the recovery of a number of biomarkers (Coutts et al., 2007). In middle- and long-distance runners, CMJ height was assessed across a competitive season, and highest and lowest CMJ height performances in the week preceding competition predicted best and worst competitive performances, respectively.

No change in jump height in residual/accumulated fatigue monitoring

However, as discussed above in relation to changes in CMJ height and acute fatigue, there are also a number of conflicting results in the scientific literature and reports from practitioners working with elite athletes, suggesting that CMJ height evaluation is a universally consistent marker of residual/accumulated fatigue.

Hamilton (2009) observed no significant change in CMJ height in daily testing of young soccer players who participated in a tournament consisting of consecutive days of matches. In volleyball players, 11 days of intensification of training load leading to increased CK levels and altered psychological measures of stress and fatigue were associated with no significant change in CMJ height (Freitas et al., 2014). In elite Judo athletes assessed across a 10-week training regime which included a normal training phase, an overtraining phase, and a tapering phase, significant changes in isokinetic strength and sprint speed were noted, but not CMJ height (Callister et al., 1990). Similarly, no significant changes in SJ or CMJ height were found in well-trained young tennis players during a period of 4 weeks of progressive overloading and a 1-week tapering period, despite the peak training loads in the 3rd and 4th week, leading to alterations in cortisol and subjectively measured stress levels (Gomes et al., 2013).

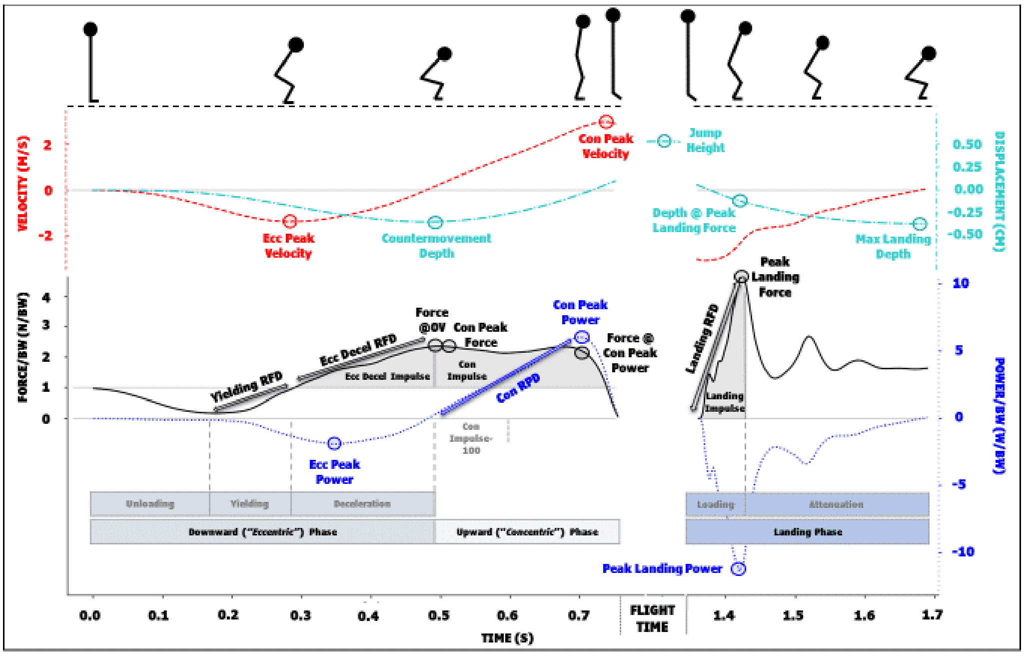
These findings are noteworthy, but, as discussed above in relation to acute fatigue and CMJ height change in the context of the larger body of evidence supporting the use of CMJ height as a marker of residual fatigue, coaches should also consider that a lack of change in CMJ height in LRM *may* also be explained by:

- Effective recovery strategies and recuperation. For example, in elite youth players tested daily, Malone et al. (2014) showed that a micro-cycle emphasising technical preparation and recuperation for an upcoming competitive match did not lead to significant variations in CMJ height. These results might not reflect inadequate sensitivity of CMJ height but a training load which was designed for, and appears to have been successful in achieving, the avoidance of fatigue-inducing overload during the micro-cycle.
- In athletes who have recently returned to training post-injury, NMF associated with training load may be masked by improvements in neuromuscular performance due to concurrent positive neural adaptations to strength/power training. Similarly, in athletes that are new to the type of jump or strength/power test being used in LRM, performance increments related to familiarisation with the test could mask accumulated underlying NMF. This is more likely to occur with a more technically difficult test, such as the drop jump, than the CMJ, but might even occur in the hands-on hips CMJ in athletes for whom jumping is not a component of the athlete’s training, sport, or performance testing program.

Alternative jump variables

Having outlined some of the conflicting evidence around the use of CMJ and SJ height as markers of acute, residual, and accumulated fatigue, it is important to now focus on the distinction between the assessment of CMJ or SJ-height and “jump-kinetics” in LRM. Beyond CMJ height, a number of other metrics described in Course “Force assessment and an introduction to Kinematics” and shown again here in figure 3, can be assessed with force platforms during the performance of a CMJ, SJ, or DJ. In the LRM literature, with some examples of comparison with SJ (Gathercole et al., 2015; Hughes et al., 2019; Hughes et al., 2022; and DJ (Oliver et al., 2008; Gathercole et al., 2015) or single leg jump (Bishop et al., 2022), the vast majority of experimental and observational evidence describes CMJ-kinetics.

Figure 3: Bilateral CMJ kinetics



Cohen & Kennedy, NSCA: Essentials of Sports Science (2021)

Source: adapted from Cohen & Kennedy, 2021 (NSCA)

Following pioneering work by Cormie et al (2009; 2010) describing the analysis of not only the force-time but also the power-time, velocity-time and displacement time curves, evidence from two research groups in particular (Cormack and colleagues) and later Gathercole and co-workers published landmark studies examining the kinetics of the CMJ in response to acute, residual, and across season fatigue and to the stimulus of training.

The paradigm shift that this work promoted was that the failure of the CMJ to consistently identify fatigue was not due to the CMJ being the wrong assessment to employ, but to the dependence on CMJ height as an output parameter. The work of Cormack et al. in elite Australian rules footballers and of Gathercole et al. (2014, a, b) in other athletes in particular provide an explanation for unexpected stability of change in CMJ height in the fatigue-recovery cycle, previously referred to. Specifically, they showed that CMJ height may be maintained under conditions of acute, residual, or accumulated fatigue as a result of alterations in jump “strategy” (Cormack et al., 2008a, b; Cormack et al., 2013; Gathercole et al., 2014; 2015a, 2015b). Strategy has now become an umbrella for the kinetic metrics that reflect neuromuscular qualities and biomechanics of the jump that are expressed in how force is applied, durations, displacement, ratios. This understanding was initiated with Cormack et all’s, 2008 observation that while CMJ jump-height displayed statistically “trivial” decrease of 1.5% and 0.8% immediately post and 24 hours after a competitive Australian rules football match, the corresponding changes in the ratio of flight time to contraction time (defined as the time between the initiation of the countermovement and toe-off, i.e., take-off) – “FT:CT”–

were 7.5% and 7.8%, representing a statistically substantial change so that despite athlete's generally showing normal CMJ height 24 hours post-match, decreased FT:CT, which was also associated with other objective markers of fatigue, such as Cortisol. Based on this and other work across the season they determined that FT: CT still remained significantly below baseline levels 72 hours post-match and concluded that this metric, but not jump height, reflects the second phase of SSC recovery.

Another study that is at the core of the evidence base for force platform CMJ assessment is that of Cormack et al. (2013) which examined the association between performance in CMJ assessments and in-match running performance across a season in professional AFL players. They evaluated associations between changes in FT: CT in a weekly CMJ (compared to pre-season baseline values) and running performance (assessed with GPS-accelerometry) during the subsequent match. Importantly, they demonstrated that statistically meaningful deficits in the FT: CT in the *vertical* CMJ were predictive of poorer high-speed running performance - underlining that the value of the assessment in detecting lower limb neuromuscular alterations that not only influence performance in the vertical vector. Decreased FT: CT was associated with less time spent at the highest running speeds, fewer accelerations, and reduced efficiency of movement. Reduced movement efficiency may promote earlier metabolic fatigue within competition via an increase in the energy cost of movement and may negatively affect technical performance and the volume of high intensity activities such as maximal speed running and accelerations (Cormack et al., 2013; Mooney et al., 2013). Importantly, FT:CT was also found to be predictive of reductions in movement efficiency in competition, of sufficient magnitude to be subjectively identified by coaches –via lower ratings of performance in match (Cormack et al., 2013; Mooney et al., 2013).The authors speculated that pacing strategies and / or alterations to vertical stiffness explained the increase in steady pace running at the lower end of the HSR continuum and reduced higher speed running and accelerations and decelerations. The authors elected to examine FT: CT based on findings of their previous work raising the possibility other CMJ kinetic variables may have shown stronger associations. In a season long analysis in AFL, Norris et al., 2021 found significant but trivial ES associations between a (player) relative increase in high-speed running (HSR) and specific CMJ-kinetic: Force at zero velocity (d=0.12, CI: ±0.12), and sum of high intensity accelerations and Eccentric deceleration RFD (d=-0.18, CI: ±0.14). They also identified that higher start of season isometric peak force (in the IMTP) and greater CMJ-concentric peak power moderated responses to in-match; higher values were associated with smaller declines in eccentric mean power and jump height. Johnston et al., 2015 also reported a lower residual fatigue response to match play in Rugby players who had higher dynamic (squat) strength and the further examination of associations between CMJ (and other jump and isometric test) -derived neuromuscular qualities and resilience or capacity to recover from match play is an important area for further research.

Other CMJ kinetics commonly examined were peak force and concentric peak/mean power may also have greater sensitivity to aspects of fatigue than jump height. College soccer players who showed no change in SJ or CMJ height immediately following a competitive soccer match did demonstrate decreases in SJ and CMJ peak force, which were directly related to playing time (Hoffman et al., 2003). In professional rugby players, while CMJ height did decrease 24-48 hours post-competition, CMJ-relative peak power, but not CMJ-jump height, varied according to subtle (2 day) differences in the length of pre-match training micro-cycles (McLean et al., 2010). In elite rugby players, decreases in CMJ-peak RFD and CMJ-concentric peak power, 30 minutes and 24 hours, post-match were associated with intensity and number of impact forces (blunt force trauma during collisions) experienced during match play, while CMJ-peak force was only reduced post-match and recovered 24 hours later (McLellan and Lovell, 2012).

Peak force appears to show some value as a marker of acute fatigue while more velocity dependent variables such as mean or peak power appears to be more sensitive to the residual inflammatory response to training/competition with peak force less affected (Johnson et al., 2013; McLellan et al., 2011; Cormack et al., 2008). This may relate to the greater impairment of the faster type II fibres, such that peak power cannot be maintained; on the other hand, an increased contribution of slower type I fibres to force production is able to compensate to maintain peak force output (Johnson et al., 2013; Friden and Lieber, 1992). As a result, it was suggested that CMJ performance variables which incorporate a velocity or time component may be more sensitive, particularly to residual fatigue, at least in HIIS (Johnson et al., 2013) and other sports with a significant high velocity component.

The continuing evolution of CMJ kinetic parameters in detecting fatigue

The publications emerging from Gathercole and colleagues mark the next phase in the evolution of CMJ kinetic analysis in LRM. Their work progressed from that of Cormack and others by examining alterations in a range of CMJ kinetics metrics from which they described as “alternative jump variables” and went on to demonstrated that these were also more sensitive indicators of acute and residual fatigue, and training adaptations than not only jump height but other “typical” (commonly reported) metrics such as concentric peak power. They examined contraction time (separated from FT: CT) and constituent eccentric and concentric phase durations and time to discrete points - such as peak force or peak power - as well as novel discrete point metrics such as force @ zero velocity. At 72h post a high intensity fatiguing protocol alterations in specific alternative jump-variables (Gathercole et al., 2015a, b) or CMJ-kinetic metrics derived from the FT curve obtained when the CMJ is performed on a force platform, were larger than the normal biological variation, but jump height was not (figure 5 below).

It was reported previously that maximum sprint speed may be maintained despite underlying acute neuromuscular fatigue - identified by altered jump height (Sjökvist et al., 2011). Gathercole et al., (2015a) showed that CMJ-kinetics was more sensitive to the residual fatigue induced by a high intensity running protocol than 20 m sprint performance. Therefore, alterations in aspects of jump-performance may represent sensitive early markers of NMF that precede significant alterations in both jump-height and other output measures of neuromuscular performance such as sprint speed.

Using the CMJ in LRM in football

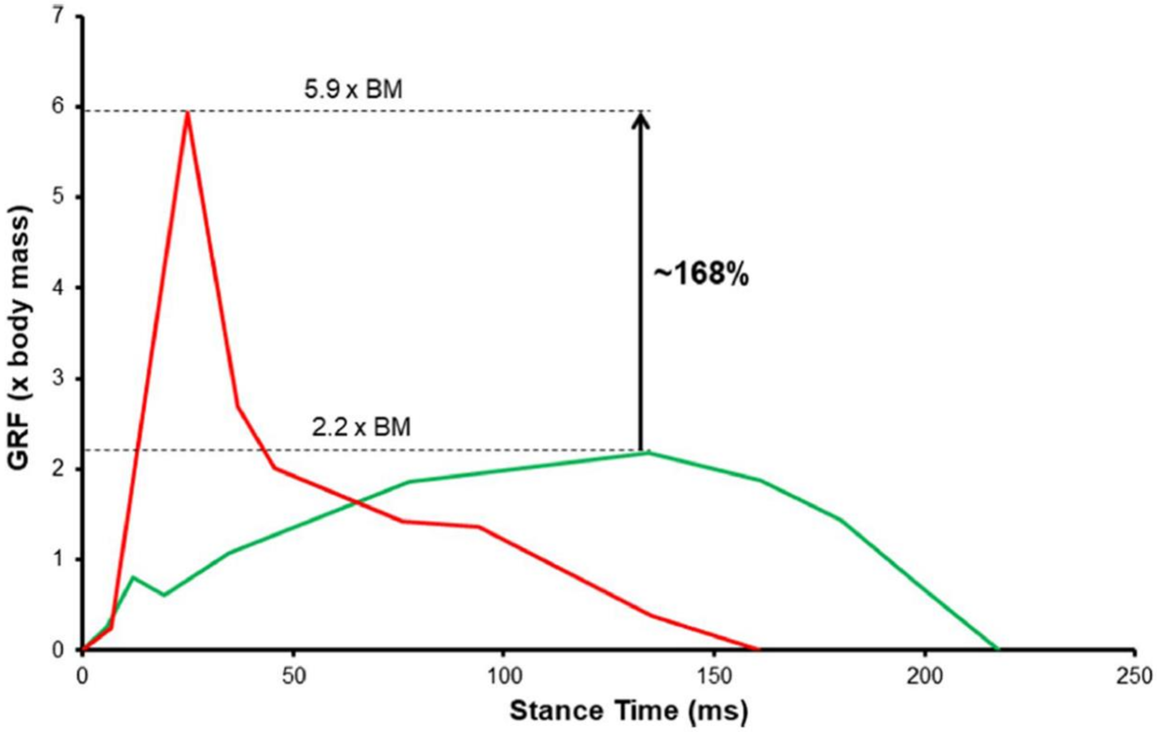
While the landmark work in this area described above being implemented in AFL, Rugby or using lab based fatiguing exercise, there is a great interest in applying the CMJ in fatigue related research in football and in LRM practice in the sport.

A meta-analysis of these concluded that particularly at 48h, associations were unclear with respect to the sensitivity of the commonly evaluated CMJ metrics – JH and Con PP – and markers of muscle damage to HID load, while more robust associations were observed in relation to very high intensity running (> 5.5 m s−1).

Indeed, in a study in elite footballers, comparing starters and non-starters and analysing the association between running load and CMJ performance, Morgans et al., (2018) reported a positive effect of high-intensity running distance on CMJ height and concentric peak power (but did not examine other metrics). Similarly, two studies of Thorpe and colleagues (Thorpe et al., 2017) in elite football suggest a similar association - whereby high-speed running distance showed a small but significant, positive correlation with CMJ-height (r=0.23, p=0.04) during a 17 day in-season period (Thorpe et al., 2015). In another study, also in elite players, high-speed running distance accumulated over the previous 3, and 4 days had a small effect size, non-significant, positive correlation with CMJ-height (r=0.21 to 0.23). This highlights that high intensity components of match play are stimuli for neuromuscular adaptation - and the corollary, that inadequate loading of this nature may be reflected in CMJ performance.

Potentially, these findings may also suggest that HSR is not the principal driver of negative neuromuscular responses which are reported in some studies after competitive match play (Hader et al., 2019). Indeed, it is argued that it is high intensity decelerations (HID) that represent the most demanding and damaging component of running load has been highlighted (Harper & Kiely, 2018), Substantially higher peak GRF’s in HID than in maximum velocity running, underline how much higher the mechanical demands associated with this action are than other components of running load (figure 4).

Figure 4: Ground reaction force (GRF) profiles during the stance phase of maximum deceleration, acceleration and velocity



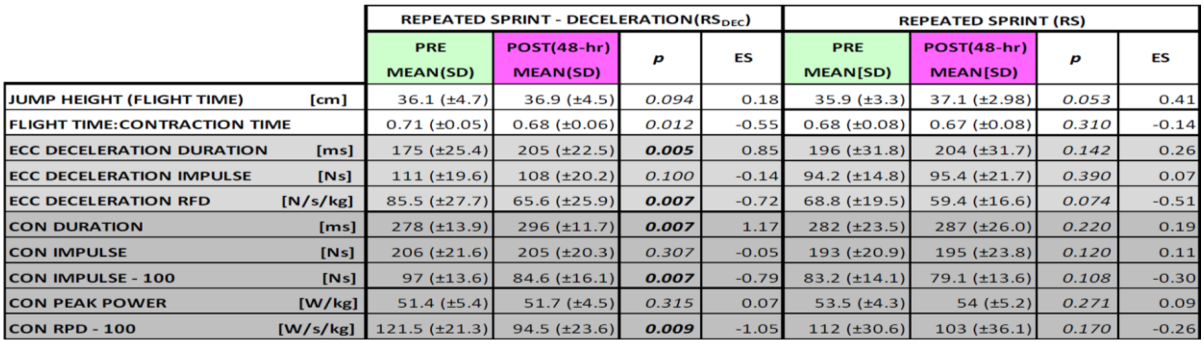
vGRF during maximum deceleration (red line) and maximum velocity (green line). BM=body mass

Source: Harper et al. 2022 (using data taken from Verheul et al. 2021).

Few studies have specifically examined associations between in-match HID load, or markers thereof, and markers of fatigue at 24 and 48h (Hader et al., 2019). Interestingly, Varley et al. (2017) found no association between number of in-match decelerations and CMJ-height change in jump assessments performed 40 or 60 h post-match (Varley et al., 2017). In an attempt to isolate the specific effects of repeated high intensity decelerations (HID) on CMJ-kinetics, Cohen et al., (2021) compared responses to two repeated high-speed running (HSR) protocols - in 16 professional footballers (U23 of a Brazilian 1st division team). Both protocols comprised 10 x 50 m HSR reps (each 50 m completed in < 7s) performed twice, with 35 s between each sprint and 5 mins between the 2 bouts of 10 reps. The deceleration version of the protocol included a 3-metre braking zone (eliciting high intensity deceleration) after each 50-metre HSR rep, while the non-deceleration protocol had a 15-metre braking zone (players decelerated and came to a stop slowly). The players performed 6 CMJ's prior to the protocol, immediately post, and 24 and 48 hours later.

The study showed that CMJ kinetics were able to differentiate the higher residual 'cost' of 20 x 3m intense decelerations in the HID protocol - relative to performing sprints without these demands. The players in the HID group showed large effect size, significant changes at 48h in specific metrics whereas those who completed the same amount of HSR but had a more extended deceleration zone showed no significant decrements in CMJ metrics at 48h, but they did show a non-significant small effect size increase in jump height. Specific durations and time-constrained CMJ variables; ECC deceleration duration and CON duration, ECC deceleration RFD, CON impulse-100, and CON RPD-100, were showed the largest negative responses to HID while global metrics such as jump height and overall ECC and CON phase impulses were stable (table 1).

Table 1: CMJ kinetics pre vs post repeated high-speed running protocol with / without high-intensity decelerations



	REPEATED SPRINT - DECELERATION(RS_{DEC})				REPEATED SPRINT (RS)			
	PRE MEAN(SD)	POST(48-hr) MEAN(SD)	*p*	ES	PRE MEAN[SD]	POST(48-hr) MEAN[SD]	*p*	ES
JUMP HEIGHT (FLIGHT TIME) [cm]	36.1 (±4.7)	36.9 (±4.5)	*0.094*	0.18	35.9 (±3.3)	37.1 (±2.98)	*0.053*	0.41
FLIGHT TIME:CONTRACTION TIME	0.71 (±0.05)	0.68 (±0.06)	*0.012*	-0.55	0.68 (±0.08)	0.67 (±0.08)	*0.310*	-0.14
ECC DECELERATION DURATION [ms]	175 (±25.4)	205 (±22.5)	***0.005***	0.85	196 (±31.8)	204 (±31.7)	*0.142*	0.26
ECC DECELERATION IMPULSE [Ns]	111 (±19.6)	108 (±20.2)	*0.100*	-0.14	94.2 (±14.8)	95.4 (±21.7)	*0.390*	0.07
ECC DECELERATION RFD [N/s/kg]	85.5 (±27.7)	65.6 (±25.9)	***0.007***	-0.72	68.8 (±19.5)	59.4 (±16.6)	*0.074*	-0.51
CON DURATION [ms]	278 (±13.9)	296 (±11.7)	***0.007***	1.17	282 (±23.5)	287 (±26.0)	*0.220*	0.19
CON IMPULSE [Ns]	206 (±21.6)	205 (±20.3)	*0.307*	-0.05	193 (±20.9)	195 (±23.8)	*0.120*	0.11
CON IMPULSE - 100 [Ns]	97 (±13.6)	84.6 (±16.1)	***0.007***	-0.79	83.2 (±14.1)	79.1 (±13.6)	*0.108*	-0.30
CON PEAK POWER [W/kg]	51.4 (±5.4)	51.7 (±4.5)	*0.315*	0.07	53.5 (±4.3)	54 (±5.2)	*0.271*	0.09
CON RPD - 100 [W/s/kg]	121.5 (±21.3)	94.5 (±23.6)	***0.009***	-1.05	112 (±30.6)	103 (±36.1)	*0.170*	-0.26

REPEATED SPRINT - DECELERATION (RS DEC) = Repeated HSR protocol with 3m Decel zone (High Intensity Deceleration protocol); REPEATED SPRINT (RS) = Repeated HSR protocol with 15m Decel zone (non-High Intensity Deceleration protocol)

ECC=Eccentric (downward phase); CON=Concentric (upward phase); RFD=rate of force development; CON impulse-100=net impulse +100ms after the start of the CON phase; RPD=rate of power development; CON RPD-100=the slope of the power curve calculated from start of the CON phase to CON start+100ms.

Source: Cohen DD, Spineti J, Neto APF, Vianna G, De Souza DF, Gathercole R, Harper DJ, Taberner M. The effects of repeated sprints with and without rapid horizontal decelerations on residual neuromuscular fatigue in professional male footballers. Sports (abstract). 2022 10,93: 8

Interestingly, it also argued that monitoring of these changes in jump mechanics may also provide a more complete picture of training adaptations and improve strength diagnostics (Cormie et al., 2009; Gathercole et al., 2015a, b; Schmitz et al., 2013). It is therefore highly recommended that, where possible, NMF monitoring be performed using a force platform to derive CMJ force-velocity and power-time curves, which may reveal alterations in jump mechanics (Cormie et al., 2009; Gathercole et al., 2015a, b) in addition to jump height and other output variables, such as peak force (Johnson et al., 2013; McLellan et al., 2011). Cohen et al. (2021) also identified specific CMJ-kinetic alterations following off-pitch COVID-19 isolation training in professional footballers, a profile highly distinct from that observed in offseason in the same team. This data also suggests that CMJ-kinetics may help reveal distinct time courses of decay in neuromuscular qualities that are promoted by removal of specific loading stimuli.

Detecting positive load-response

Collectively the studies described above provide evidence suggesting that kinetic variables, particularly durations, rate- or time-constrained metrics increase the practitioner's ability to detect neuromuscular fatigue that are not expressed in such “output metrics” as jump height and concentric peak power. In the literature and often in practice the assessment and the metrics have become synonymous with the potential to provide a deeper insight into *negative* neuromuscular responses and alterations in movement strategy – as part of FRM. However, as highlighted at the start of this module kinetics enhances LRM (which may reveal positive trends, negative trends or stability), and evidence also demonstrates that CMJ-kinetics can also reveal positive adaptations to training and competition that have not manifested in significant changes in jump height. As such the CMJ assessment should be seen also as a tool to verify that training prescription is broadly driving positive adaptations, or in a specific neuromuscular quality. Several studies have demonstrated larger improvements in specific kinetic metrics than observed in jump height or significant changes in these metrics alongside non-significant changes or stability in jump height over the same period in a short (Kijowski et al., 2015) or longer-term training programs (Cormie et al., 2009; Gathercole et al., 2015b), during a season in college Basketball players (Heishman et al., 2020), and across a season in elite Rugby 7 players (Lonergan et al., 2022). Selected metrics from Lonergan et all’s study (table 3) highlight at a high level that FT: CT demonstrates a greater sensitivity to the positive input of loading, and broadly that amongst kinetic metrics, those that represent rates or time-constrained metrics were also more responsive to the input of specific training aimed at enhancing performance in the last block of the team’s season – leading into Olympic qualifiers. An important finding in the context of the interest in concentric and eccentric deceleration impulses, principally on the basis of their reliability, was that due to opposing change in the duration component (reduced) and in force (increased) overall impulse in the eccentric and concentric phases remained stable. This supports indications of the value of using time constrained impulse; for example, concentric impulse-50 or -100 ms or examining impulse “shape” (Mizuguchi et al., 2015) as highlighted in a case study in Course “Force assessment and an introduction to Kinematics”, Module 2. Lonergan et al concluded that if only the most commonly reported outputs (jump height and concentric peak power) were considered, one “*may falsely conclude that their conditioning prescription has been ineffective*”.

Table 2: CMJ metrics at the start and the end of a Rugby 7's season

CMJ metric	START OF SEASON	END OF SEASON	ES	p-Value
Jump Height	45.2 ± 5.9	45.5 ± 3.7	0.06	1.0
Flight Time:Contraction Time	**0.95 ± 0.1**	**1.11 ± 0.1**	**1.28**	**0.00***
Concentric Impulse	264 ± 23	251 ± 24	0.55	0.45
Concentric Impulse-100ms	**166 ± 19**	**189 ± 29**	**0.98**	**0.04***
Peak Power / BM	60.8 ± 7.1	63.6 ± 5.2	0.46	1.0
Concentric RPD/BM	**399 ± 110**	**546 ± 146**	**1.14**	**0.00***
Eccentric Deceleration Impulse	137 ± 14	130 ± 11	0.52	1.0
Eccentric Deceleration RFD / BM	**166 ± 53**	**243 ± 95**	**1.03**	**0.01***

CMJ assessments obtained in male elite Rugby players (n=15)

ES = effect size; /BM= variable expressed relative to bodyweight; ms = milliseconds; RFD = rate of force development; RPD = rate of power development;

Source: Adapted from Lonergan et al., 2022. p.84

From Paper to Training ground

We have now outlined the evidence base for the use of jump assessments in load-response monitoring in sports. Hopefully we have communicated that the force platform CMJ in particular, is both feasible to implement, even in the most demanding high-performance settings and a tremendous source of insights on athlete neuromuscular status and changes thereof. We have also shown that a CMJ-kinetic metrics may detect very specific types of loading and load-responses and provide a level of sensitivity that reveals change not identified by other "classic" variables. As a high-performance practitioner, the potential for enhancing your practice and outcomes is impossible to ignore. Evidence showing that a metric is reliable or that it responds to the input of high intensity decelerations is relevant and useful, but the question remains - *how do I generate these insights and apply this in my athletes?* Even if you work in a sport for which studies showing value are available, you must take data you have or will collect in your context through a stepwise process to enable meaningful change to be defined **in your group**. Below in the "toolbox" section, we define the statistical tools and describe the process by which practitioners can translate this evidence from the research paper to the training ground to obtain athlete insights.

Assessment of neuromuscular fatigue using jump tests when force platforms are not available

While we strongly recommend the use of a force platform in LRM monitoring, it is recognised that, in many cases, only a contact time device (such as a contact mat or optical timing systems) is available. We have outlined substantial evidence that changes in CMJ or SJ height (estimated from flight time) may be a useful marker of NMF. We have also discussed evidence which does not support jump height as a sufficiently sensitive marker and shown that the athletes may alter jump strategy under fatigued conditions and, in doing so, maintain or minimise loss of jump height. Specifically, alterations in the eccentric phase of the CMJ have recently been highlighted (Gathercole et al., 2014a, b; Mooney et al., 2013).

NMF has previously been shown to reduce the ability to impair elastic energy utilization and to tolerate impact forces, resulting in a slower transition from eccentric to concentric phases, which are reflected in longer ground contact times in a drop jump (Nicol et al., 1991; Paavolainen et al., 1999). On this basis, if only a contact time device is available, the drop jump may be a useful alternative means of jump-FRM (Hamilton 2009; Comyns et al., 2011), which could fatigue related changes in the eccentric phase/transition.

DJ provides two variables sensitive to NMF:

> Contact time, which refers to the time between the landing on the device/floor from the box until toe-off for the vertical jump. As discussed above, flight time may be maintained despite fatigue by alterations in the biomechanics and the eccentric contraction time during a countermovement. In the CMJ, these alterations cannot be detected with a contact time device, but in a drop jump, a longer eccentric phase would manifest as a longer contact time. Therefore, in theory, monitoring of contact time, flight time, and its ratio –the reactive strength index– has similar characteristics as monitoring CMJ-FT: CT, which shows value as a marker of NMF and predictor of performance.

There is evidence that contact time increases with acute and residual fatigue (Horita et al., 1996; Hamilton, 2009), but several studies of acute fatigue show no change in contact time, but a decrease in DJ-height (Nicol et al., 1991; Oliver et al., 2008). This aligns with the concept that changes in contact time relate more to the secondary inflammatory response and reflect alterations in stretch reflex sensitivity due to muscle damage and residual fatigue (Nicol et al., 1996; Horita et al., 1996; Millet and Lepers, 2004), which reduces the magnitude of muscle activation stimulated by a given degree of muscle stretch.

As reported for the CMJ, underlying NMF may (Nicol et al., 1996) or may not, result in reduced DJ-flight time/height achieved in the vertical jump that follows the drop landing. RSI reflects the interaction between the two goals of the test –to minimise ground contact time and maximise jump height, and to provide a single value, which may also be an indicator of NMF in either the contact time or flight time phase or both (Hamilton, 2009a/b).

Therefore, at sites where there is no access to a force platform or linear transducer, the assessment of the contact time or RSI is potentially a more effective means to capture biomechanical change associated with SSC fatigue than a contact time device derived CMJ-jump height/flight time (Hamilton, 2009a/b; Oliver et al., 2008). Like CMJ, decreases in DJ performance are observed not only after fatiguing SSC dominated plyometric exercise (Comyns et al., 2011) or HIIS (Oliver et al., 2008; Hamilton, 2009a/b), but also after endurance events such as a marathon (Nicol et al., 1991). However, despite suggestions that DJ-performance is a better measure of NMF than CMJ height (Hamilton, 2009a/b), few comparisons have been published (Nicol et al., 1996; Oliver et al., 2008), and, at least regarding acute fatigue following HIIS, the SJ, CMJ and DJ-height all showed significant changes with the largest mean change seen in CMJ height (-3.0 cm), followed by DJ-height (-2.3 cm) (Oliver et al., 2008).

Moreover, while practitioners within elite sports have presented data showing that RSI varies in accordance with changes in training load, suggesting it is a potential marker of accumulated NMF, there is also a lack of literature describing DJ-performance changes over periods longer than a week. Nonetheless, the main disadvantages of the DJ compared to CMJ measurement in FRM are practical:

- The DJ will require a longer period of familiarisation than that of the CMJ, prior to which it cannot be used as a marker NMF. As a result, the CMJ could be preferable if there is little opportunity for familiarisation before the monitoring period.
- Due to the perception of greater loading and musculoskeletal stress compared to the CMJ, athletes/practitioners may be less willing to perform the DJ in-season FRM.

5CMJ

The mean flight time of 5 consecutive CMJ’s (5-CMJ), both 1 jump every 5 seconds (Mohr & Krustrup, 2013) and 5 continuous jumps (Cormack et al., 2008) protocols can be implemented with a contact time device. 5-CMJ mean flight time/jump height was reported to compare favourably to a single CMJ in terms of sensitivity to acute fatigue 5CMJ (1 every 5 seconds), but not CMJ showed significant 6% decrease after competitive soccer played in a hot environment (Mohr & Krustrup, 2013).

In addition, Cormack et al (2008) also found that 5CMJ was a better marker of accumulated fatigue than CMJ height, but was inferior to a single CMJ-FT:CT. The superiority of 5CMJ-flight time to CMJ-flight time may be related to the greater power to detect meaningful changes previously shown when employing a higher number of trials, in contrast to the 3 trials with which single CMJ height is commonly evaluated. It may also be a function of the physiological demands of the 5CMJ being more reflective of the nature of fatigue produced by HIIS, aligning with the greater decrements in repeated versus peak sprint speed reported following competitive soccer (Mohr and Krustrup, 2013).

The toolbox

For reasons described above, the measurement of neuromuscular status in athletes has become increasingly popular amongst practitioners working across multiple sports. It has also become the topic of numerous research studies conducted in “active” subjects or lower-level athletes, while being applied in professional and elite populations. As with other technologies such as GPS, which deliver metrics extracted and processed from large volumes of continuous data - decisions have to be made by the technology provider and / or by the practitioner on which should be shown / reported on. The same applies if you are using Matlab or your own spreadsheet to calculate metrics from the raw FT curve. As highlighted above a large number of metrics can be calculated from the derived force-, velocity-, power-, and displacement - time curves. Navigating the list of available variables can seem unwieldy and overwhelming, and may be an obstacle to the use of information by the practitioner in the fast-moving environment of high-performance sport.

In his editorial 'In the Age of Technology, Occam’s Razor Still Applies' (Coutts, 2014), Distinguished Professor Aaron Coutts posits the following:

> “Irrespective of the chosen metrics, to best cope with the increased volume of information, sport scientists must develop better skills in data management and learn new methods of analysing data…We should avoid the temptation to overutilize the technology and all its data, before proof of concept and validity and reliability trials are completed. Without the ability to separate signal and noise in measures, we cannot make meaningful inferences in practice. We should also look to establish parsimonious systems that are both cost- and time-effective. This scientific approach will allow us to take advantage of the recent technological advancements and best position us to have a positive impact on elite sporting performance.”

So why are there so many metrics and which in this mysterious list should I use?

One force platform system provider completely avoids the issue of selecting metrics issue by providing the user with 3 variables and no access to raw data - a simple approach yes, but also one that creates a black box that is not satisfactory for many practitioners and implies that all we need to know about metrics for all sports, levels, genders is already known. Another system at the other end of the spectrum, a system such as Vald Performance-ForceDecks, provides over 80 variables (and asymmetries therefore where appropriate), evolving as researchers published or practitioners requested new variables or ratios. As we discuss in Course “Force assessment and an introduction to Kinematics”, Module 2, waveform (point by point) analysis represents a means to retain all the data within the movement - as each data point expresses and represents potential insight into the athlete's motor pattern. The waveform analysis allows the practitioner to implement an entirely metric free, agnostic evaluation of what differs between groups or what has changed over time. However, even amongst practitioners who use waveform analysis, some characterisation of specific phases / subphases and features is of interest. Nonetheless, are 3 variables adequate, do I need to examine 80?

How do force platform system providers, researchers and gurus who assume the role of advising practitioners, decide which metrics to deliver in the simpler, shorter more manageable list of metrics? Generally, by keeping variables that are typically reported, that they have used, that the most recent publications have used, or that those with large twitter or Instagram followings use. In other words, reducing the list to those metrics based on internal research, convention, and bias of those with the large research outputs. Metrics are also discarded on the basis that they were not reliable in a given study or in their experience.

Data (metric) reduction is a useful process - it allows the practitioner to generate a less cluttered, more parsimonious reporting dashboard for immediate feedback and analysis, and the quick identification of players with undesirable trends. On the other hand, systematically discarding variables risks losing information that may be important in understanding changes in neuromuscular status in a specific athlete or indeed in the whole group. The authors recommend using metric reduction, to create some degree of parsimony, but to retain all information in a way that additional layers, time points, subphases etc can be accessed easily. We do provide examples of the variables that show the largest response to loading (above). However, the aim of this section is not to conclude with a list of the best variables, but to provide the learner with the best data reduction processes/tools with which to determine the most useful metrics within the context in which you are working. We also highlight some of the limitations within the “metric literature” which could mislead or misdirect the practitioner away from what may be useful metrics and insights into their athletes’ load-response.

As amongst the jump tests CMJ kinetics are the most researched and the test is the most easily integrated into high-performance environments, the practitioner has both ‘weight of evidence’ and ‘weight of good practice’ to help guide them in the implementation of the CMJ in their environment. This has made the CMJ a nearly ubiquitous test in the profiling of athletes in many sports, not just those dependent on jumping in their performance. This arises from early studies that validate the performance results of CMJ against other more ‘ecologically relevant’ activities such as sprinting and change of direction. These relationships are important in contextualising the use of the CMJ as a measure of neuromuscular status. The insight possible from using this test is valuable as it is a maximal task (requires full effort from the performer) but creates negligible resultant fatigue and to means frequent assessments can be implemented without impacting other performance - factors contributing to its qualification as an optimal monitoring tool. Nonetheless, with some statistical and logical ‘tools’, we hope to elucidate further the value of this test.

Why a toolbox and what does it contain? Why can’t I just have a list of the metrics I should use?

The toolbox has several compartments and types of tools, we have described metrics in the first part of this module and in other modules in reference to profiling the healthy athlete or monitoring and classifying the status of the injured athlete. However, because the characteristics of your population may differ from that of the studies in professional athletes principally referred to in this module or to the populations examined in other published research, in a number of different ways - level, sport, training history, conditioning exposure etc - to optimise/maximise your understanding and classification of change in your athletes you will not only need to understand metrics, but also eventually need statistical tools that allow you to logically and systematically determine which of them will be included in your screening, testing, or monitoring battery. While the first section described the impact of exposure to specific types of loading on a range of metrics in healthy athletes and highlighted those that respond to the types of inputs that they are exposed to and those that are not /or less responsive, this section focuses on the process of evaluating the measurement characteristics of these and other metrics that you will encounter in your force platform system. This aims to go beyond metric selection based on them being responsive or being reliable, and instead allows you to reduce the number of variables in a more systematic way that considers all of these factors and most importantly - within your loading context and in your athletes.

Given that "more things should not be used than necessary" for data application, using cohort specific data-driven processes of metric reduction to create “intelligent parsimony” is a prudent activity given the real-world demand in high-performance sports teams, where time and clarity of information are critical to practitioners.

The principal tools / processes used to achieve this are:

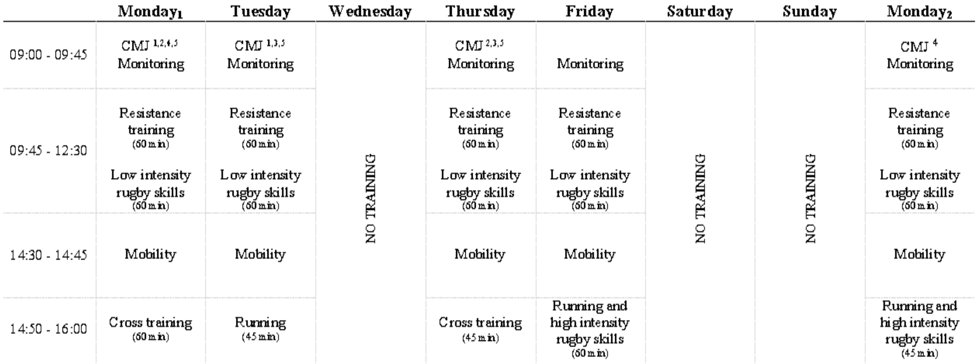
1. Evaluating the measurement characteristics of each metric; their reliability and sensitivity, and the impact of the data treatment method on these characteristics
2. Principal Components Analysis (PCA) to understand the measurement traits of each metric
3. Mixed-Effects Modelling to establish the dose-response relationship of each metric in relation to internal and external load

Measurement Characteristics

Reliability

One of the most important concepts in the initial investigation of data is the test/retest reliability of the outputs (metrics). While there are numerous examples in the literature where reliability is used to refer to variability across a series of trials within a single session, we refer here to interday reliability whereby two (or more) days are selected on which testing can be repeated under similar conditions. In a laboratory setting, conditions are likely to be highly controlled, so all potential influences on the individual's neuromuscular state (e.g., fatigue or potentiation induced by training, dietary influences) are eliminated. However, this degree of control is typically not feasible for the practitioner collecting the data, particularly in team sports scenarios. Conceptually, this can be overcome by picking two days within a relatively short proximity or, indeed, at the interval of choice for monitoring in a longitudinal sense (i.e., within a week or week-to-week) where the athletes complete the test under very similar conditions. One example of this would be to test on the morning of the first training day of two consecutive weeks of preseason (i.e., the first and second Monday). Some alternative day combinations within the most common period (preseason) for establishing baseline data are shown in Table 3. More detailed discussion of conditions/factors with recognised impact on jump performance such as time of day, warm-up etc are discussed in detail in Course "Force assessment and an introduction to Kinematics".

Table 3 - Sample pre-season schedule with reliability testing sessions for CMJ



	Monday$_1$	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday$_2$
09:00 - 09:45	CMJ [1,2,4,5] Monitoring	CMJ [1,3,5] Monitoring	NO TRAINING	CMJ [2,3,5] Monitoring	Monitoring	NO TRAINING	NO TRAINING	CMJ [4] Monitoring
09:45 - 12:30	Resistance training (60 min) Low intensity rugby skills (60 min)	Resistance training (60 min) Low intensity rugby skills (60 min)		Resistance training (60 min) Low intensity rugby skills (60 min)	Resistance training (60 min) Low intensity rugby skills (60 min)			Resistance training (60 min) Low intensity rugby skills (60 min)
14:30 - 14:45	Mobility	Mobility		Mobility	Mobility			Mobility
14:50 - 16:00	Cross training (60 min)	Running (45 min)		Cross training (45 min)	Running and high intensity rugby skills (60 min)			Running and high intensity rugby skills (45 min)

CMJ = countermovement jump; Cross training = combination of aerobic and anaerobic conditioning, including high intensity interval training on cycling and rowing ergometers, high repetition dumbbell and kettlebell work, rope and medicine ball training; Monitoring = musculoskeletal assessments (closed-chain ankle dorsi-flexion, sit and reach, adductor strength) and wellness questionnaire; 1= CMJ data used in Condition 1 (Monday1-Tuesday); 2 = CMJ data used in Condition 2 (Monday1-Thursday); 3 = CMJ data used in Condition 3 (Tuesday-Thursday); 4 = CMJ data used in Condition 4 (Monday1-Monday2); 5 = CMJ data used in Condition 5 (Monday1-Tuesday-Thursday)

Source: Howarth et al, 2021, "Establishing the noise: Interday ecological reliability of countermovement jump variables in professional rugby union players''.

Once the 2-3 days data is collected, its reliability can then be evaluated using the two measures widely used to establish the test/retest reliability of metrics in sports performance and science (Hopkins):

1. Intraclass Correlation Coefficient (ICC)
2. Typical measurement error expressed as a coefficient of variation (CV%)

1. Intraclass correlation coefficient (ICC)

The ICC evaluates the consistency of the rank-order of each day of subjects' results. ICC's range between 0 and 1, with 0.7 considered as a threshold for acceptable reliability. Conceptually, the ICC can be thought of as evaluating the consistency between two raters, those being represented by Day 1 and Day 2. It is typically used to understand the difference in rating a score between two different people or two different technologies. For this case, it is a measure of 'relative reliability' (rank-order variation between subjects) and acts as a quality control for test execution and variable measurement protocols. A good ICC is important for comparing athletes across a group such as in profiling - it means that independent of whether the values might be different in retest the next day the athletes rank within the group would likely be the same.

2. Typical Error of Measurement (CV%)

The typical error of measurement is used to evaluate the expected variation in metric values resulting from both methodological and biological error. The values for a given metric differ in individuals; for example, two days of CMJ testing may result in mean values (± standard deviation) for Concentric Peak Power across 3 jumps of 6000 (± 155) W for test A and 4500 (± 115) W for test B. However, when these results are expressed as a percentage of their respective means, the resultant change is very similar (test A: SD = 2.55%, test B: = 2.58%). By aggregating the change scores and standard deviations for a group of athletes across each day, the typical error can be calculated (TEM = SDdiff2/√2 - Hopkins 2000) and expressed as a percentage of the mean score (as a CV%) to characterise the 'absolute reliability' (normal methodological and biological variation) of a metric for that group.

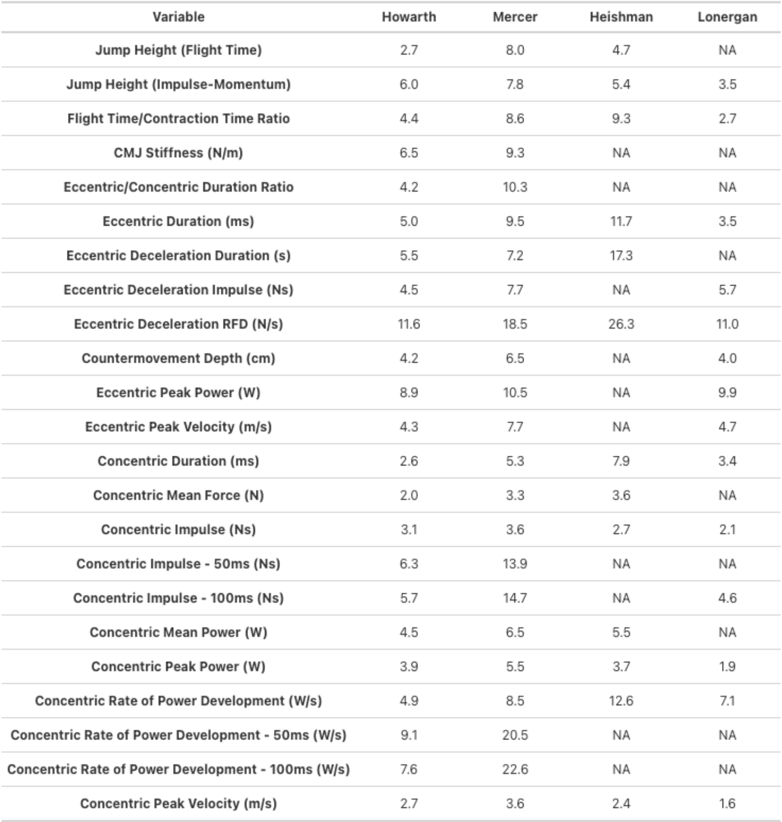
This is clearly also an important measurement characteristic and is even more important than the ICC when examining longitudinal trends with the aim of identifying "meaningful change". Because of this, poor test or metric reliability has been used as a criterion for data reduction (metric exclusion) with a 10% CV% cut-point to qualify as "reliable" pervasive in the literature (Cormack et al. 2008; Claudino et al. 2017; Anicic et al. 2023). This approach is justified by findings suggesting that variables with CV >10% are less likely (by odds ratio) to be sensitive (Claudino et al. 2017). However, the very same research cited by Claudino et al. as the rationale for exclusion of variables with CV >10% (Kraufvelin, 1998) also states:

> “A variable that is highly variable might therefore still be very useful as an effective test endpoint, if the treatment causes a response large enough. We should thus not only look for less variable test variables. We might as well still have use for highly variable test variables, as long as they have an inherent tendency to show large deviations from the control mean once subjected to stress. A variable with a low CV is still of limited use if the corresponding deviations in the treatments may be expected to be very small also.”

In other words, it is suggested that we use the reliability of a metric not as a standalone qualification criterion for 'usefulness', but as a reference point. Specifically, this measure of 'normal methodological and biological variation' can be thought of as 'noise' in measurement arising from normal changes in the person (mechanical, physiological, mental etc) and equipment (environment, thresholds, processing). By establishing the noise, we can reference changes in 'signal' against it, therefore measuring sensitivity directly, rather than making assumptions based on “half of the information”. However, the other half of the metric’s measurement characteristic requires repeated measures of the intended target group - athletes - a process that is a lot harder to implement in a university setting, a potential reason for this data being less commonly reported in research studies.

Table 4 shows the results of the analysis of typical error (CV%) across a number of metrics taken from different studies all of which acquired CMJ data using the same force plate system (Vald Performance-ForceDecks). These results and the differences evident likely reflect the influence of the varied contexts and conditions, as mentioned above. These CVs ± the CIs can then be used to directly assess the level of change in each metric, with results varying outside of this bandwidth of normal methodological and biological variation indicating a significant difference to baseline. Note the large difference in CV for example eccentric decel RFD results for Howarth vs Heishman in table 4 below.

Table 4 - Comparison of absolute reliability (CV%) from four studies using similar methods



Variable	Howarth	Mercer	Heishman	Lonergan
Jump Height (Flight Time)	2.7	8.0	4.7	NA
Jump Height (Impulse-Momentum)	6.0	7.8	5.4	3.5
Flight Time/Contraction Time Ratio	4.4	8.6	9.3	2.7
CMJ Stiffness (N/m)	6.5	9.3	NA	NA
Eccentric/Concentric Duration Ratio	4.2	10.3	NA	NA
Eccentric Duration (ms)	5.0	9.5	11.7	3.5
Eccentric Deceleration Duration (s)	5.5	7.2	17.3	NA
Eccentric Deceleration Impulse (Ns)	4.5	7.7	NA	5.7
Eccentric Deceleration RFD (N/s)	11.6	18.5	26.3	11.0
Countermovement Depth (cm)	4.2	6.5	NA	4.0
Eccentric Peak Power (W)	8.9	10.5	NA	9.9
Eccentric Peak Velocity (m/s)	4.3	7.7	NA	4.7
Concentric Duration (ms)	2.6	5.3	7.9	3.4
Concentric Mean Force (N)	2.0	3.3	3.6	NA
Concentric Impulse (Ns)	3.1	3.6	2.7	2.1
Concentric Impulse - 50ms (Ns)	6.3	13.9	NA	NA
Concentric Impulse - 100ms (Ns)	5.7	14.7	NA	4.6
Concentric Mean Power (W)	4.5	6.5	5.5	NA
Concentric Peak Power (W)	3.9	5.5	3.7	1.9
Concentric Rate of Power Development (W/s)	4.9	8.5	12.6	7.1
Concentric Rate of Power Development - 50ms (W/s)	9.1	20.5	NA	NA
Concentric Rate of Power Development - 100ms (W/s)	7.6	22.6	NA	NA
Concentric Peak Velocity (m/s)	2.7	3.6	2.4	1.6

Source: Adapted from the results from four studies: Rugby Union - Howarth et al, 2021, "Establishing the noise: Interday ecological reliability of countermovement jump variables in professional rugby union players"; Professional Basketball - Mercer et al., 2021, "Finding the signal in the noise - Interday reliability and seasonal sensitivity of 84 countermovement jump variables in professional basketball players"; College Basketball - Heishman et al., 2018, "Countermovement jump reliability performed with and without arm swing in NCAA division 1 intercollegiate basketball players", and; Rugby 7's - Lonergan et al., 2022, "A comparison of countermovement jump performance and kinetics at the start and end of an international Rugby Sevens season".

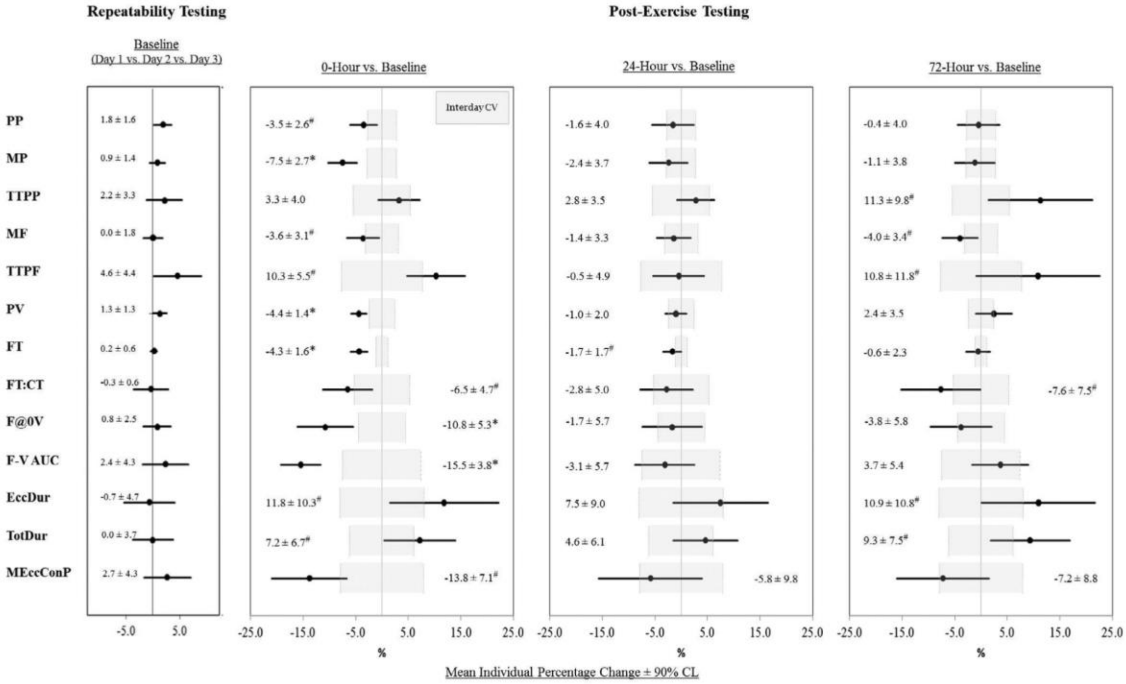
Sensitivity

On face value, sensitivity is used interchangeably with responsiveness - the magnitude or % change of a given variable. This is only part of the sensitivity equation as sensitivity also takes into account the noise described above. It is evaluated by comparing the change in a metric in response to a stimulus (e.g., training, competition, microcycle) and relating it to (dividing by) the expected 'normal' change in a variable (i.e., test/retest reliability). Remember, the "normal change" means obtaining repeated tests under conditions specifically selected to minimise the influence of load or recovery from it, and of other physiological factors. Comparison of these two constructs is achieved (typically) by creating a signal (response to stimulus)-to-noise (normal methodological and biological variation) ratio (SNR) of which the results can be interpreted as follows:

- SNR < 1.0 - Signal does not exceed the noise; it is NOT SENSITIVE
- SNR > 1.0 - Signal exceeds the noise; it is SENSITIVE

Most CMJ studies have evaluated the acute (i.e., immediately post stimulus) and or residual (24-72 hours post stimulus) response of metrics to the fatiguing protocols or match stimulus. Gathercole et al. 2015a examined the acute response of a variety of 'typical' (which they defined as commonly reported metrics) and 'alternative' (defined as novel metrics or those that are infrequently or not evaluated) metrics to repeated Yo-Yo IR2 tests as a fatiguing protocol. They examined the magnitude of the change (effect size – ES) immediately post, and 24- and 72-hours post, in reference to the % CV (based on interday reliability) for that metric, previously determined in the same group. Their findings are shown in figure 5 below.

Figure 5 - sensitivity of typical and alternative variables to repeated Yo-Yo IR2 tests



The mean and 90% confidence level (CL) for the percentage change between baseline, 0 hours, 24 hours, and 72 hours post exercise for select variables and the interday coefficient of variation (CV) (n = 8; 16 countermovement jumps per participant). The interday measurement CV is shown for each parameter in light grey.

PP, peak power; MP, mean power; TTPP, time to peak power; MF, mean force; TTPF, time to peak force; PV, peak velocity; FT, flight time; FT: CT, ratio of flight time to contraction time; F@0V, force at zero velocity; F-VAUC, area under the force–velocity trace; EccDur, eccentric duration; TotDur, total duration; MEccConP, mean eccentric and concentric power over time. *Mean ± CL change ≥ interday CV. #Mean change ≥ interday CV.

Source: Gathercole et al., 2015, "Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue".

While this study, and more broadly the research of Gathercole and colleagues, represents landmark work from a metric perspective - taking the examination of CMJ kinetics in monitoring into a new age - such studies of acute responses to fatiguing protocols provide a snapshot of acute-residual responses to a controlled (protocol) or chaotic (match) load, and help understand the response and fatigue recovery profile of specific metrics to specific or nonspecific loading. However, they do not create a framework for the delivery of the longitudinal monitoring that is needed in many high-performance environments. There are several factors that suggest caution in direct transfer/translation of the findings of the short cycle stimulus response studies to the season long monitoring application.

The change seen in a single cycle, may not align with what an athlete demonstrates over a full season as it may be moderated as a consequence of their adaptation to such discrete stimuli. Furthermore, medical and performance personnel intervene throughout the season as these stimuli promote positive or negative adaptations. Therefore, the period between tests is filled with moderating and mediating factors that affect neuromuscular status and load response. On this basis, an approach aimed at understanding the 'typical' response of an athlete over a season can also provide important information on the 'ecologically relevant' sensitivity of a variable. We use the term ecological to denote that, as demonstrated above with respect to reliability, the sensitivity of a given metric may also not be a fixed intrinsic property but depend on the athlete, sport, and conditions of testing; in particular its proximity to the chaotic/uncontrolled component of the loading week - the competition.

An approach adopted by the authors is to evaluate the ‘typical error’ once again, but this time with a much larger data set and include assessments taken across the whole season. To evaluate athletes on a 'level playing field', meaning to reduce the highly variable influence of minutes played and load components in the most recent match on NMP, the assessments performed weekly on a day where the load conditions - input from training and games - are as homogenous as possible across the squad are included in the analyses. Taking into account the evidence from acute-residual response studies (Cormack et al. 2008a, Cormack et al. 2008b, Gathercole et al. 2015), tests obtained >72 hours post-game are ideal, as athletes who did not compete (non-selected) will have had the opportunity to complete additional conditioning and those who did compete, the opportunity to recover. The acute-residual stimulus from training is likely to have been similar as well. Where these schedules cannot be adhered to due to match congestion - gaps between games of <72 hours (e.g., NBA, NHL, EPL) - it may be that the testing sessions that align with the desired conditions will be less frequent (i.e., not weekly) and the “criteria” of > 72 hours needs to be relaxed. For example, in an NBA schedule, assessments on the second training day after a game could provide similar circumstances for testing and be done often enough to carry out longitudinal evaluation. Using this day for longitudinal monitoring, not just sensitivity evaluation, is likely to be best for understanding 'low frequency' changes in athlete status. When implementing this retrospective evaluation in your setting - whether you were always able to implement tests on the ideal day or not - the analysis should either include apples (i.e., match day + 2) or oranges (i.e., match day + 3) even if you are regularly (or irregularly) implementing both.

The resultant CV% (i.e., typical error from week-to-week change) can be thought of as a signal, and the ratio of this number divided by noise for a given metric is indicative of its ‘ecological-longitudinal sensitivity'. The larger the number the more responsive to stimuli, however, to further qualify the sensitivity of a metric, visual inspection of the 95% confidence intervals (95% CI) for 'signal' and 'noise' to identify those metrics with non-overlap should be conducted. The non-overlap of the 95%CIs indicates that within the whole group that metric is likely to have a signal that varies more than noise. In other words, the metric is sensitive in all/almost all players. It does not mean that for specific uses other metrics are not more insightful, but it suggests that for most players these variables will be responsive to stimuli throughout the season.

Table 5 - Comparison of sensitivity between two studies using similar methods

Variable	Howarth	Mercer
Jump Height - Flight Time (cm)	1.4	1.2
Jump Height - Impulse-Momentum (cm)	1.5	1.7
Flight Time/Contraction Time Ratio	1.2	1.6
CMJ Stiffness (N/m)	1.8	5.5
Eccentric/Concentric Duration Ratio	1.9	1.7
Eccentric Duration (ms)	1.5	3.1
Eccentric Deceleration Duration (s)	1.3	4.8
Eccentric Deceleration Impulse (Ns)	1.1	5.2
Eccentric Deceleration RFD (N/s)	1.2	1.8
Countermovement Depth (cm)	1.9	4.5
Eccentric Peak Power (W)	1.3	4.3
Eccentric Peak Velocity (m/s)	1.3	5.2
Concentric Duration (ms)	1.1	1.7
Concentric Mean Force (N)	1.4	1.3
Concentric Impulse (Ns)	1.6	1.6
Concentric Impulse - 50ms (Ns)	1.5	1.5
Concentric Impulse - 100ms (Ns)	1.7	1.3
Concentric Mean Power (W)	1.6	1.5
Concentric Peak Power (W)	1.3	1.4
Concentric Rate of Power Development (W/s)	1.2	1.5
Concentric Rate of Power Development - 50ms (W/s)	1.6	1.3
Concentric Rate of Power Development - 100ms (W/s)	1.7	1.2
Concentric Peak Velocity (m/s)	1.5	1.7

Source: Adapted from Howarth et al., 2022, “Sensitivity of countermovement jump variables in professional rugby union players within a playing season” and Mercer et al., 2021, “Finding the signal in the noise - Interday reliability and seasonal sensitivity of 84 countermovement jump variables in professional basketball players”.
An important consideration in interpreting these results is that the SNR itself is a cohort-specific measure, and 95% CIs should be used to evaluate the ‘strength’ of the response, as a smaller sample-size will create larger CIs as they make assumptions about the width of results in a population, thereby increasing the bandwidth of these in order to allow for the lower confidence in these assumptions. The sample sizes and testing sessions in these studies were 28 (professional) Rugby Union players for 30 test sessions in Howarth et al., and 13 G-league (professional) players for 11 test sessions in Mercer et al.

It is important to clarify that the results of such a signal to noise analysis do not demonstrate the direction of individual changes, merely that in response to the stimulus the metric demonstrates a greater variation than the expected methodological and biological variation. This means that a metric could increase or decrease across the season or week to week but that that change is likely to be due to the stimuli not the metric's noise. Also note this refers to the recovered (> 72 hour) test cycle and the results may not be generalisable to a match day +2 assessment cycle in which there is a much greater influence of the competition. This analysis is specifically conducted to characterise variables. For the insight into direction of change and individual responses, another analysis - the mixed model - is more appropriate (discussed below).

Data Treatment Methods

A seemingly simple, but actually somewhat complex decision for the practitioner to make, is the question of whether to use in further analysis the 'best' jump or the average results for the set of trials performed (typically 3-5). While a recent review of the use of CMJ in monitoring (Claudino et al. 2017) concluded that the mean should be used, and the issue has been addressed in some studies (Kennedy & Drake 2018; Howarth et al. 2021) it is often left to the discretion or bias of the practitioner - and there are arguments for use of best, at least in profiling.

Indeed, the question of the level of athletes' effort and intent in maximal tests such as the CMJ is often debated in practice and research. It is evident from inspection of eccentric peak velocity - a metric which is indicative of intent - across trials, that many elite athletes “pace themselves” across 3 trials i.e., show increasing levels of intent. This phenomenon could challenge the use of the mean for all athletes, and indicates that practitioners should examine their data for results by best jump in order to understand your players' intent to perform.

The issue of collecting jump data that is accurate (i.e., reflects the true maximal capacity of the athlete at a given time point) is one that is best discussed in the context of environment and motivation. In the authors' experience, when the staff communicate the use and aim of jump data and provide some immediate results feedback to players, the player is more likely to buy-in to the process and appreciate the purpose and use of them as it relates to training programming and overall care of the athlete. In addition, creating a competitive environment between the players using leader boards that update in real-time engenders group encouragement and helps elicit the maximal effort across trials. As the athlete jump height is the most recognisable metric within the jump, it is generally selected for leader boards. However, in sports with large positional differences in this metric, positional leader boards are more appropriate than whole team lists. In addition, some athletes are more motivated by competing against their own scores so immediate feedback referenced to their own data may also be pertinent as well as, or instead of, a group leader board.

In relation to the data treatment, studies in rugby union (Kennedy & Drake 2018; Howarth et al. 2021) and basketball (Mercer et al. 2021) have shown that the average of several jumps results in lower CV% than the 'best' jumps, selected as either the data from the jump with highest jump height or the jump with the greatest flight time/contraction time ratio (FTCT). In addition to this, studies of sensitivity in those same sports (Howarth et al., 2022; Mercer et al. 2021) have shown that using the average results in greater sensitivity for most metrics in the ecological-longitudinal analysis. Interestingly, however, Howarth et al. showed similar results for sensitivity using the Best FTCT as a data treatment method (see figure 6 below). This is encouraging for practitioners who are not confident in the effort put forth by their athletes throughout their jumps: By selecting the results from the trial with the best FTCT, the practitioner can monitor variable changes from the most efficient jump (i.e., best combination of height and time spent - equivalent to reactive strength modified) performed. This could be thought of as a 'minimum viable jump' approach to CMJ testing. Using the best FTCT also has the effect of “cleaning up” a set of trials, whereby jumps performed with low intent (low or even “inadequate” eccentric velocity - as discussed in Course “Force assessment and an introduction to Kinematics”), are not retained for further analysis. In practice, using the mean will require inspecting data to identify trials that might warrant exclusion.

Figure 6 - Comparison of sensitivity results using different data treatment methods

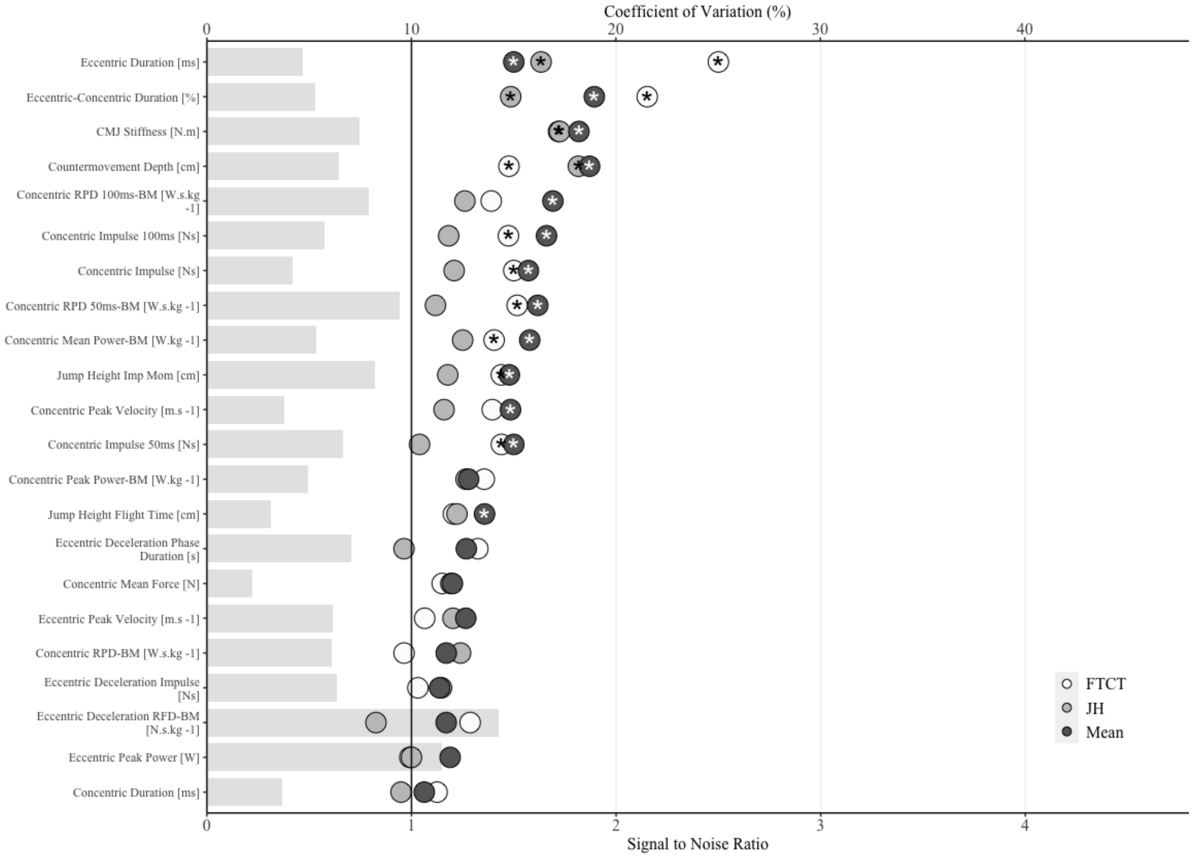


Figure adapted from the work of Howarth et al., 2022, “Sensitivity of countermovement jump variables in professional rugby union players within a playing season”. Variables are ordered from highest to lowest based on the average SNR for the three data treatment methods for calculating CMJ metrics (i.e., Mean = average of 3 jumps; JH = trial with the best jump height by flight time; FTCT = trial with the best flight time/contraction time ratio). Grey bars represent average test/retest CV% (noise) for the three data treatment methods. * = data treatment method has non-overlap of 95% CIs for signal and noise measures

Measurement Traits

Principal Components Analysis (PCA)

Until this point, we have described the process used to examine the measurement characteristics of jump metrics, giving us insight into their expected variability at baseline and longitudinally and shown results of such analyses in Rugby and Basketball (Howarth et al., 2022; Mercer et al. 2021). The results of the reliability component have often been used in prior research as the sole criteria for the inclusion exclusion of variables in future research and practice. Sensitivity has also been used as a sole inclusion criterion. However, measurement characteristics alone do not determine the usefulness of a variable - not only because, as discussed, the two characteristics need to be combined in an SNR analysis but also because there are variables identified as reliable and sensitive that may measure the same or very similar constructs. Therefore, while they qualify based on sensitivity, analysis of multiple variables demonstrating redundancy (providing the same information as another metric) in monitoring fails to meet our goal of parsimony. Owing to the typically temporal nature of force, velocity, power and impulse analyses, a substantial number of variables have overlapping time points and measures (see figure 3 above).

To solve this, we can use a statistical technique called Principal Component Analysis (PCA). PCA is a procedure whereby the scores for a set of variables are analysed for covariance between subjects[1] with the aim of determining if metrics are so correlated that they are likely to be measuring the same construct. In the PCA, metrics are examined on different axes (referred to as “dimensions of analysis”) to see which demonstrate the strongest relationships to each other (referred to as “loading value”). The practitioner can use a loading cut-off value to identify which component (dimensions) the variable is most strongly loaded to (e.g., 0.6). The components are organised numerically by which has the most influence over all the metrics being analysed (% variance explained). Accordingly, the first principal component (PC) explains the most variance in all the metrics, the second PC the second-most, and so on.

There are 4 statistical rules that the practitioner must be aware of when using PCA:

1. Multicollinearity: Repeated measures cannot be entered into a PCA, as the process analyses variance within a group, and multiple measures of individuals create “an artificial” covariance that skews results, particularly for extreme values (very high or

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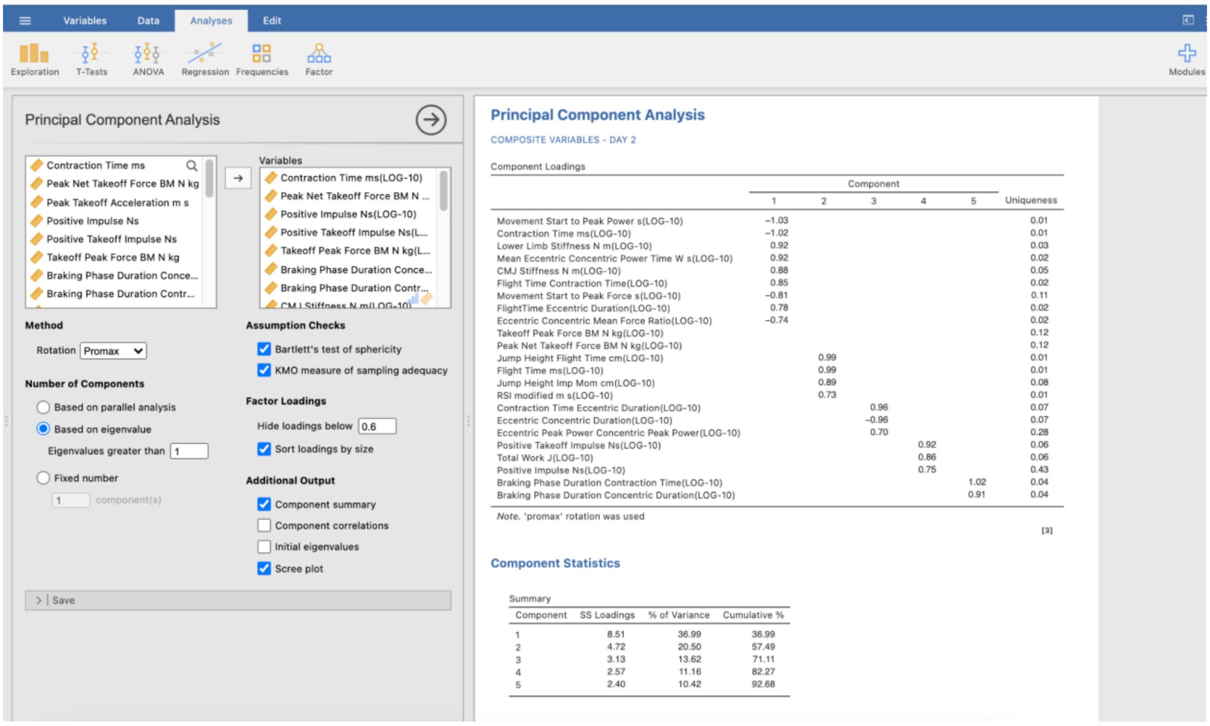
[1] Analysis can be used in the reverse manner, grouping subjects according to their results in certain tests.

very low) within the group (Matsunaga 2010). The PCA is used to evaluate the important components of the jump not within a set of monitoring data, but this analysis is used to help us understand where redundancy in metrics may exist for monitoring (i.e., metrics measuring the same construct/component) or indeed for profiling. PCA was not designed for analysis of longitudinal sensitivity or response to stimuli

2. Sample size and metric number: One of the rules of the PCA is that the dataset must include at least 1 more subject than the number of metrics (Matsunaga 2010). This may not therefore be feasible for the practitioner who is beginning this process with data obtained from their team sport squad (typically 20-30 players) and a contemporary force platform system (with a substantially large number of variables available). One approach to circumvent this limitation of the PCA in studies with inadequate sample sizes to include an extensive list, has been to include only a limited number of metrics. However, this approach, by definition, involves pre-exclusion of metrics based on prior research, bias and/or expert opinion and could be said to undermine the objective of conducting a PCA - to examine an extensive (full) range of variables available and determine redundancy and reduce metric number using an agnostic statistical process. Another approach, which allows all metrics to be retained, is to analyse them in groups. For example, phase-by-phase (i.e., eccentric/downward, concentric/upward, landing and ‘composite’ [not bound to one of these phases or crossing them]). This allows a reduction in the number of metrics in each PCA while still exploring all the variables available to the practitioner.
3. Validation of results: As stated the aim of the PCA is to reveal the important kinetic components of the CMJ. To be confident that these are persistent across different athlete monitoring contexts/conditions, we suggest repeating the PCA at two different time points, i.e., the criteria used to select e.g., two reliability testing sessions and indeed these two days can be used for the PCA “validation”.
4. Data treatment: An important aspect of treatment of data being analysed in the PCA is the scaling of values for each metric - such as using log10 transformation (Matsunaga, 2010). This allows the evaluation of variables for common measurement traits in each component, independent of the magnitude of the measured unit of the variable. This ensures that the components are based on actual variance and provides more confidence in asserting the resulting redundancies revealed. Indeed, when examining the variables that make up each component, common measurement traits emerge, giving the practitioner insight that aids the selection of representative variables for each identified component. Combined with an understanding of the other measurement characteristics of these metrics, the practitioner could confidently include those demonstrating the highest sensitivity (non-overlap of 95% CIs) in their list of metrics used to monitor changes in neuromuscular status.

As suggested earlier, examining the variables in their temporal groupings will help the practitioner manage the data while still examining all metrics. While associations between phases will not be identified as in other research (Richter, O'Connor et al. 2014, Sole, Mizuguchi et al. 2018), the fidelity of each metric is retained and can be analysed based on the impact it has on that phase of the CMJ. A demonstration of this can be seen in figure 7 below, showing the components resulting from such an analysis in Jamovi on 'composite' variables.

Figure 7 - A demonstration of PCA in Jamovi using 'Composite' metrics from CMJ



Principal Component Analysis

Contraction Time ms
Peak Net Takeoff Force BM N kg
Peak Takeoff Acceleration m s
Positive Impulse Ns
Positive Takeoff Impulse Ns
Takeoff Peak Force BM N kg
Braking Phase Duration Conce...
Braking Phase Duration Contr...

Variables
Contraction Time ms(LOG-10)
Peak Net Takeoff Force BM N ...
Positive Impulse Ns(LOG-10)
Positive Takeoff Impulse Ns(L...
Takeoff Peak Force BM N kg(L...
Braking Phase Duration Conce...
Braking Phase Duration Contr...
CMJ Stiffness N m(LOG-10)

Method

Rotation Promax

Number of Components

○ Based on parallel analysis
● Based on eigenvalue
Eigenvalues greater than 1
○ Fixed number
1 component(s)

Assumption Checks

☑ Bartlett's test of sphericity
☑ KMO measure of sampling adequacy

Factor Loadings

Hide loadings below 0.6
☑ Sort loadings by size

Additional Output

☑ Component summary
☐ Component correlations
☐ Initial eigenvalues
☑ Scree plot

Principal Component Analysis

COMPOSITE VARIABLES - DAY 2

Component Loadings

	Component					
	1	2	3	4	5	Uniqueness
Movement Start to Peak Power s(LOG-10)	–1.03					0.01
Contraction Time ms(LOG-10)	–1.02					0.01
Lower Limb Stiffness N m(LOG-10)	0.92					0.03
Mean Eccentric Concentric Power Time W s(LOG-10)	0.92					0.02
CMJ Stiffness N m(LOG-10)	0.88					0.05
Flight Time Contraction Time(LOG-10)	0.85					0.02
Movement Start to Peak Force s(LOG-10)	–0.81					0.11
FlightTime Eccentric Duration(LOG-10)	0.78					0.02
Eccentric Concentric Mean Force Ratio(LOG-10)	–0.74					0.02
Takeoff Peak Force BM N kg(LOG-10)						0.12
Peak Net Takeoff Force BM N kg(LOG-10)						0.12
Jump Height Flight Time cm(LOG-10)		0.99				0.01
Flight Time ms(LOG-10)		0.99				0.01
Jump Height Imp Mom cm(LOG-10)		0.89				0.08
RSI modified m s(LOG-10)		0.73				0.01
Contraction Time Eccentric Duration(LOG-10)			0.96			0.07
Eccentric Concentric Duration(LOG-10)			–0.96			0.07
Eccentric Peak Power Concentric Peak Power(LOG-10)			0.70			0.28
Positive Takeoff Impulse Ns(LOG-10)				0.92		0.06
Total Work J(LOG-10)				0.86		0.06
Positive Impulse Ns(LOG-10)				0.75		0.43
Braking Phase Duration Contraction Time(LOG-10)					1.02	0.04
Braking Phase Duration Concentric Duration(LOG-10)					0.91	0.04

Note. 'promax' rotation was used

[3]

Component Statistics

Summary

Component	SS Loadings	% of Variance	Cumulative %
1	8.51	36.99	36.99
2	4.72	20.50	57.49
3	3.13	13.62	71.11
4	2.57	11.16	82.27
5	2.40	10.42	92.68

Analysis of CMJ data collected from professional rugby union players. To complete the analysis, the free open-source software Jamovi provides a convenient and validated process. Furthermore, several groups have used functions from the psych package available in R along with created packages and apps that complete the analysis and provide detailed reports on the data, such as FactoMineR and FactoShiny that have been developed under the guidance of Francois Husson.

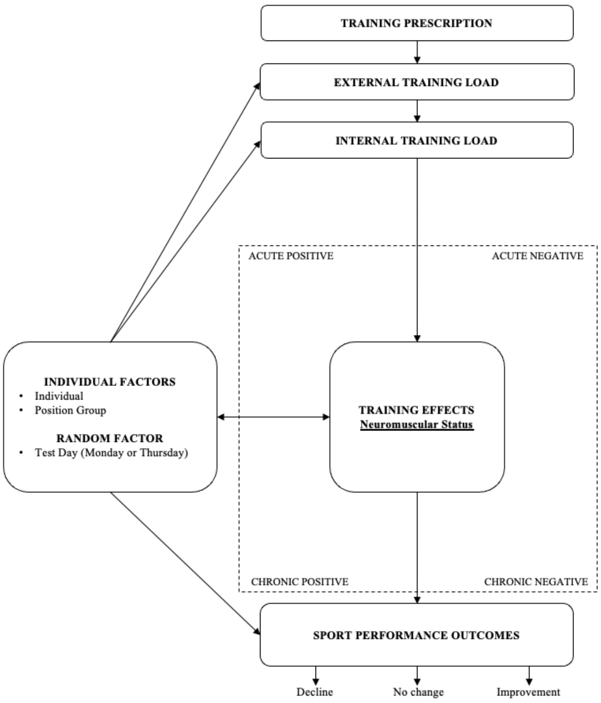
Examining the Dose-Response Relationship with Load: Mixed-Effects Modelling

Quantifying the response of individual athletes to load across varying timeframes is essential given the biological complexity of human adaptation (Kiely 2012), and the high demands of modern sporting competition (Mercer et al. 2022). In fact, using the CMJ as part of a holistic, multifaceted framework that measures athlete input (load) and output (performance) - and thus load response, is at the core of athlete care and underpins best practice in performance, S&C, sports science, medical with specific models championed in recent publications (Jeffries et al. 2021, Mercer et al. 2022). The CMJ offers the practitioner an agnostic, non-fatiguing test of maximal neuromuscular capacity that can be deployed multiple times a week and in relative proximity to game play. Consequently, it can be used to quantify the neuromuscular response to acute, residual, or chronic load inputs. But as highlighted above, the practitioner should bear in mind that assessments performed under the different conditions should not be entered into the same signal analysis i.e., if matchday + 2's and matchday -1 are both performed across the season would form two separate analyses. An additional analysis might be performed on match day + 2 versus matchday - 1 to evaluate recovery trajectories during the week but this would not be an SNR analysis.

We argue that the processes described so far are valid and appropriate tools to apply to interday reliability and weekly/repeated across season "recovered athlete" CMJ data with the aim of determining metric sensitivity and begin metric reduction within an athlete group. However, as highlighted above, due to the variability of input across the athlete group, we also suggest that this same process would NOT be applied to CMJ assessments conducted <72 hours post competition. Instead, another method would be used to quantify the response of metrics to differing loads - mixed effects modelling.

Once the metrics have been processed (i.e., measurement characteristics and covariance analyses performed on within-cohort data), the practitioner now has a dashboard of monitoring variables that they can examine within the context of a holistic programme aimed at quantifying the effects of load on neuromuscular status and overall well-being. These can be detailed in a conceptual framework detailing the probable training effects of internal and external load (moderators) and other individual factors (mediators).

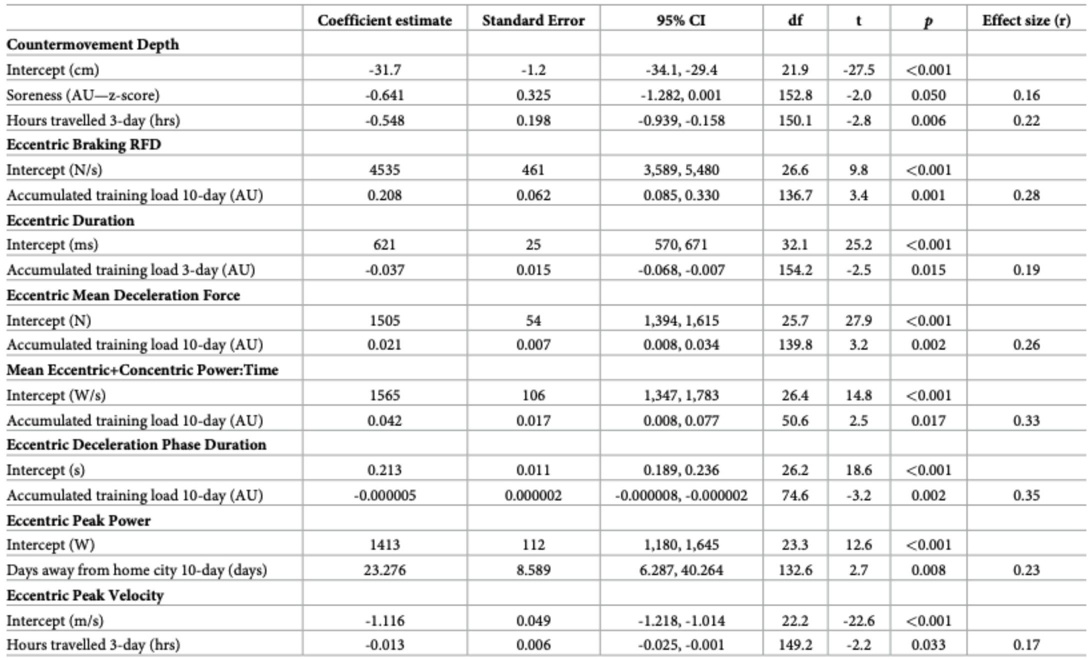
Figure 8 – Schematic of a conceptual framework of training load dose-response in sports



This schematic can be used to visualise the believed effects of the performance and medical staff of training load and individual factors on training effects.
Source: Adapted from Jeffries et al. 2021 "Development of a Revised Conceptual Framework of Physical Training for Use in Research and Practice".

Using this conceptual framework to guide the application of a mixed model; the variables we are examining are the changes in CMJ metric at different time points (i.e., training effects), the fixed effects are the training load (i.e., quantified internal and external load), and the random effects are individual and contextual factors (e.g., age, position etc). A demonstration of this process can be seen in research by Mercer et al. in professional basketball (G-League - USA), where they measured the effect of game time, training load, travel, and perceived well-being on performance in metrics they had previously determined as being sensitive using a longitudinal approach as suggested above. Although this research lacks the application of a PCA to data (thus potentially introducing redundancy to their examination), the simple effects of cumulative load and stress can be evaluated. Significant results for the effect of accumulated load and acute/residual stimuli (in this case, travel) can be found, but the effect size is small. As mentioned earlier in this module, this is likely because of the moderating and mediating effects of athlete adaptation and staff intervention. Large effect size changes in applied settings are unlikely if the performance, medical and coaching staffs are managing athlete training and fatigue well!

Table 6 - Effect of training and travel load on CMJ measures in professional basketball



	Coefficient estimate	Standard Error	95% CI	df	t	*p*	Effect size (r)
Countermovement Depth							
Intercept (cm)	-31.7	-1.2	-34.1, -29.4	21.9	-27.5	<0.001	
Soreness (AU—z-score)	-0.641	0.325	-1.282, 0.001	152.8	-2.0	0.050	0.16
Hours travelled 3-day (hrs)	-0.548	0.198	-0.939, -0.158	150.1	-2.8	0.006	0.22
Eccentric Braking RFD							
Intercept (N/s)	4535	461	3,589, 5,480	26.6	9.8	<0.001	
Accumulated training load 10-day (AU)	0.208	0.062	0.085, 0.330	136.7	3.4	0.001	0.28
Eccentric Duration							
Intercept (ms)	621	25	570, 671	32.1	25.2	<0.001	
Accumulated training load 3-day (AU)	-0.037	0.015	-0.068, -0.007	154.2	-2.5	0.015	0.19
Eccentric Mean Deceleration Force							
Intercept (N)	1505	54	1,394, 1,615	25.7	27.9	<0.001	
Accumulated training load 10-day (AU)	0.021	0.007	0.008, 0.034	139.8	3.2	0.002	0.26
Mean Eccentric+Concentric Power:Time							
Intercept (W/s)	1565	106	1,347, 1,783	26.4	14.8	<0.001	
Accumulated training load 10-day (AU)	0.042	0.017	0.008, 0.077	50.6	2.5	0.017	0.33
Eccentric Deceleration Phase Duration							
Intercept (s)	0.213	0.011	0.189, 0.236	26.2	18.6	<0.001	
Accumulated training load 10-day (AU)	-0.000005	0.000002	-0.000008, -0.000002	74.6	-3.2	0.002	0.35
Eccentric Peak Power							
Intercept (W)	1413	112	1,180, 1,645	23.3	12.6	<0.001	
Days away from home city 10-day (days)	23.276	8.589	6.287, 40.264	132.6	2.7	0.008	0.23
Eccentric Peak Velocity							
Intercept (m/s)	-1.116	0.049	-1.218, -1.014	22.2	-22.6	<0.001	
Hours travelled 3-day (hrs)	-0.013	0.006	-0.025, -0.001	149.2	-2.2	0.033	0.17

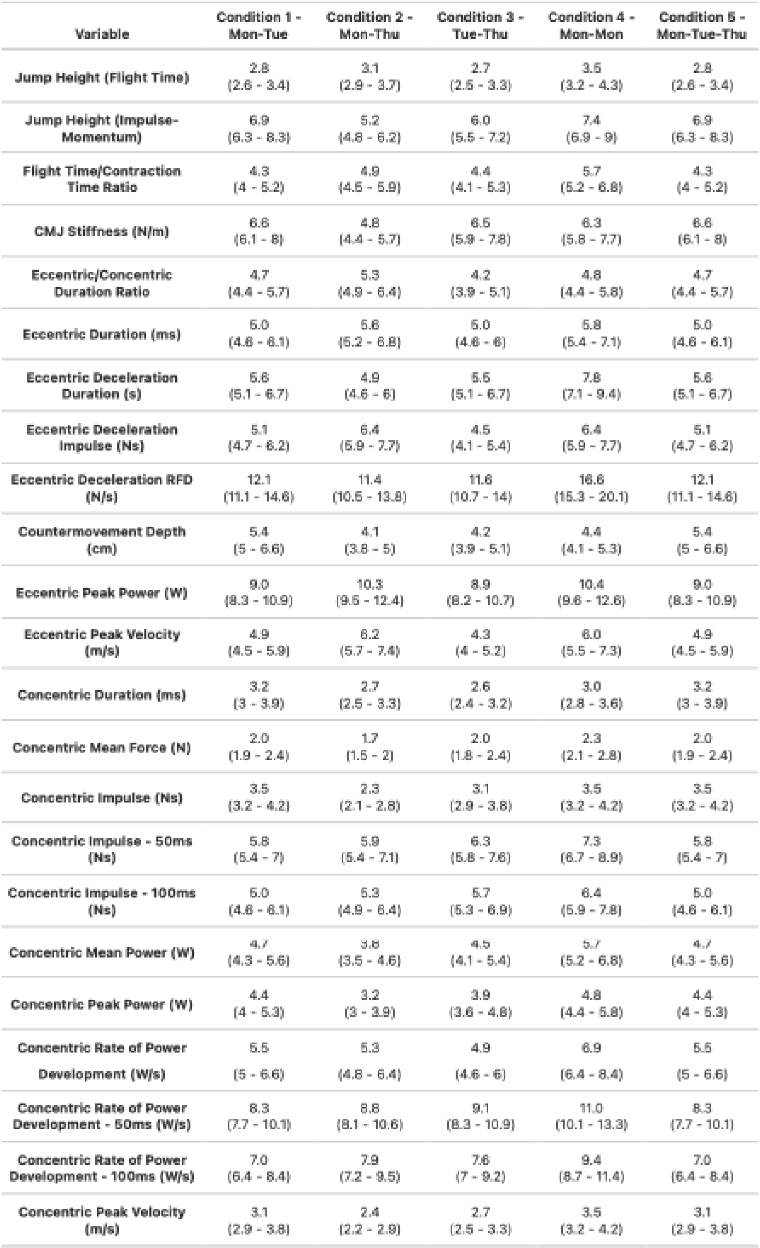
Source: Mercer et al., 2022, “Understanding ‘monitoring’ data–the association between measured stressors and athlete responses within a holistic basketball performance framework”.

AU, Arbitrary Unit; CI, confidence interval for coefficient estimate. The key statistics are the p-value that determines significance of the results (significant = $p \leq 0.05$) and the effect-size (r-value) which can be interpreted as: <.1 = trivial; .10-.29 = small; .30-.49 = moderate; .50-.69 = large; .70-.89 = very large; .90- .99 = almost perfect; 1.0 = perfect

Conclusions

The above is a practical toolbox of statistical tools that sits alongside evidence-based practices for collecting useful data when evaluating CMJ. Furthermore, these analyses equip the practitioner with the knowledge they need to confidently determine when a real change has occurred. By working through the process and taking the time to understand the response and redundancies, the practitioner avoids selecting variables that may not be as useful for the intended purpose for their athletes. An important understanding is that these measurement characteristics vary between cohorts, as demonstrated in tables 4 and 5. The practitioner can utilise this toolbox to implement a cohort-specific analysis process that underpins an ecologically sound basis of identifying key metrics and creating a more parsimonious optimal dashboard with minimal redundancy. In the process, a statistically robust process for classifying/qualifying magnitude of change is also produced - key in converting CMJ kinetic data into insights to inform decision making.

Table 7 - Comparison of absolute reliability - CV% (95%CIs) - of CMJ metrics using different testing conditions (day combinations in the first week of pre-season)



Variable	Condition 1 - Mon-Tue	Condition 2 - Mon-Thu	Condition 3 - Tue-Thu	Condition 4 - Mon-Mon	Condition 5 - Mon-Tue-Thu
Jump Height (Flight Time)	2.8 (2.6 - 3.4)	3.1 (2.9 - 3.7)	2.7 (2.5 - 3.3)	3.5 (3.2 - 4.3)	2.8 (2.6 - 3.4)
Jump Height (Impulse-Momentum)	6.9 (6.3 - 8.3)	5.2 (4.8 - 6.2)	6.0 (5.5 - 7.2)	7.4 (6.9 - 9)	6.9 (6.3 - 8.3)
Flight Time/Contraction Time Ratio	4.3 (4 - 5.2)	4.9 (4.5 - 5.9)	4.4 (4.1 - 5.3)	5.7 (5.2 - 6.8)	4.3 (4 - 5.2)
CMJ Stiffness (N/m)	6.6 (6.1 - 8)	4.8 (4.4 - 5.7)	6.5 (5.9 - 7.8)	6.3 (5.8 - 7.7)	6.6 (6.1 - 8)
Eccentric/Concentric Duration Ratio	4.7 (4.4 - 5.7)	5.3 (4.9 - 6.4)	4.2 (3.9 - 5.1)	4.8 (4.4 - 5.8)	4.7 (4.4 - 5.7)
Eccentric Duration (ms)	5.0 (4.6 - 6.1)	5.6 (5.2 - 6.8)	5.0 (4.6 - 6)	5.8 (5.4 - 7.1)	5.0 (4.6 - 6.1)
Eccentric Deceleration Duration (s)	5.6 (5.1 - 6.7)	4.9 (4.6 - 6)	5.5 (5.1 - 6.7)	7.8 (7.1 - 9.4)	5.6 (5.1 - 6.7)
Eccentric Deceleration Impulse (Ns)	5.1 (4.7 - 6.2)	6.4 (5.9 - 7.7)	4.5 (4.1 - 5.4)	6.4 (5.9 - 7.7)	5.1 (4.7 - 6.2)
Eccentric Deceleration RFD (N/s)	12.1 (11.1 - 14.6)	11.4 (10.5 - 13.8)	11.6 (10.7 - 14)	16.6 (15.3 - 20.1)	12.1 (11.1 - 14.6)
Countermovement Depth (cm)	5.4 (5 - 6.6)	4.1 (3.8 - 5)	4.2 (3.9 - 5.1)	4.4 (4.1 - 5.3)	5.4 (5 - 6.6)
Eccentric Peak Power (W)	9.0 (8.3 - 10.9)	10.3 (9.5 - 12.4)	8.9 (8.2 - 10.7)	10.4 (9.6 - 12.6)	9.0 (8.3 - 10.9)
Eccentric Peak Velocity (m/s)	4.9 (4.5 - 5.9)	6.2 (5.7 - 7.4)	4.3 (4 - 5.2)	6.0 (5.5 - 7.3)	4.9 (4.5 - 5.9)
Concentric Duration (ms)	3.2 (3 - 3.9)	2.7 (2.5 - 3.3)	2.6 (2.4 - 3.2)	3.0 (2.8 - 3.6)	3.2 (3 - 3.9)
Concentric Mean Force (N)	2.0 (1.9 - 2.4)	1.7 (1.5 - 2)	2.0 (1.8 - 2.4)	2.3 (2.1 - 2.8)	2.0 (1.9 - 2.4)
Concentric Impulse (Ns)	3.5 (3.2 - 4.2)	2.3 (2.1 - 2.8)	3.1 (2.9 - 3.8)	3.5 (3.2 - 4.2)	3.5 (3.2 - 4.2)
Concentric Impulse - 50ms (Ns)	5.8 (5.4 - 7)	5.9 (5.4 - 7.1)	6.3 (5.8 - 7.6)	7.3 (6.7 - 8.9)	5.8 (5.4 - 7)
Concentric Impulse - 100ms (Ns)	5.0 (4.6 - 6.1)	5.3 (4.9 - 6.4)	5.7 (5.3 - 6.9)	6.4 (5.9 - 7.8)	5.0 (4.6 - 6.1)
Concentric Mean Power (W)	4.7 (4.3 - 5.6)	3.8 (3.5 - 4.6)	4.5 (4.1 - 5.4)	5.7 (5.2 - 6.8)	4.7 (4.3 - 5.6)
Concentric Peak Power (W)	4.4 (4 - 5.3)	3.2 (3 - 3.9)	3.9 (3.6 - 4.8)	4.8 (4.4 - 5.8)	4.4 (4 - 5.3)
Concentric Rate of Power Development (W/s)	5.5 (5 - 6.6)	5.3 (4.8 - 6.4)	4.9 (4.6 - 6)	6.9 (6.4 - 8.4)	5.5 (5 - 6.6)
Concentric Rate of Power Development - 50ms (W/s)	8.3 (7.7 - 10.1)	8.8 (8.1 - 10.6)	9.1 (8.3 - 10.9)	11.0 (10.1 - 13.3)	8.3 (7.7 - 10.1)
Concentric Rate of Power Development - 100ms (W/s)	7.0 (6.4 - 8.4)	7.9 (7.2 - 9.5)	7.6 (7 - 9.2)	9.4 (8.7 - 11.4)	7.0 (6.4 - 8.4)
Concentric Peak Velocity (m/s)	3.1 (2.9 - 3.8)	2.4 (2.2 - 2.9)	2.7 (2.5 - 3.3)	3.5 (3.2 - 4.2)	3.1 (2.9 - 3.8)

Source: Adapted from Howarth et al., 2021, "Establishing the noise: Interday ecological reliability of countermovement jump variables in professional rugby union players". The results for typical error and the 95% CIs can be used to establish a bandwidth of typical error in results around a baseline, for all future measures to be compared to in order to determine whether a difference is 'meaningful'.

As we have reiterated throughout this course, in order to make meaningful and valid interpretations of kinetic measures, it is critical to understand the context in which the data was collected and from whom. Generalising results collected from one sport or even one level within a sport to another could lead both to misdirect the practitioner in terms of metric selection and also to inaccurate conclusions within LRM and profiling in the healthy and rehabilitating athlete - potentially having a negative impact on athlete management. In the authors experience, the following represent the key considerations for understanding the athlete and data context:

- **Sport**: The biggest determinant of an athlete's kinetic profile is likely to be the stimulus that they are repeatedly exposed to... their sport and the associated technical and physical conditioning! This doesn't mean that every sport will have an entirely distinct kinetic "signature" but it does mean that if there is no kinetic literature available, collection of data and analysis of profiles and responses should be prioritised over engaging in interpretation and interventions.
- **Athlete Level:** In endurance athletes it has been shown that while a higher VO2 max is associated with better performance when comparing different levels of athlete, in higher level athletes, other physiological markers become better predictors of performance. In terms of jump performance, jump height or concentric peak power should be higher across age groups and broadly across levels, but other CMJ-kinetic metrics become better indicators of performance / more discriminatory across the elite and sub-elite level (as shown in Course "Force assessment and an introduction to Kinematics", Module 2: Professional versus College Basketball)
- **Training Age:** Younger athletes show varied movement patterns as they learn and are exposed to varied loading (and technical) demands as they are exposed to different sports. Variability also manifests in the kinetics of the jump assessments in poorer (within session and interday) reliability of metrics in younger athletes (Nibali et al., 2015) - and practitioners will need to adjust their expectations and ensure that reliability is measured within these athletes when using assessments to monitor response to input of training and competition over time. Familiarisation becomes a more important aspect of all physical tests.
- **Purpose of test / use of data:** Is the data being used to profile/screening the athlete - benchmarking to understand the typical movement pattern of an individual in the event of injury, or to profile the athlete and compare to sport/positional peers? or is it principally for LRM purposes - to understand response to competition and training load input or to support programming decisions and quantify the neuromuscular qualities affected by a specific training protocol? The consideration of the performance or injury related question the data obtained being used to help answer is an essential consideration in metric selection / value. These applications provide guidance on what other data might be needed, the type of data analysis and the statistical tools used to do so. The practitioner will also find that certain metrics are more useful for profiling - defining differences between athletes or positions but may not be the most sensitive or responsive in the LRM context.

While there are other intrinsic and extrinsic factors that influence the degree of information gain/insights that a given metric provides for a specific athlete or athlete group, these four factors are identifiable features of the athlete and test that clearly modulate the value/usefulness of a metric within a given cohort by modifying either its measurement characteristics and / or its measurement traits. Ultimately, this also affects the insights gained by the practitioner from the assessment, the interpretation of results and how they inform the training, recovery and performance programs for their athletes. In light of this, we recommend that all practitioners take the time to follow these protocols to understand the measurement characteristics and measurement traits of kinetic metrics in their cohort. This information can then be built-in to a conceptual framework for analysing the response of these metrics, and by extension the neuromuscular status of their athletes, to varying doses of load throughout a season.

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