# Can Vertical Stiffness Derived from Accelerometers Embedded in GPS Units and Collected During a Sub-Maximal Yo-Yo Test be Used as a Reliable Alternative to Counter Movement Jump Testing when Testing Elite Youth Soccer Players' Level of Fatigue?

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## Abstract

This study aimed to discover whether vertical stiffness (Kvert), recorded via accelerometers embedded within Global Positioning System (GPS) units, could be used to monitor the level of neuromuscular fatigue for elite youth soccer players. 17 male outfield soccer players (age: 18.4 ± 1.1years; height: 179.8 ± 6cm; weight: 74.7 ± 6.5kg) took part in the study. Testing took place on match day (MD)-1 and MD+2, and GPS units were worn during matches. The testing consisted of 3 maximum effort counter movement jumps (CMJ), with the highest jump being analysed, and a submaximal Yo-Yo Intermittent Recovery Test Level 1 which lasted for 6 minutes. Flight time:contraction time (FT:CT) was recorded from the CMJs, and Kvert was recorded from the Yo-Yo test using the sine wave method via the software Athletic Data Innovations (ADI). It was discovered that there was no significant change ($p > 0.05$) in Kvert from MD-1 to MD+ 2 (31.75 ± 7.09kN/m and 31.23 ± 6.38kN/m) for players that played >60 minutes in matches. There was no correlation ($p > 0.05$) between the change from match to match for any GPS match variable and the change in Kvert from MD-1 to MD+2 for players that played >60 minutes. The only significant change was found for players playing <60 minutes in matches, with a significant decrease ($p < 0.05$) for FT:CT between MD-1 and MD+2 (0.8 ± 0.13 and 0.75 ± 0.13, Cohen's D effect size = 0.4). The small sample size of the study results in an increased risk of type 1 and type 2 errors however, meaning that this statistically significant difference is possibly due to an error. Power calculations were performed on the data collected, with it being clear that a far larger sample size would be required for reliance to be placed on the statistical results. Due to the limitations of the study and results from previous studies such as from Morin and colleagues in 2006 and Girard and colleagues in 2011 and 2010 which discovered Kvert is affected by level of fatigue, I believe further research is warranted due to the potential of using Kvert to monitor neuromuscular fatigue of large groups of players simultaneously. It is however recommended that further research focuses on obtaining Kvert in another method than during the 6-minute Yo-Yo test, due to the significant load this places on a squad of players over the course of a season if performed multiple times per week.

**Contents**

## List of Tables

## List of Figures

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## Abbreviations

| | |
|---|---|
| ADI | Athletic Data Innovations |
| AFL | Australian Football League |
| ANOVA | Analysis of Variance |
| ATT | Attacker |
| $Ca^{2+}$ | Calcium Ions |
| CB | Centre Back |
| cm | Centimetre |
| CM | Central Midfielder |
| CMJ | Countermovement Jump |
| CI | Confidence Interval |
| CoM | Centre of Mass |
| CSV | Comma Separated Values |
| CT | Contraction Time |
| CV | Coefficient of Variation |
| FB | Full Back |
| FIFA | Federation Internationale de Football Association |
| FT | Flight Time |
| FT:CT | Flight Time: Contraction Time |
| GPS | Global Positioning System |
| h | Hour |
| ICC | Intraclass Correlation Coefficient |
| J | Joule |
| kg | Kilogram |
| Km | Kilometre |
| Kvert | Vertical Stiffness |
| m | Metre |
| MD | Match Day |
| RPE | Rate of Perceived Exertion |
| s | Second |

| | |
|---|---|
| SPSS | Statistical Package for the Social Sciences |
| SSC | Stretch Shortening Cycle |
| UEFA | Union of European Football Associations |
| USA | United States of America |
| USB | Universal Serial Bus |
| W | Watt |
| WM | Wide Midfielder |

# Introduction

## Soccer Overview

### Introduction to Soccer

Association football, also known as soccer, is regarded as the most popular sport in the world. In 2007, FIFA estimated that 265 million people worldwide participated in soccer (FIFA, 2007), and this number is almost certainly far higher today. Its popularity is further demonstrated by the fact that, during the 2018 FIFA World Cup, a combined 3.75 billion viewers watched the tournament, and 1.12 billion tuned in to watch the final contested between France and Croatia in Moscow, Russia (FIFA, 2018).

### Physical Demands of Soccer Match Play and Training

Soccer is a high intensity intermittent sport, consisting of periods of high intensity running, jumping and tackling, and is interspersed with periods of low intensity activity such as jogging and walking. Players performing at the elite level tend to cover 10-13km during matches, with the vast majority of this being covered while walking or low intensity running, which is usually defined as <15km/h (Bangsbo et al, 2006; Abt and Lovell, 2009). When analysing match data from English Premier League matches, it was discovered that high-intensity running (>19.8km/h) was performed for just 3% of total time (Di Mascio and Bradley, 2013). It is crucial for soccer players to have a wide range of physical capabilities, with both anaerobic and aerobic endurance being vital in order to compete at the professional and elite level. However, soccer relies heavily on many other abilities such as technical skill and tactical knowledge, strength and power, and a balance between all of these needs to be met. The physical demands of soccer can vary depending on what positional role a player has, with midfielders covering a greater total distance ($p < 0.05$) than defenders and attackers (ATT), with central midfielders (CM) and wide midfielders (WM) covering 12027m ± 625m and 11990m ± 776m respectively, as opposed to centre backs (CB) and full backs (FB) covering 10627m ± 893m and 11410m ± 708m respectively and ATTs covering 11254m ± 894m. CBs cover less distance at high intensities than any other position, whereas WMs cover more distance at high intensities than any other position, with CBs covering 397m ± 114m between 19.1 – 23km/h and 215m ± 100m > 23km/h and WMs covering 738m ± 174m between 19.1 – 23km/h and 446m ± 161m >23km/h. The vast majority of playing time is spent without possession of the ball, and just 1.2-2.4% of the total distance covered during a game for any player is spent with the ball at their feet, with CBs spending the least time with

1.2% ± 0.6% and WMs spending the most time with 2.4% ± 1.1% of the game in possession of the ball (Di Salvo et al, 2007).

Soccer is played with 11 players (10 outfield and 1 goalkeeper) on each team, with matches lasting 90 minutes (two 45-minute halves) plus injury time. Up to three substitutions are permitted during matches, with an additional substitute being introduced recently for knock out games that proceed to extra time should the score be level. If knock out matches finish as a draw after extra time, penalty kicks are then used to decide which team advances to the next round. The length of a pitch must be between 90m and 120m and the width between 45m and 90m.

Typically, professional teams play one game per week, usually taking place on Saturday afternoons. However, due to domestic and continental cup competitions, this can frequently increase to three games per week, and during busy fixture periods there can be as many as 10 games in a month. In addition to this, international players also compete in friendlies, qualifiers and tournaments for their nations, meaning players at the elite level can participate in well over 60 matches over the course of a season. Examples of this include Mexican Jesús Gallardo who participated in 72 games during the 2018/19 season (57 for his club and 15 for his nation), which amounted to the most appearances in world soccer that season. Similarly, Scotsman Callum McGregor completed 5,894 minutes for his club and nation over the same period, which totalled more than any other player (Transfermarkt, 2019). Busy periods with fixture congestions can cause issues for players, as 48-72 hours is often needed for full recovery of performance markers and also muscle trauma and metabolic homeostasis for elite level players (Ispirlidis et al, 2008; Russell et al, 2015; Nedelec et al, 2014). However, some variables have been found to return to baseline within 24 hours of matches, such as muscle sarcoplasmic reticulum $Ca^{2+}$ reuptake, which returned to baseline level 24 hours following the completion of a competitive match involving seven 1$^{st}$ and 2$^{nd}$ division Danish soccer players, as well as certain CMJ variables returning to baseline in this time frame which has been discussed previously (Krustrup et al, 2011; McLellan, 2012).

As well as the demands of matches, players also have to handle the load of training that takes place, with players at the elite level rarely having more than 1 day off per week. A 2010 study which monitored the load, recovery and performance of youth elite soccer players discovered that players spent an average of 394.4 ± 134.9 minutes per week on training and game play, and that the average rate of perceived exertion (RPE) of the sessions was 14.4 ± 1.2, which is regarded as "somewhat hard" when using the Borg RPE scale (Brink et al, 2010; Borg, 1998). The intensity and duration of each training session varies from session to session depending on the number of days to the next match and the intensity of the training sessions in the days previously, which is known as training periodisation. The pattern is usually an increase in training load up until match day (MD) minus three and then a decrease in training load until the match (Los Arcos et al, 2017), with the coaches purposefully periodising the contents of the training sessions for the MD-3 training session to have the highest training load. Los Arcos and colleague's study discovered that there was substantial differences between the training load for MD-6 < MD-4 < MD-3 > MD-2 > MD-1 (Effect size ranging from small to very large). The same study also discovered that starters (players who played more than 45 minutes in the match that week) had a higher weekly training load than non-starters (players who played less than 45 minutes in the match that week) and this was solely down to the training load attributed to the weekly match, with starters having a respiratory and muscular session RPE training load of 554 ± 170 and 590 ± 189 respectively for matches in comparison to non-starters having a respiratory and muscular session RPE training load of 109 ± 72 and 94 ± 67 for matches (Effect size for respiratory training load between starters and non-starters: -2.59 ± 0.20; For muscular training load: -2.60 ± 0.20; both effect sizes indicate a most likely very large change). An obvious reason for this is the length of time spent on the pitch for starters in comparison to non-starters.

The significance of each MD and how it affects the training week can be explained by the above 2017 study by Los Arcos and colleague's, with training load varying depending on the proximity to MD. This can be shown by data collected by Los Arcos and colleague from a 5-day training lead into a MD. In figure 1, the perceived respiratory and muscular training loads for players that started the match are shown. As mentioned above, there was substantial differences between the training load for MD-6 < MD-4 < MD-3 > MD-2 > MD-1. This training schedule is common, with the players being given the opportunity to recover in time for MD.

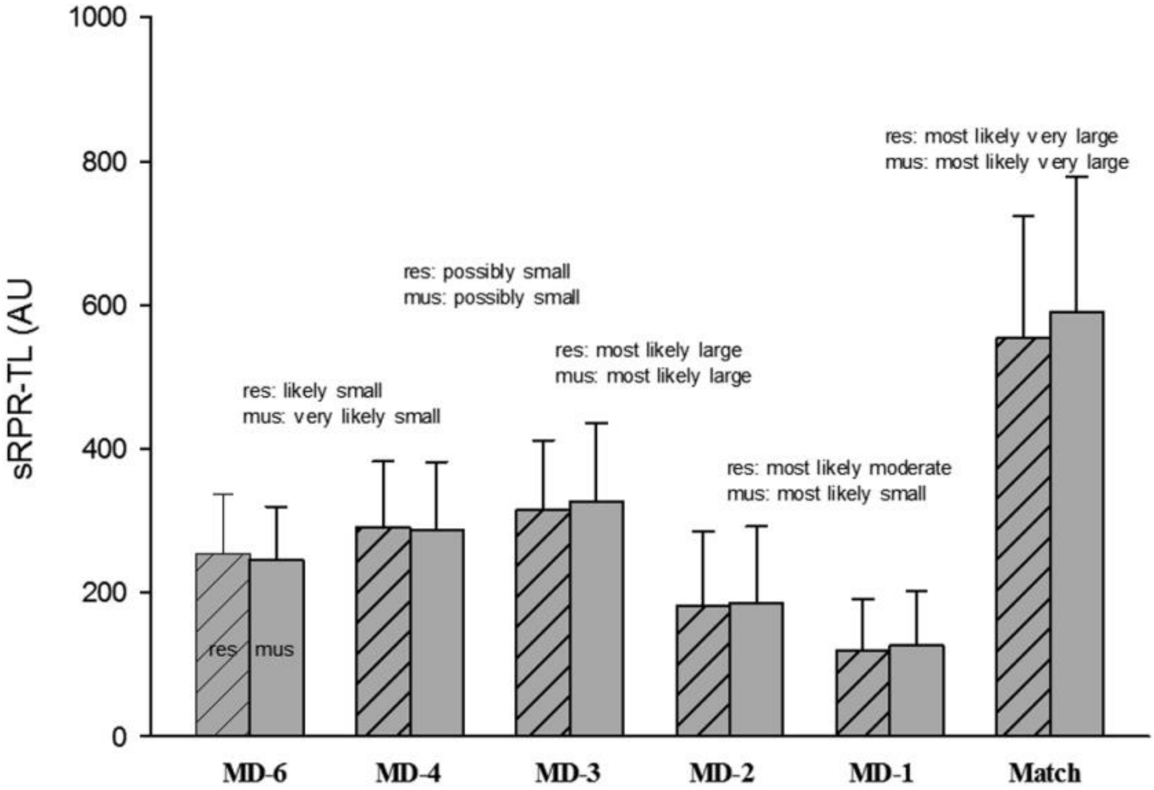


*Figure 1* – Seasonal perceived respiratory and muscular training loads for starters dependent on days until match and match day (Los Arcos, 2017).

Another study, which collected data throughout the course of a season for the outfield squad of an English Premier League team, displayed data that showed that all positions trained for less time, covered less total distance, and had a lower RPE load for MD-1 training sessions in comparison to MD-2, MD-3 and MD-5 training sessions ($p < 0.05$) (Malone et al, 2015), with MD-4 most often being a day off. The results also showed that there was a significant difference ($p < 0.05$) between CBs when compared to CMs and WMs, with CBs covering less total distance for every day of training. The stage of the season can also have an impact on the duration and intensity of the training sessions, as Malone and colleague's study discovered that total distance was significantly higher during the start of the season (weeks 7-12 of their training) than compared to the end of the season (weeks 37-42 of their training) for all player's positions, with daily total distance covered being 1304m greater in weeks 7-12 than 37-42 of their season, with 95% CI (434, 2174). This could be due to players still building fitness following the end of pre-season and the start of the playing season, following the detraining that occurs during the offseason (Reilly, 2007). The coaches may also have wanted to give players a rest as they were coming towards the end of the season following a long period of work which would have resulted in accumulative fatigue.

## Monitoring Load

Why Load is Monitored

In an attempt to increase levels of performance and decrease the likelihood of injuries, the area of sports science within soccer has grown rapidly over the past couple of decades or so, with Sir Alex Ferguson stating in 2013 that "sport science is the biggest and most important change in my lifetime" (The Guardian, 2014). Several types of injury occur during training sessions and matches for soccer players, with knee, ankle and muscle injuries all being common (Tucker, 1997). 12-16% of all injuries in elite soccer are hamstring muscle strains, and this type of injury is believed to have one of the highest levels of injury reoccurrence for any muscle injury (Woods et al, 2004; Orchard et al, 2005). A study using information from English Football League clubs over a 2-year period discovered that there was an average of 90 days and 15 matches missed per club per season due to hamstring injuries (Woods et al, 2004). With this being the case for hamstring injuries alone, being able to monitor the condition of players as much as possible is a process that all clubs want to successfully manage in order to limit injuries.

Internal and External Load

Several techniques are used to monitor the condition players are in, with internal and external load being collected and assessed daily to inform whether players are adapting to a training programme and/or matches. By obtaining this data it can allow the risk of overreaching, illness, and injury to be reduced (Halson, 2014). Overreaching can be defined as a less severe variation of overtraining, which can be recovered from in a few days as opposed to weeks or months (Fry and Kraemer, 1997). To put it simply, overreaching can occur when excessive training and incomplete recovery take place. An indication of overreaching taking place is a decrease in performance measures (Meeusen et al, 2006). One study which tested elite youth players over the course of a season discovered that individuals who had suffered performance decrements were found to have scored higher on depression and anger than the control group. In addition, it was discovered that the players whose performance measures had fallen had lower cortisol levels when compared to the control group (Schmikli et al, 2011). The performance measure test that was used was a submaximal interval shuttle run test, with the tests being performed every month prior to the training session commencing.

“Athletes with an elevated heart rate response of ≥5 beats per minute and a relative heart rate increase of at least 5% persisting for at least 1 month (and measured at consecutive field tests) were included as overreaching related performance decreased athletes.”

The eight athletes that had a performance decrease were tested in a laboratory along with seven athletes in a control group, however it should be noted that one of the eight athletes was a long-distance runner and four of the seven athletes in the control group were middle-long distance runners.

By using several techniques to obtain measurements this allows a “training load” to be estimated, and there is evidence that shows a relationship between training load and performance and training load and risk of injury exists (Hägglund et al, 2013; Eirale et al, 2012). In a study conducted by Akenhead and Nassis in 2016, it was discovered that over 50 variables were listed as being used to quantify training load from information sent to them from 41 elite clubs. As previously mentioned, there is an external and internal load. The external load is defined as the work completed by the athlete, independent of their internal characteristics (Halson, 2014), for example the total distance covered in a training session or match. Internal load, on the other hand, is the relative physiological and psychological stress produced by exercise, and two of the most commonly used variables for measuring internal load are RPE and heart rate (Brink et al, 2010; Buchheit et al, 2011).

Of the 41 clubs involved in the Akenhead and Nassis study mentioned previously, 40 used GPS and heart rate monitors for every player during training sessions, with the one remaining club objectively measuring training load for every session by using a subgroup of the squad due to limited equipment. Just under 30 clubs were discovered to use RPE, which when multiplied by the duration of a session, can give a number often used as training load. Using RPE allows a training load to be calculated very inexpensively, and it has been discovered to be a reliable alternative to other more expensive methods of measuring internal load. In a 2004 study, an Italian translation of the CR10-scale modified by Foster and colleagues was used alongside training load measures obtained from three different heart rate-based methods over a 7-week training period with a group of 19 Italian youth soccer players (Foster et al, 1995; Impellizzeri et al, 2004). The results obtained found that session-RPE can be considered a moderate to good indicator of global internal load of soccer training (from $r = 0.50$ to $r = 0.85$, $p < 0.01$), allowing coaches to use this method as a viable approach to monitor and control internal load, and to design periodisation strategies.

It should be noted however, that these correlations were lower than separate research that found calculations from RPE to be a good indicator of training load ($r = 0.84$) (Borresen and Lambert, 2008). The lower correlation in the Impellizzeri study (from $r = 0.50$ to $r = 0.85$) could be due to the increased anaerobic exercise that is present during soccer training. Previous research has discovered that despite heart rate and $\dot{V}O_2$ remaining the same when compared between steady state and intermittent protocols that have been matched for work, RPE was increased for the intermittent exercise (Drust et al, 2000). Since soccer training and matches are defined by a combination of anaerobic and aerobic exercises rather than steady state exercise, this provides a possible explanation for reduced strength in correlation when comparing the Impellizzeri study and Borresen and Lambert study (Bangsbo, 1994). As a result, a combination of methods being used simultaneously to calculate internal load for training and matches is the preferred option to achieve as much valid and reliable data as possible to inform the coaches on each individual player.

## Methods of Monitoring Load

Time motion analysis, in the form of GPS units, has become the main method of measuring external load in team sports and has been used in soccer for over 40 years (Reilly and Thomas, 1976). The most common time motion analysis technology used to monitor what players have done in training and matches is GPS and video footage (an example being Prozone), with these technologies producing a variety of variables (Castellano et al, 2011). These variables can be absolute or relative to individual players, with data relating to total distance covered, total distances covered at certain speed thresholds and also what speeds have been reached, as well as both count and intensity of accelerations and decelerations. With the use of accelerometers embedded within GPS units, it has also become possible to calculate Kvert in the applied setting, which will be discussed further in this thesis. Recent developments in technology has led to the rapid growth of elite level clubs using these types of systems, and more and more clubs even out with the elite level are now able to afford to use various forms of the technology discussed (Carling et al, 2008). Now, almost all elite clubs rely on time motion analysis to track player's physical contributions in both training and match scenarios.

## Problems with Monitoring Load

Some issues arise when using time motion analysis, with speed thresholds often differing from system to system. An example of this would be sprint distance being reported as distance covered >30km/h, >24km/h and >23km/h in three different studies (Mohr et al, 2003; Di Salvo et al, 2006; Roberts et al, 2007). Due to this, it becomes more of a challenge to compare work rate data between studies that have used differing speed thresholds. However, it has become increasingly possible for technology to be able to be adapted to fit the needs of the club or personnel using it, meaning practitioners can set thresholds for speed and acceleration to values that they want to use. Another issue arising that concerns speed thresholds is the strictness of the speed boundaries that result in an effort being defined as a "sprint" or a "high intensity run". If a player goes above and below a certain speed threshold several times while performing a single run or sprint, that data can be collected as if the player is performing more than one sprint, which is untrue, meaning the number of sprints a player performs in a training session or match can be overestimated (Carling et al, 2008). In addition to this, certain speeds may be a sprint for one player but a high intensity run for another, with wide players being found to have a higher max speed than central defenders and midfielders (Djaoui et al, 2017). This can mean that if a sprint is defined as a set speed for all players, for example >24km/h, it may be a different percentage of max speed between different players. This issue also relates to the 6-minute Yo-Yo test that is used during this thesis. The test is used as it is a submaximal test, however the player's level of fitness can affect whether the test is truly submaximal. A player's top speed may also affect the extent to which the test is "submaximal", as a player with a lower top speed will be running at a higher percentage of their top speed by the end of the test than a player with a higher top speed. As a result of this, some players may be close to maximal effort by the end of the 6 minutes.

Another flaw of using time motion analysis is that sprinting is often regarded as the most exertive activity a player performs on the pitch, which leads to an under estimation of energy expended during training sessions or matches, and high-energy movements such as competing for possession of the ball with an opponent and vertical jumps are not factored into the data collected by many time motion analysis methods (Carling et al, 2008). In addition to this, many forms of time motion analysis do not take into account that players are not always moving in a forward direction, and that they can be moving sideways or backwards. This can contribute to data suggesting that a lower energy expenditure has been exerted over a certain period as these movements have been found to often use more energy than moving in a forward direction (Reilly, 2006; William et al, 2007). This is explained by Cavagna and colleagues, who state that running forward in humans is defined by a greater average force being exerted after touching the ground and a lower average force being exerted before leaving the ground. However, when running backwards, humans exert a lower average force after touching the ground and a higher average force before leaving the ground, resulting in a 15% decrease in the mechanical efficiency of running backwards as opposed to running forwards, leading to more metabolic energy being spent when running backwards rather than forwards (Cavagna et al, 2011).

Another factor that is often overlooked by time motion analysis is the time spent running when in possession of the ball. As a result, the energy cost expended can potentially be underestimated, due to findings from Piras and colleagues study which showed that running in possession of the ball required 9.6 ± 2.42% more energy than running without possession of the ball at 10km/h (4.60 ± 0.2J/kg/m vs 4.19 ± 0.33J/kg/m), which was regarded as a moderate to very likely difference (Piras et al, 2017).

Monitoring acceleration and deceleration is another issue that practitioners are still attempting to solve. Considering the energy cost of accelerations and decelerations has been emphasised by many due to the high metabolic demand that is related with them, despite running speed not necessarily being high during these actions (Sonderegger et al, 2016). Similar to the speed threshold issue with sprint speed classification, several different acceleration thresholds have been set by various authors, with low: 1–2 $m/s^2$, moderate: 2–3 $m/s^2$ and high: >3 $m/s^2$ acceleration thresholds being set by Akenhead and colleagues, medium: 2.5–4.0 $m/s^2$ and high: >4.0 $m/s^2$ accelerations being set by Bradley and colleagues and also all accelerations >2.78$m/s^2$ being considered as maximal accelerations by Aughey (Akenhead et al, 2013; Bradley et al, 2010; Aughey, 2010). This creates an issue when comparing results from different studies that have employed contrasting acceleration thresholds. Another key point to consider is that maximal voluntary acceleration can be expected to be lower when starting from a walk, jog or sprint, when compared to starting from a standstill. This is due to acceleration being the result of change of speed over the change of time, meaning acceleration is at its highest at the beginning of a run and then levels out while running speed increases (Arsac and Locatelli, 2002). As a result of this, accelerations initiated from a standing start can be overestimated and accelerations starting whilst running can be underestimated, leading to false information regarding the energy expended performing these actions.

Summary of Monitoring of Load

By using all the methods and resulting variables that have been discussed, the intention is to be able to record all the actions performed and energy expended by the players whilst training and competing in matches. Having this information can then inform coaches which players have potentially been over trained and may be suffering from fatigue, allowing the opportunity for players to be rested. However, rather than assessing the energy expended by a player over the previous days, weeks and months, there are several different methods of testing players that can provide details of the physical condition a player is in, with the CMJ being one of these and will be discussed next, and also by measuring Kvert of players which will be discussed subsequently.

## Countermovement Jump

Why the Countermovement Jump is used

To reiterate what has been aforementioned, the CMJ is used to estimate the explosive power of the lower extremities and researchers have used variations of vertical jumps to discover explosive leg muscle power for almost a century (Sargaent, 1921). It was discovered that there was a significant relationship between team average CMJ height and team success when players from the top two tiers of Icelandic soccer were tested (Arnason et al, 2004). In comparison to this, the team averages for peak $O_2$ uptake were found to have no relationship with team success, displaying why the CMJ is such a frequently used and important test for soccer players. It should be noted however that aerobic fitness has also been found to positively correlate (Spearman's rho = -0.67, $p < 0.05$) with final league position for teams in the top division of the Singapore professional soccer league during 2003, but not during 2002 and 2004 (Spearman's rho = -0.37, $p > 0.05$) (Aziz, Newton and Kinugasa et al, 2007). It could be possible that the findings from Aziz, Newton and Kinugasa's study are the result of causation rather than by correlation, however. In addition to this, comparing football matches which take place in significantly different conditions should be done so with caution. This is due to potential tactical changes being made due to hot or humid conditions affecting the requirements of the production of power and running. It has previously been discovered that an increase in temperature from ~21°C to ~43°C reduces total distance covered by 7% during a soccer match (Mohr et al, 2012) This increase in temperature can potentially lead to greater fatigue, with the fatigue response to exercising in increased temperatures having a high inter-individual variation (Nybo, Rasmussen and Sawka, 2011). Exercising in high temperatures is a challenge for the cardiovascular system, with a balance needing to be met between maintaining arterial blood pressure and the increase in blood flow to exercising muscles and skin. Moreover, humans have an increased sweat rate when working in hot environments, with dehydration from sweat loss leading to a decrease in blood volume which in turn reduces heat loss and can result in an elevated core temperature (Sawka et al, 1993). This is not always the case in hot conditions however, with results obtained in Mohr and colleagues 2012, study mentioned above, showing that an increase in temperature from ~21°C to ~43°C did not affect ($p < 0.05$) average heart rate, body weight loss or post game sprint performance. This is likely due to players adjusting to the way they play the game in warmer conditions, with total distance and high speed running distance (>14km/h) both significantly lower in the cooler temperature.

A possible reason for why the correlation between CMJ height and team success was apparent is that most actions that take place in soccer, such as running, kicking and jumping, are all dependent on leg strength and power, which have an impact on CMJ performance. This theory is supported by results from a 2018 study which discovered that professional Polish strikers had a direct relationship between the peak muscle torque in knee extensors and CMJ height ($p < 0.05$) (Busko et al, 2018).

It has also been discovered that CMJ positively correlates well with maximal strength in half squats ($r = 0.78$, $p < 0.05$), and 10m ($r = 0.72$, $p < 0.05$) and 30m ($r = 0.6$, $p < 0.05$) sprint times (Wisløff et al, 2004). This applies well to soccer, as it has been discovered that the average sprint distance during matches is 15m, with maximum sprint distance being 40m (Ekblom, 1994). As has been discussed previously, another reason the CMJ is a preferred testing procedure is due to the fact it uses a SSC. The SSC is used to describe the action of an eccentric phase being followed by an isometric transitional period and leading into an explosive concentric phase (Turner et al, 2010), and SSC actions are involved heavily throughout soccer matches, with two common examples being jumping and acceleration. In 2005, Kotzamanidis and colleagues completed a study that attempted to discover how resistance and speed training sessions developed several athletic abilities of a group of soccer players in comparison to only resistance training sessions and a control group. It was found that following 13 weeks of training, the group that had completed both resistance and speed training sessions had improved significantly ($p < 0.05$) more when performing a 30m sprint, squat jump and CMJ in comparison to the resistance only and control group (Kotzamanidis et al, 2005). As sprint speed improved alongside CMJ performance in the study mentioned, it is believed that CMJ testing is an applicable method of testing the performance levels of players, due to sprint speed being a vital attribute for soccer players.

CMJ testing has grown in popularity due to the ease of administering them efficiently, with additional fatigue not being an issue, unlike testing which relies on sustained maximal exercise. Another advantage of using CMJ testing is that it can be used for several different reasons, with it being carried out to performance profile and injury risk screening of athletes, as well as monitoring fatigue and finally, also being used for training and rehab for players. There are several different methods of measuring CMJs, with rotary encoders, contact mats and force platforms all being used, with force plates being considered the criterion method, with portable force platforms being used in this thesis (Buckthorpe et al, 2011). One key advantage of using force platforms are that they provide information on the mechanisms of why a jump height was reached rather than just the jump height itself. The validity of force platforms has been rigorously tested, which has resulted in them being regarded as the criterion method, with an ICC showing an almost perfect agreement for jump height when recorded by force platform and video analysis (ICC = 0.916, CI 95%= 0.882 to 0.940, $p < 0.001$) (Ramon et al, 2017). Moreover, the reliability of portable force platforms has also been tested, with CMJ height of 10 subjects being recorded as $0.33 \pm 0.07$m and $0.33 \pm 0.06$m for days one and two of testing, respectively. It was discovered that these two figures were not significantly different and “showed no fixed or proportional bias, and 95% limits of agreement results were practically acceptable” (Lake et al, 2016). One issue regarding the use of portable force platforms however is apparent when using them on different surfaces. It was discovered that there was an ICC of 0.49, which is considered poor reliability, for the ratio between flight time and contraction time when the force platforms were used on different surfaces (Raymond et al, 2018). This is an issue that was considered in the study taking place, with all CMJ testing being performed on the same surface throughout the study.

Performing SSC actions that take place throughout soccer matches leads to muscle damage and impaired muscle structure, metabolism and function (Jones et al, 1986; Asp et al, 1998; Clarkson et al, 1992). It is as a result of this that strength is reduced along with impaired muscle structure, metabolism and function and therefore CMJ testing is used to monitor the neuromuscular fatigue of players throughout their season, as a reduction in performance in jump variables is an indicator that a player is fatigued and performing below their peak performance level because of this. It has been discovered that muscles contract and relax slower when fatigued, and this contributes to a reduction in strength (Westerblad, Lännergren and Allen, 1997).

In figure 2, the stages of a CMJ are shown, with the correlating mechanical power also displayed at each phase of the jump. The pre stretch dropping action, which occurs during the "countermovement" phase, in this diagram is an example of the SSC which has been mentioned above. A result of this action being utilised by athletes is that they can jump higher during a CMJ than a squat jump, which does not allow the SSC to take place. These findings were from a simulation that used a model that simulated CMJs and squat jumps that closely resembled jumps of human subjects. The CMJs ranged from 0.4cm to 2.5cm higher than the squat jumps (Bobbert and Casius, 2005). The reasoning for this outcome was a greater work output of the hip extensor muscles, which was due to these muscles producing more force and work during the opening phase of the CMJ. This was due to these muscles having a higher active state during CMJs than squat jumps. The end of the countermovement phase occurs when "zero velocity" takes place, with the athlete at the end of their movement downward, and therefore stationary for split seconds, and ready to propel themselves upward. The phase that follows once zero velocity has taken place is the "push-off" phase. This phase consists of the athlete propelling themselves upward, with the heel leaving the ground and then eventually the front of their foot also leaving the ground. These two actions are referred to as the "heel-off" and the "take-off". During the push-off phase the athlete's centre of mass is propelled vertically. With the centre of mass travelling upward the feet eventually leave the ground during the take-off phase, and this is the beginning of the "aerial" phase. The aerial phase consists of the athlete's centre of mass increasing vertically, eventually reaching the "peak". This is followed by the athlete travelling downward until landing on their feet, which is the beginning of the "landing" phase, which is not shown in figure 2.

How an athlete performs certain phases of the CMJ can affect the variables that are recorded by force platforms. An example of this would be FT:CT, with the CT being defined as the duration of time between the countermovement phase and the take-off phase. The FT is defined as the duration between the take-off and the landing phases. Therefore, an athlete spending less time during the countermovement phase and longer during the aerial phase will lead to an increase in FT:CT. Results from Cormack and colleague's 2008 study showed that 24 hours post-match FT, which is used to calculate jump height, had changed <1% in comparison to 48 hours pre-match. However FT:CT was reduced by 7% which was considered a substantial change, showing that the countermovement phase, and therefore the CT, had increased in duration (Cormack et al, 2008). This is an example of how the use of different variables other than jump height can produce further information in relation to jump performance.

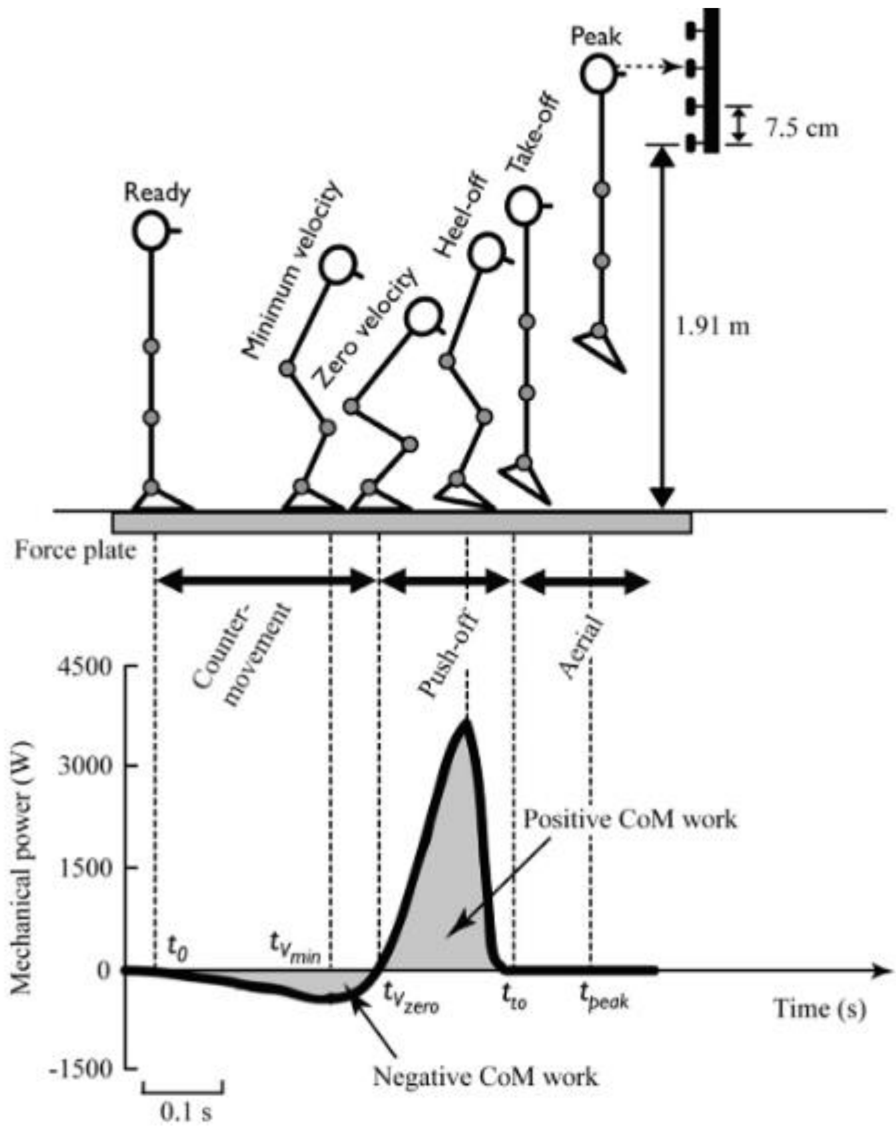


*Figure 2 - Simplified steps in vertical jumping with countermovement. The counter-movement jump (CMJ) consists of four sequential steps, including the counter-movement, push-off, aerial, and landing (not shown in the figure) (Centre of mass; CoM) (Kim et al, 2014)*

Variables Assessed

Several variables are calculated when using force plates, with Young and colleagues stating, “jump height and peak power/weight are useful variables to describe leg muscle explosive function” for athletes who must perform sprints as part of their sport (Young et al, 2011). In addition, FT:CT is commonly used as a measure of neuromuscular fatigue for athletes competing in team sports (Cormack et al, 2013; Cormack et al, 2008; Cormack et al, 2008). Variables such as FT:CT can inform practitioners more than jump height as they gather more information than just how high an athlete has jumped. An example of this that has been previously mentioned is that although jump height can potentially remain similar over two separate jumps, alterations can be made to the jump strategy for a similar jump height to be obtained. This example is displayed by results from Cormack and colleagues study which discovered that FT, which is used to calculate jump height, during CMJ had a <1% decrease, which was regarded as an unclear change, 24 hours post-match in comparison to 48 hours pre-match, whereas FT:CT was reduced by an average of 7%, which was regarded as a substantial change, over the same time period (Cormack et al, 2008).

Another study which involved team sport athletes performing at college level obtained results which also showed that by adapting jump strategy CMJ height remained the same whilst other variables were affected by fatigue. CMJ height returned to baseline level 72 hours post exercise (baseline: 0.44 ± 0.11m vs 72 hours: 0.46 ± 0.08m), which consisted of a fatiguing Yo-Yo test, however FT:CT (baseline: 0.753 ± 0.131 vs 72 hours: 0.695 ± 0.106), time to peak power (baseline: 0.655 ± 0.143 vs 72 hours: 0.713 ± 0.093) and total duration of the jump (baseline: 0.498 ± 0.138s vs 72 hours: 0.536 ± 0.122s), amongst other variables, all showed that there was still a difference regarded as small in comparison to baseline levels (Gathercole et al, 2015).

The speed that CMJs are performed at may also be of importance to analyse as previously mentioned, with the time requirements of performing actions in soccer and most sports being vital and split-second movements often being the difference between winning and losing. With typical CMJ variables such as jump height and FT, the time taken to perform the jump is not taken into account. Therefore, alternative variables such as eccentric duration, concentric duration and total duration of the jump may give additional relevant information when analysing neuromuscular fatigue (Gathercole et al, 2015).

The reliability of using CMJ testing to analyse fatigue is also a reason it is used so frequently. A study which tested athletes at baseline, 0, 24 and 72 hours after fatiguing exercise, discovered that of the 22 CMJ variables assessed, 16 intraday and 11 interday exhibited a coefficient of variation (CV) of <5% and 20 intraday and 21 interday exhibited CVs of <10%, suggesting that the CMJ test can produce highly consistent results (Gathercole et al, 2015). This is advantageous as a lower CV indicates that there is less random noise which results in the testing method in question having a higher likelihood of being able to identify real change in performance (Hopkins, 2000). By having a lower CV between tests, it means that whenever there is a change in results, a higher percentage of change can be attributed to an increase or decrease in performance levels and a lower percentage to the variation that occurs from test to test.

Limitations of Using CMJ Testing to Measure Neuromuscular Fatigue

By measuring CMJ performance at baseline and post-match at various time points, it becomes possible to assess the time period in which fatigue affects performance, as reduced jump height indicates a player has not yet fully recovered to base line level performance (Brownstein et al, 2017). Following fatiguing exercise metabolites accumulate within fibres, which is known as metabolic fatigue. This can lead to a reduction in jump height due to muscle contraction being reduced and therefore leading to a reduction in speed, force and power (Perry, 2019). As time passes the level of fatigue is reduced until a player is able to perform a CMJ to the same height, indicating the player has recovered to baseline level. However, although CMJ testing is frequently chosen over several other forms of testing to measure fatigue caused by training and match load, it is still a time-consuming method if a full squad of players are having their level of fatigue or match readiness monitored in this manner. With squads of more than 30 players highly common, it would take 30-60 minutes to CMJ test the whole squad, if not longer. Because of this, more time efficient testing is being sought after that can measure the level of fatigue of players. GPS units with embedded accelerometers and consistent sub maximal runs are possibly the answer to this issue, and this study will attempt to ascertain their effectiveness.

Another concern of using CMJ testing to measure fatigue is the motivation of participants, and not being certain they have put their maximum effort into a jump, or set of jumps. Furthermore, deciding what depth to let the participants bend down to when bending their knees before pushing off and performing a CMJ is another factor that may alter the efficacy of CMJ testing. A study involving college level male basketball and volleyball players discovered that "the knee flexion interferes with the performance and the biomechanical variables at the CMJ", and it was found that when a higher squat depth was used, greater heights were reached when compared to jumps with lower squat depth (Gheller et al, 2014). This showed there is more variables to consider when CMJ testing an individual or group of athletes. As CMJs have been used for several decades, practitioners are always attempting to discover new methods to be able to streamline the collection of data that will be able to inform them of their athlete's level of fatigue, and using Kvert to achieve this is one possibility being researched.

**Utilisation of GPS Units to Measure Fatigue**

Introduction to Vertical Stiffness

It has been discussed that by monitoring a player's accelerometer data over time, their level of neuromuscular fatigue can be assessed as a result, leading to information about a player's match readiness and what their training prescription should be as a result (Barret et al, 2016). One such variable that can be calculated from accelerometer data is Kvert. To start off simply, stiffness can be defined as the resistance of an object or a body to a change in length, or deformation, and this can be calculated as the ratio of force to length (Brughelli and Cronin, 2008), with Kvert being defined as the ratio of the maximal force to vertical displacement (Girard et al, 2010).

Stiffness can be measured from the modelling of an entire body as a mass and spring all the way down to a single muscle fibre. Kvert can be measured during many different movements, from running to hopping and when performing a drop landing, with perhaps the easiest described during a drop landing. When a drop landing is performed, the lower body does not stay the same length. Instead of remaining the same length, once the feet hit the ground the ankles, knees and hips all begin to flex which result in the vertical distance between the hip joint, which is where the centre of mass is located, and the ground being reduced. Once the feet hit the ground, the centre of mass continues to travel vertically downwards towards the ground. The distance that the centre of mass travels downward vertically once the feet touch the ground is the change in length that is used for the Kvert calculation (Blickhan, 1989). What is also needed is the force applied by the body, including bodyweight, which is the force that causes the vertical displacement of the centre of mass. Once all this information is recorded, it is possible to calculate Kvert as the applied force divided by the vertical displacement of the centre of mass following the feet touching the ground (Morin et al, 2005). To be able to record the necessary variables for this equation in this setting, a force plate would be needed to calculate the applied force, and a video camera would be needed to calculate the vertical displacement of the centre of mass following ground contact. This is not a viable option to use in the field and therefore other methods of calculating Kvert are needed, which will be further discussed.

As previously mentioned, the Kvert ratio is also apparent during running. When the "spring mass model" is in action, it consists of the musculoskeletal structures of the legs storing and returning elastic energy. This results in the athlete's body mass being referred to as the mass and the legs being referred to as the springs in this "spring mass model" (Morin et al, 2005), which can be seen in figures 3 and 4. Kvert is defined as the ratio of the maximal force to vertical displacement, and the maximal force being referred to is the maximal ground reaction force produced at the point of contact with the ground, and the vertical displacement being referred to is the vertical displacement of the centre of mass as it reaches its lowest point, also known as the middle of the stance phase (McMahon and Cheng, 1990). Kvert is vital to allow the storage and re-utilisation of elastic energy in SSC activities such as jumping. In the previous paragraph the movement at the ankles, knees and hips are all mentioned when describing the movement of the body during a drop landing when the feet meet the ground. When measuring Kvert, the estimate is a combination of many muscles from each of these areas that aggregate together to then find the overall stiffness. In addition to this, the tendons will also play a key part in energy storage when performing movements. It has been discovered that tendon stiffness changes with stretching, with a study obtaining results that showed the muscle–tendon unit had reduced stiffness when the muscle–tendon unit was taken to the end of range of movement and held there for 1 minute, with results compared pre-stretching and post-stretching (Morse et al, 2008).

In addition to the tendons playing a key part in energy storage, the foot is also known for its ability to recycle energy during movement. Kelly and colleagues state that during locomotion the foot contributes "up to 17% of the energy required to power a stride". It is thought that this is facilitated by the elastic ligaments that are found within the arch of the foot (Kelly et al, 2019). The energy stored in the arch of the foot is ignored when considering the spring mass model, which is one of its weaknesses. Another weakness is that the deformation of shoes and the surface that movement is being performed on is not considered. One study tested 13 male recreational runners on a treadmill with a control shoe and the same shoe with carbon fibre plates inserted being used, which increases the midsole bending stiffness. It was discovered that by changing the midsole bending stiffness of the shoe used to run in, the "mechanics of other compliances changed as well" (Cigoja et al, 2020). One compliance that changed due to increased midsole bending stiffness was reduced deformation of the arch of the foot. The type of shoe that is worn is often not considered when performing tests that involve the spring mass model, which is a flaw when considering Cigoja and colleague's studies' results. As well as the type of shoe possibly having an effect, the type of surface may also play a part in any results from a test looking at the spring mass model. A 2013 study consisted of 20 males and 19 females running at 3.5m/s on various surfaces both barefoot and with shoes on. Whilst barefoot running, the harder surfaces tended to decrease knee flexion moments, with the difference in knee flexion moments between the softest and hardest surface being 5% (Willwacher, Fischer and Bruggemann, 2013). It should be noted however that the study does not mention whether the 5% change is statistically significant. The results from the studies mentioned display why footwear and surface should be taken into consideration when performing tests that include the spring mass model, with both potentially having an effect on the results of testing.

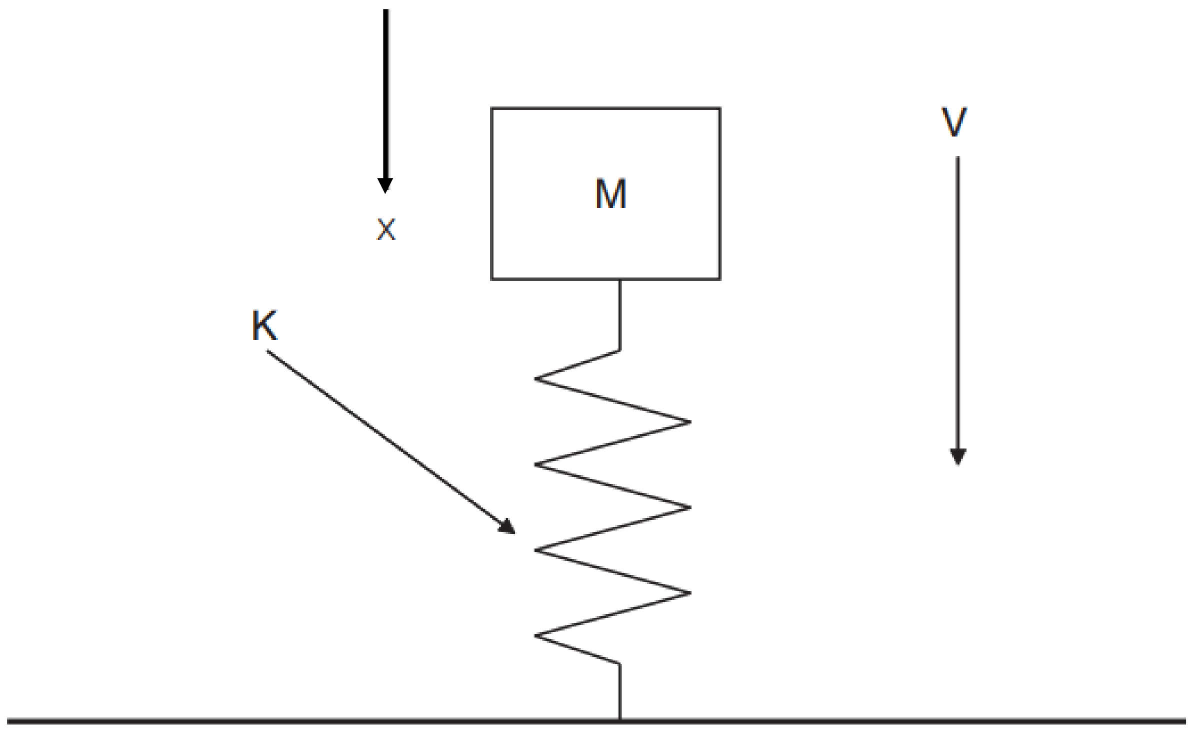


*Figure 3 - Schematic representation of the spring-mass model. K = spring stiffness; M = mass; V = downward vertical velocity; x = downward displacement. (Brughelli and Cronin, 2008)*

It has been discussed that by possessing greater stiffness characteristics, it is possible for extra elastic energy to be stored during ground contact and therefore allowing an athlete to produce more concentric force output at push-off which would result in an increase in jump height and running speed, amongst other SSC movements (Brazier et al, 2017). As a result of this, it can be expected that it would be desirable for an athlete to possess a high Kvert score during exercise, however several studies have indicated that a greater injury risk is present when Kvert is increased, with possible reasons for this being increased peak forces, increased shock and joint motion being reduced in the lower extremity (Flanagan et al, 2008; Padua et al, 2006). It has also been discovered that low levels of stiffness may have a heightened risk of soft tissue injury as a result of excessive joint motion occurring (Butler et al, 2003).

Figures 4 and 5 are labelled with “A”, “B” and “C”. “A” represents the start of the stance phase and consists of the initial contact between the foot and the ground following being in the air. Depending on running style and the speed being travelled at it can be different parts of the foot that make contact with the ground first, but it is most often the heel. The first stage of the stance phase is concluded once the forefoot is in direct contact with the ground, and this is represented by “B” which is known as the mid-stance. During the mid-stance the foot flattens on the ground in order for support to be provided as the body moves forward over the leading foot during the opposing foot being in the swing phase. Finally, “C” represents the toe off part of the stance phase. It begins with the heel leaving contact with the ground, and plantar flexion of the ankle taking place which results in the toes being able to then leave the ground (Novacheck, 1998).

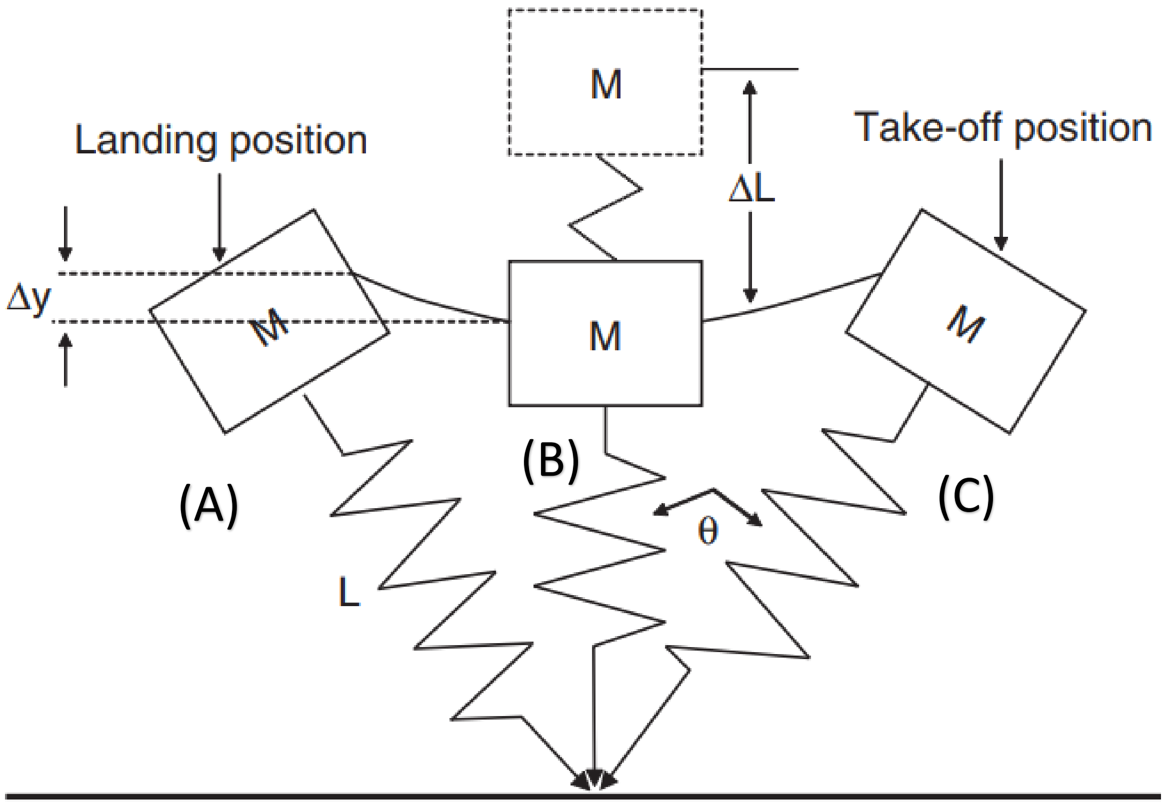


*Figure 4 - Centre of mass (CoM) displacement and change in leg length during the stance phase in running. Schematic representation of the spring-mass model as the leg spring travels through its arc during the stance phase. L = leg spring length; M = mass; y = vertical displacement of the CoM. (Brughelli and Cronin, 2008)*

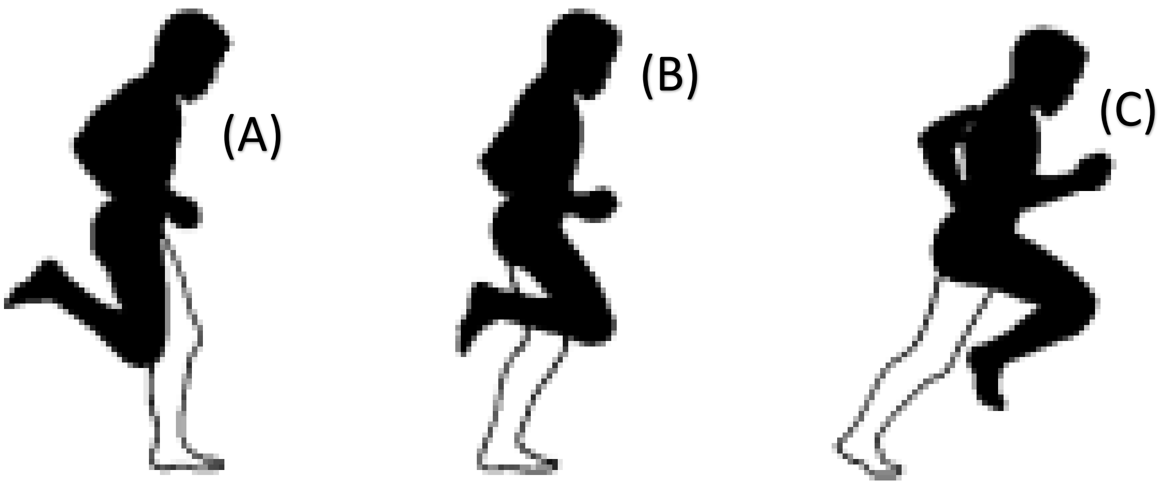


*Figure 5 – Human silhouette example of figure 4, with highlighted leg going through same process as leg springs in figure 3 (Adelaar, 1986).*

Methods of Measuring Vertical Stiffness

Several different methods are used to calculate Kvert, with force plates being the criterion method (Eggers et al, 2017). Treadmills with mounted force platforms and video motion-analysis can also be used, but this type of equipment is costly and impractical for field-based measurements (Morin et al, 2005). In the past few years, GPS and accelerometers have started to be used as an alternative due to force plates not being a feasible option for assessing Kvert in team sports (Buchheit et al, 2015). In a 2015 study, a team sport player performed six runs at 10, 17 and 24 km/h with or without their right ankle taped, which aimed at creating a stride imbalance. With an accelerometer embedded GPS unit placed on his back, it was possible to calculate Kvert via the treadmill and also the accelerometer, via the use of ADI. Kvert was calculated from the same runs but via the two different methods previously mentioned, being via a treadmill with a mounted platform and the accelerometer embedded GPS unit. ADI is a software that uses the raw accelerometer data to discover a player's imbalances and Kvert amongst many other variables, and it is used in this thesis to calculate Kvert. It was stated that biases were small (13.3%, 90% CI -14.6, -11.9), and specifically that the typical error of the estimate was small for Kvert (6.3%, 90% CI 5.5, 7.5), meaning it is likely an accurate predictor of Kvert (Hopkins, 2000). It should be considered that these results were from a single participant however, resulting in low statistical power when analysing the results obtained. It was also stated that there were nearly perfect correlations for Kvert derived between treadmill and accelerometer ($r = 0.98$, 90% CI 0.97, 0.99), meaning that measuring Kvert via GPS-embedded triaxial accelerometers can potentially be assumed as being an accurate method of measuring in comparison to calculating Kvert from a treadmill (Buchheit et al, 2015).

However, it should be noted that another study published shows that accelerometer derived Kvert potentially should not be accepted as reliable. For this study, 17 active university sport and exercise students completed a two-minute continuous 20m over ground shuttle run at 12km/h, which was then repeated 7 days later. The participants had their Kvert during the run calculated via accelerometer data and force plate ground contacts, which is the criterion method. The validity of the method was tested, and a Pearson Correlation of 0.66, which can be considered as large, was found when comparing accelerometer derived Kvert with force-plate derived Kvert (Sedgwick, 2012). However, the reliability of this method was also assessed, with an ICC of 0.71 achieved for accelerometer derived Kvert in comparison to an ICC of 0.89 for force plate derived Kvert (Eggers et al, 2017), with these figures being regarded as moderate and good reliability respectively (Koo and Mae, 2016). Although these figures can be regarded as good and excellent respectively when using Cicchetti's guidelines (Cicchetti, 1994). Despite Sedgwick's studies' results displaying that accelerometer derived Kvert was less reliable than accelerometer derived Kvert from Buccheit and colleague's study, it should be noted that even when using Koo and Mae's ICC scale, Sedgwick's study still provided evidence that accelerometer derived Kvert had moderate reliability and was 0.04 from being classed as good reliability. In addition to this, when considering that this method of measuring Kvert could be regarded as having good reliability when using Cicchetti's guidelines, the evidence suggests it could be possible that accelerometer derived Kvert is an acceptable form of measuring Kvert in the field when testing or monitoring athletes. However, more studies are needed to definitively prove whether this method of measuring Kvert is fully reliable. It was also stated that a limitation of the study was that only five ground contacts were used for each shuttle run and that accepted assumptions and equations were used to "estimate centre of mass displacement from force-plate data, an approach which demonstrated weak measurement accuracy" (Eggers et al, 2017). It is also of importance to note that the Buccheit and colleague's 2015 study was performed with only one participant, with underpowered studies being found to have an increased type 2 error rate, with an increase in sample size resulting in increased power of a test when other things remain equal (Brysbaert, 2019). This increased chance of type 2 error rate should be considered when comparing the results from Buccheit's study to studies with a larger sample size, with a difference in any results possibly being due to a difference in sample sizes.

Calculations Required to Calculate Vertical Stiffness via Accelerometer Data

The "Sine-wave" method for measuring Kvert during running was created by Morin in 2005 and this is the method that ADI uses. It was based on a model that was used for vertical jumps by Dalleau and colleagues in 2004 and considers the force as a function of time during the contact to be a simple sine function (equation shown below).

$$F(t) = F_{\max}\sin\left(\frac{\pi}{t_c}t\right)$$

Kvert ($\hat{k}_{vert}$) is calculated as the ratio of maximal force ($\hat{F}_{max}$) over vertical centre of mass displacement ($\Delta\hat{y}_c^{\,-1}$).

$$\hat{k}_{\text{vert}} = \hat{F}_{\max} \cdot \Delta\hat{y}_c^{\,-1}$$

In the below equation to calculate maximal force, m = body mass (kg), g = the gravitational acceleration, $t_f$ = flight time, and $t_c$ = contact time.

$$\hat{F}_{\max} = mg\,\frac{\pi}{2}\left(\frac{t_f}{t_c}+1\right)$$

The below equation is used to calculate vertical centre of mass displacement.

$$\Delta\hat{y}_c = \frac{\hat{F}_{\max}t_c^{\,2}}{m\,\pi^2} + g\,\frac{t_c^{\,2}}{8}$$

Based on the modelling of the force-time curve by a sine function, which can be seen in figure 6, the sine wave method allows Kvert to be estimated from a few simple mechanical parameters: body mass, forward velocity, leg length, flight time, and contact time (Morin et al, 2005). These are the variables that ADI uses to calculate Kvert, and all of these were recorded during the present study, with the exception of leg length, however this was calculated according to the anthropometric equations of Winter (1979). The participants leg length is modelled as $L_{mod}$ = 0.53h where h represents the participants height in metres. It was discovered by Morin and colleagues that the leg length equation stated above led to a mean error bias of 1.94 ± 1.51%, and that the linear regression was significant between the measured leg length and the leg length obtained via the stated equation, meaning the equation can be used to produce valid leg length for future studies, including the present study. Full equations showing how these equations were calculated can be found in Morin's 2005 study, "A Simple Method for Measuring Stiffness during Running".

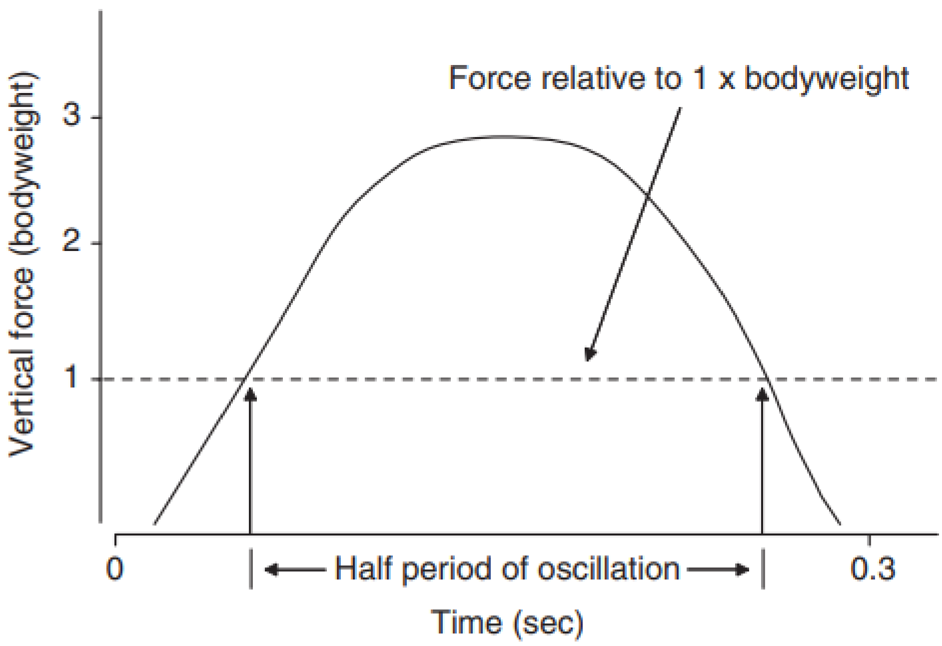


*Figure 6 - Force-time curve relative to body mass. Schematic representation of the half period of oscillation in the force-time curve. The half period of oscillation is measured as the time when force is greater than bodyweight during the stance phase of a bouncing gate. (Brughelli and Cronin, 2008)*

Within ADI, detection algorithms are used to calculate foot strikes based on the magnitude vector and relationship between the Y and Z components of the data from the accelerometer. By utilising primarily the X component of the accelerometer, a two-pass algorithm is used in ADI to assign the side of the foot strike to either left or right. The contact time and flight time for the above calculations are calculated by using the filtered accelerometer-derived data by discovering the time between the foot meeting the ground and the foot leaving the ground (this is the contact time), by using the detection algorithm mentioned earlier. Therefore, the time between the foot leaving the ground and the next time the foot meets the ground can then be used as the flight time. In figure 7 the magnitude vector measured via an accelerometer is shown at three varying running speeds and from these steps, contact time and flight time are able to be calculated as a result of the detection algorithms that are used during ADI which is mentioned above.

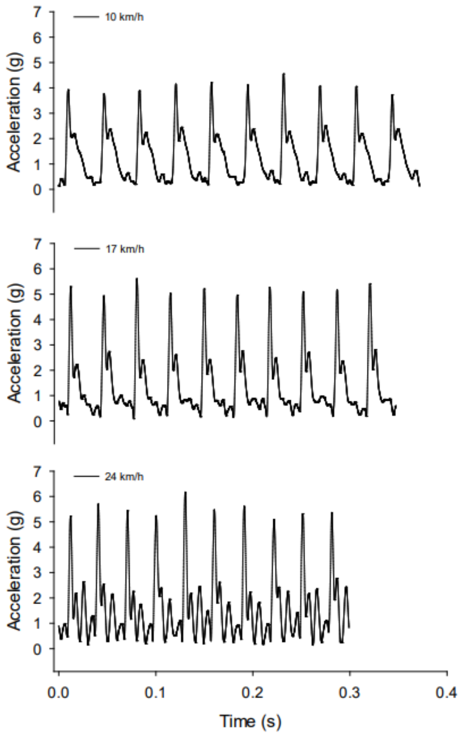

*Figure 7 - Accelerometer-derived magnitude vector during 10 successive steps, as measured for three different running speeds. (Buchheit et al, 2015)*

Summary of Vertical Stiffness Research

There is currently little research regarding Kvert in comparison to the majority of other areas of research in sports science. The majority of research that has taken place has investigated how Kvert changes as a result of differing running speeds. A smaller sample of research has been completed in regard to how fatigue affects Kvert, with this study aiming to discover more surrounding that area. Two studies that did however look into how fatigue affects Kvert had differing results from one another. Firstly, a 1990 study which consisted of 10 active males hopping to maximum height during a fatiguing 60s trial. The results published showed that Kvert increased from initial to fatigued state, with an increase from 262 ± 26.3N $cm^{-1}$ (standard error) to 289 ± 25.9 N $cm^{-1}$ with a $p < 0.05$. A separate study's findings are possibly the reason for this. Bosco researched the effect of fatigue on storage and re-use of elastic energy in slow and fast types of human skeletal muscle and greater amounts of stored energy were able to be used from fast-twitch fibres than slow-twitch fibres following muscle fatigue, when exercises involving the SSC, such as running and hopping, took place (Moritani et al, 1990; Bosco et al, 1986). However, a later study, which consisted of 11 active males hopping before and after fatiguing exercise, found that there was no significant change in Kvert between the two periods of hopping, with a pre fatigue Kvert score of 37.53 ± 20.51kN/m and post fatigue score of 40.85 ±

16.31kN/m (Padua et al, 2006). Although, it was shown that there was an 8% non-statistically significant ($p > 0.05$) increase in Kvert post fatigue, with low subject number possibly being the reason for non-significant results. However, Padua and colleagues believe that the fatiguing task does not influence Kvert and that this finding is not a result of low participant numbers for the study. This is due to the small effect size for Kvert between pre fatigue and post fatigue conditions being 0.247 which can be considered a very small magnitude of difference (Cohen, 2013).

Rather than Kvert being affected following fatiguing exercise, it may be the case that individuals adapt muscle activation patterns and coactivation ratios from non-fatigued to fatigued state (Padua et al, 2006). With slightly contrasting findings from similarly performed studies being apparent, it is clear more investigation needs to be carried out, as well as more testing that is more applicable to the sport of soccer. It should also be noted that the studies mentioned tested their participants directly after fatiguing exercise, whereas the present study measured Kvert ~48 hours after the completion of each match. Moreover, in both studies previously mentioned the exercise performed was hopping which possibly results in a different Kvert score when compared to when other forms of exercise are used when measuring Kvert such as running, due to differing displacements of the centre of mass. Whether Kvert increasing or decreasing for athletes can be decided as being a wholly positive or negative cannot be so easily determined, with it being influenced by the individual and by the exercise being performed, with body mass, limb length and strength qualities of the athlete in question all affecting the Kvert score, as well as whether the exercises being performed contain running, jumping or changing of direction (Brazier et al, 2017).

### 6-minute Yo-Yo Test

The 6-minute Yo-Yo test has been developed, amongst other Yo-Yo intermittent tests, because researchers have suggested that certain tests previously used to assess the capacity of an athlete are not relevant. These tests include the Leger shuttle-run test, 12-minute running test, or a maximum oxygen uptake test (Bangsbo, Iaia and Krustrup, 2008). Various metrics can be analysed during Yo-Yo tests, with one example being heart rate response. One study performed with elite youth soccer players discovered that HR measures displayed good levels of reliability (ICC: 0.95–0.98 and CV: 1.1–1.3%) during three separate 6-minute Yo-Yo tests that had passive recovery, over a 2-week period (Doncaster et al, 2019). The player’s HRs were recorded at 10, 20, 30, 60, 120 and 180s during the passive recovery and at 3 and 6 minutes during the 6-minute test. The HR’s measured at 3 and 6 minutes were found to have little variance between the 3 separate trials as stated above. It has also been discovered that the 6-minute Yo-Yo can detect changes during the season of player’s endurance capacity, with a lower HR being recorded for the same test during the season in comparison to preseason (Krustrup et al, 2003), which displays that the test is sensitive to training. The 6-minute Yo-Yo test was utilised due to research published regarding its reliability, with a recent study discovering that there were small variations between trials of the 6-minute submaximal Yo-Yo test when a group of sub elite youth soccer players performed the test on 3 separate occasions (CV of 1.4%) (Gibson et al, 2020). In addition to the reliability of the Yo-Yo test, it's ease of administration is also a notable advantage. An issue that should be considered, however, is weighing up the players' risk of injury and the quality of data recorded. If the players' risk of injury was to be ignored, maximal effort tests could be performed throughout the season, however this is clearly something that would be of no benefit. Therefore, performing tests that allow good quality data to be collected from the players but also doesn't increase their risk of injury is vital.

The submaximal 6-minute Yo-Yo has been found to have good test-retest reliability when testing a group of elite youth soccer players (Owen, Jones and Comfort, 2017). It was discovered that the ICC was above 0.81 for HR recorded at 6, 30, 60, 90 and 120 seconds after the test, when the test was repeated 1 week apart from each other. However, there was an ICC of 0.58 and 0.68 for HR recovery at 30 and 60 seconds after the test. Another study which tested elite soccer players found that the submaximal Yo-Yo test produced results which correlated with performance in the maximal Yo-Yo test ($p < 0.05$) when analysing the percentage of maximum HR after 4 and 6 minutes of the 6-minute Yo-Yo (Bradley et al, 2011). In addition to this, the submaximal Yo-Yo also correlated with the high-intensity distance covered by players ($p < 0.05$). Both of these findings indicate that the test can provide important information on the fitness levels of players without the load of a maximal test having to be undertaken.

An additional reason why a 6-minute Yo-Yo test could be preferable to a CMJ test that is only recording a couple seconds of data is the relevance to the player's usual movements and actions during a match. A player will maximally jump only a handful of instances throughout a match, whereas they cover 10-12km at various speeds during matches (Stolen et al, 2005), which will be similar to their movements during the Yo-Yo test.

**Research Proposal**

There is currently little research surrounding Kvert and the potential role it could play in monitoring neuromuscular fatigue following training and match load in comparison to the number of studies obtaining similar information but by using CMJ testing. Therefore, the aims of this study are:

1. To discover how the player's level of neuromuscular fatigue is affected by match load 2 days post-match in comparison to their baseline performance at 1 day pre-match by using testing that will obtain a measurement of Kvert. CMJs will be used as a marker of performance and Kvert derived from accelerometers embedded within GPS will be used as a marker during a 6-minute sub maximal Yo-Yo run. Although several studies analysing Kvert often discover the Kvert during sprints, the 6-minute sub maximal Yo-Yo is preferable as it is a lower intensity. This allows the test to be carried out on any training day other than MD+1, due to players who played >60 minutes not being on the pitch during those days. In comparison, sprints would not be recommended for players on training days such as MD-1. Moreover, the Yo-Yo test has set speeds which the players must run at, rather than requiring greater player buy in by needing the players to perform maximal or near maximal sprints.
2. To investigate whether there is any correlation between CMJ performance and Kvert, as this could allow for GPS and accelerometer data to indicate a player's return from neuromuscular fatigue to non-fatigued state, rather than relying on CMJ testing. This could therefore provide information for each individual player on their match readiness in a far less time consuming and more efficient method.

The hypothesis of the study is that when players play >60 minutes, their Kvert will have decreased from MD-1 to MD+2. In addition to this, it is expected that there will be a positive correlation between CMJ performance and Kvert from MD-1 to MD+2.

# Literature Review

## Rationale

At the elite level of soccer, match schedules can be extremely busy over the course of a season, with club and international friendlies, domestic league and cup matches, continental matches and international matches all potentially taking place. This often leads to busy fixture lists, with three matches in the space of a week or 8 days being common. As players suffer from post-match fatigue, how they cope with several matches over a short period becomes vitally important in order to lower their risk of injury, illness and reach their maximum performance levels. By competing in a single match, players can suffer from post-match fatigue which is characterised by a reduction in physical performance levels over the following hours and days (Andersson et al, 2008), and it can be generally defined as any decline in muscle performance associated with muscle activity (Allen, Lamb and Westerblad, 2008). In Andersson and colleagues' 2008 study, results obtained showed that in comparison to pre-match levels, there was a significant decrease in sprint performance and CMJ height and muscles soreness. Sprint ability returned to pre-match level 5 hours post-match, whereas muscle soreness took 69 hours to return to pre-match level and CMJ height still had not returned to pre-match level by this time point.

Counter movement jump (CMJ) testing is often used to assess recovery post-match, with at least 48 hours being needed to return to pre-match CMJ levels (Doeven et al, 2018). This is an indicator that physical performance levels have returned to the level they were at whilst not fatigued. In comparison, very little research has used vertical stiffness (Kvert) to analyse neuromuscular fatigue of soccer players or other athletes following match load or exercise. Kvert is the ratio of vertical displacement to maximal force exerted on the ground when the feet come into contact with the ground. This can be shown in an equation as:

$$\text{Kvert} = \text{peak vGRF}/\Delta\text{CoML}$$

(Kvert = Vertical Stiffness, peak vGRF = peak vertical ground reaction force during contact with ground, ΔCoML = vertical displacement of the centre of mass during loading phase)

The aims of this review will be to research current literature and present knowledge of how fatigue from match load affects athletes' CMJ and Kvert directly after exercise and over the days following competition or exercise.

This review will attempt to discover how CMJ performance is affected post-match due to fatigue at various different post-match durations. As well as this, how fatigue affects Kvert will also be analysed.

## Methods

The eligibility criteria given to decide which studies would be included in this review were that the sport in question must be an intermittent, high intensity team sport. As well as this, the participants in each study had to be 16 years old or above, with either male or female participants being acceptable.

The databases used to search for studies that would be included in the literature review were Google Scholar, PubMed and Web of Science.

The key words used for the search were as follows:

1. Neuromuscular Fatigue AND (Team Sport) (Soccer) (Football) (AFL) (Rugby) (Basketball) (Field Hockey)

2. Neuromuscular Fatigue AND Counter Movement Jump

3. Neuromuscular Fatigue AND Vertical Stiffness

4. Counter Movement Jump AND Vertical Stiffness

5. Counter Movement Jump AND Team Sport

6. Vertical Stiffness AND Team Sport

The selected articles were then filtered by reading the title and abstract, with studies that did not meet the criteria being discarded from the review. Review articles were not used for the literature review. In total, 28 studies that involved the analysis of CMJ performance following fatigue or Kvert being affected by fatigue or velocity were included.

## Findings

### <u>CMJ Findings</u>

The CMJ is used in order to estimate the explosive power of the lower extremities, and researchers have used variations of vertical jumps to discover explosive leg muscle power for almost a century (Sargaent, 1921). During a professional soccer match, players perform up to and beyond 50 turns which comprise of sustained forceful contractions, and this highlights the importance of lower limb strength and power (Withers et al, 1982). It is key for athletes to be able to produce powerful contractions, but also important to produce continuous submaximal movements, as is displayed in the findings from Withers and colleagues' study. The importance of strength is displayed by the results from a 2005 study which tested fourteen university soccer player's ability to kick the ball with maximal effort. Using an isokinetic dynamometer, the players tested their isokinetic concentric peak torque with knee extension and flexion and hip extension, flexion, abduction, and adduction. The players then were assessed for kicking performance, which involved kicking a stationery ball at a target 15m away from 3 different angles, 2.36 radius, 1.57 radius and a self-selected angle. There was a target that the players were aiming at, with a speed gun positioned behind the target to record the speed of the ball. A schematic illustration can be seen at figure 8 displaying the test. The fourteen players were split into two groups, with seven in each, with significantly higher results for "group A" for the kicking performance test. For group A it was discovered that the velocity of the ball when kicked from the 2.36 radius significantly correlated ($p < 0.05$) with isokinetic concentric peak torque during knee extension and hip flexion of the kicking leg. However, when approaching the ball from a self-selected angle, there was no significant correlations ($p > 0.05$) between mean velocity of the ball and the strength of either the kicking or supporting leg in group A (Masuda et al, 2005). These results indicate that muscle strength can determine maximal ball velocity, which is key in soccer due to players kicking the ball when shooting at goal and when kicking the ball for long passes in the air (Bacvarevic et al, 2012). It was discovered that 55 English Premier League players completed a mean of 5.9 ± 6.7 long passes, with defenders attempting 9.7 ± 6.9 long passes during the 2003/04 league season when data was obtained (Bloomfield, Polman and O'Donoghue, 2007).

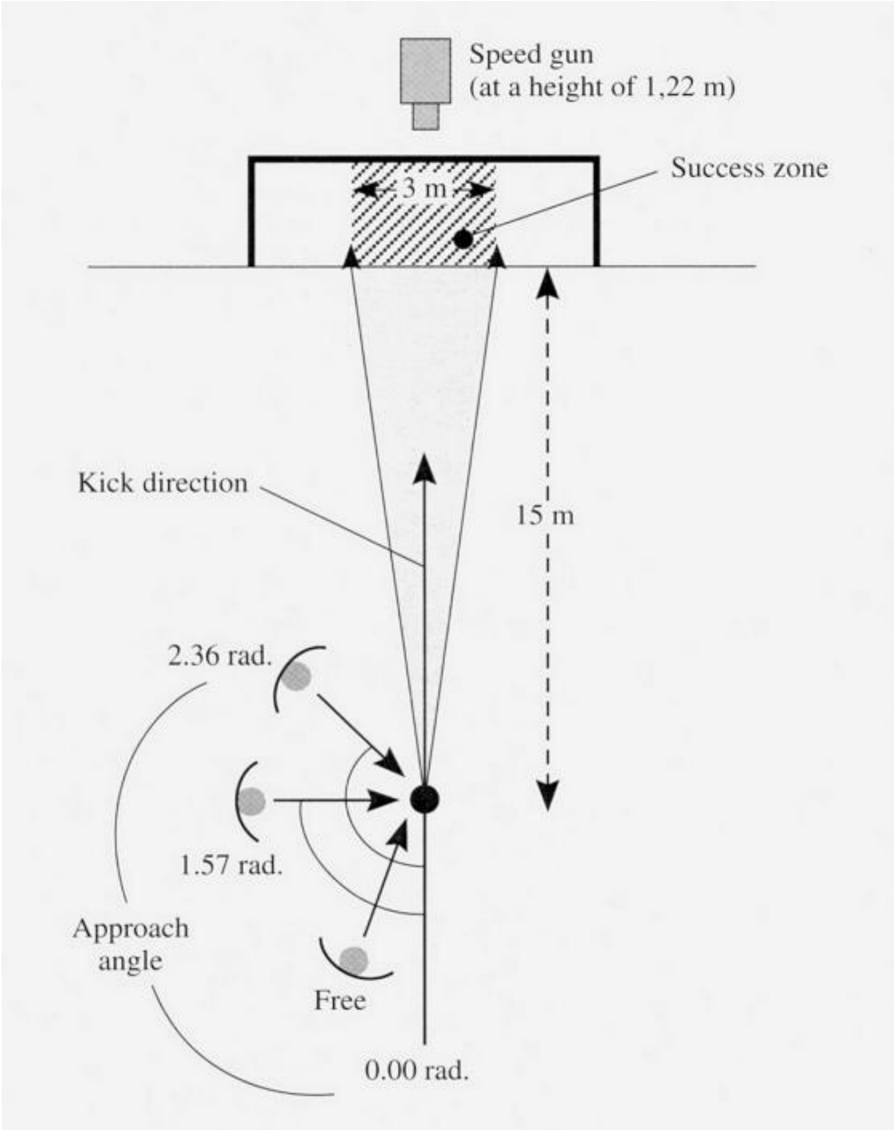

*Figure 8 – Schematic illustration of kick performance test showing 2.36 radius, 1,57 radius and free angle that players kicked the ball from (Masuda et al, 2005).*

It has also been discovered that there was a significant relationship between team average CMJ height and team success when players from the top two tiers of Icelandic soccer were tested (Arnason et al, 2004), showing why CMJ is such a frequently used and important test for soccer players. This was also the case when three teams from the professional Greek soccer league were tested, with one team among the best three teams in the league, one in the middle and one at the bottom. CMJ height was recorded, and it was discovered that the team near the top of the table had a significantly higher ($p < 0.05$) CMJ height (47.2 ± 4.3cm) than the other two teams (42.4 ± 4.2cm and 41.9 ± 4.3cm). Testing took place after the competition period had finished (Kalapotharakos et al, 2006). Moreover, CMJ positively correlates well with maximal strength in half squats, and 10m and 30m sprint times (Wisløff et al, 2004). Another reason CMJ is a preferred testing procedure is due to the fact it uses a stretch shortening cycle (SSC), which refers to the 'pre-stretch' action that is commonly observed during typical human movements, with SSC actions being involved heavily throughout soccer matches.

By measuring CMJ performance at baseline and post-match at various time points it becomes possible to assess the time period in which fatigue affects performance, as reduced jump height indicates a player has not yet fully recovered to baseline level performance. There are varying results from studies that have tested CMJ post-match, with some discovering that jump performance did not return to baseline level until anywhere between 2 hours and beyond 72 hours post-match (Duffield et al, 2011; Fatouros et al, 2010; Nedelec et al, 2014). It should be noted that many different factors affect fatigue and therefore the performance of the CMJ, such as "the point in the training and competition cycle, nutritional status, use of recovery techniques and general life stressors" (Pao-Yen Wu et al, 2019). The time point of the competition cycle can affect performance, with their being off season, preseason and during the season. Week to week can change as well, with some weeks having a single match in comparison to three matches in a week. The varying levels of load experienced can affect the performance of players. Nutritional status can also have a large impact on performance, and recovery capacity. Carbohydrate rich foods are vital to satisfy energy needs and for glycogen resynthesis, with the importance of this heightened during busy fixture periods (Dos Santos, 2017).

Due to the wide range of factors affecting performance, an issue that arises is that it cannot be said with absolute certainty what exactly is causing fatigue or a reduction in performance for a player.

A study conducted by Silva and colleagues tested a group of 7 soccer players 24-, 48- and 72-hours post-match and compared those results with their 72-hour pre-match CMJs, with a force platform being used to measure flight time and therefore jump height. It was discovered that 24 hours post-match (40.75 ± 1.80cm; mean ± standard error of the mean), the group's jump performance was significantly ($p < 0.05$) reduced. However, their CMJ height returned to baseline level 48 hours post-match (43.15 ± 2.30cm) and remained similar 72 hours post-match (43.60 ± 2.31cm), when compared to their baseline jump 72 hours pre-match (43.83 ± 2.40cm) (Silva et al, 2013). This studies' results therefore indicated that players were recovered 48 hours following the completion of their match. The match that took place during Silva and colleague's study was a professional Portuguese league match. Unfortunately, no match data was provided in the study, which would be beneficial to have when considering the CMJ results.

Although most studies that use CMJ testing focus mainly on jump height, such as Silva and colleague's study mentioned above, there are several others which use CMJ to calculate outputs such as flight time:contraction time (FT:CT), contraction time (CT), flight time (FT), peak power, peak force, mean power and mean force instead. One such study used CMJ to calculate peak power 24 hours pre-match and also 24- and 48-hours post-match for players playing for an English Premier League under 21 team with an average age of 21. The results showed that high intensity distance covered, high intensity distance covered per minute, sprint distance, sprint distance per minute, high-speed running distance, high-speed running distance per minute, the number of sprints per minute, the number of hard accelerations and the number of hard accelerations per minute positively correlated ($p < 0.05$) with peak power output 24 hours post-match. It was also discovered that none of these variables positively correlated ($p > 0.05$) with peak power output at 48-hours post-match (Russell et al, 2016a), indicating performance levels had returned to baseline. Hoffman and colleagues also used CMJ testing to calculate peak power for female collegiate soccer players 24 hours' pre- and post-match. It was found that peak power was significantly ($p < 0.05$) reduced 24 hours post-match in comparison to pre-match for players who started the match (Average time on pitch: 56.5 ± 14.0min; mean ± standard deviation). Non-starting players (29.0 ± 13.9min) had no significant difference ($p > 0.05$) between pre- and post-match peak power output calculated from CMJ (Hoffman et al, 2003). Exact values are not given in Hoffman and colleague's study as the results are presented in graphs, however an estimation of the mean power during the CMJ for starters pre-match is 3,000W and of post-match is 2,700W. For non-starters the estimated mean power during the CMJ pre-match is 3,300W and for post-match is 3,200W.

Studies have also been undertaken involving players from other team sports rather than soccer, such as Rugby League, with professional National Rugby League players being CMJ tested at several time points from 24 hours pre-match to 5 days post-match. Their peak rate of force development and peak power was the same 30 minutes (Peak rate of force development: 12,952 ± 3,583N/s, peak power: 4,539 ± 976W; mean ± standard deviation) and 24 hours (13,887 ± 5,125N/s, 4,743 ± 835W) pre-match as it was 48 hours (13,260 ± 5,514N/s, 4,286 ± 1,142W) post-match, whereas their peak force returned to pre-match levels (24 hours pre-match: 2,563 ± 838N, 30 minutes pre-match: 2,496 ± 612N) 24 hours (2,632 ± 344N) post-match (McLellan, 2012). The standard deviations for these results are relatively high, meaning that the results were spread out. During the CMJs in McLellan's study, players were instructed to use their arms when jumping if wanted, with the amount of arm movement being "individually determined by each subject". This causes an issue due to players potentially adopting different techniques when jumping at different time points throughout the study which could affect the results of their jumps. In addition, CMJs with arm swings are thought to be more relevant to sport specific performance, whereas the CMJ with no arm swing may be more beneficial for detecting changes in neuromuscular fatigue (Heishman et al, 2020). It is suggested by some that by eliminating any arm swing, it isolates lower extremity force production whilst also mitigating the potential variations that are encountered when the CMJ involves an arm swing (Cormack et al, 2008; Cormie, McBride and McCaulley, 2009). When different techniques are adopted when performing CMJ testing, it can result in a high variation in the results, with the McLellan study previously mentioned being an example of this. To avoid such issues, it is crucial that there is strict adherence to a standardised protocol when performing CMJ testing to obtain reliable results.

A similar study was performed with professional Rugby Union players, with CMJ baseline testing taking place 36 hours pre-match and then 12-, 36- and 60-hours post-match following a 7.30pm kick off time. The results showed that peak concentric power and relative peak concentric power were both significantly ($p < 0.05$) reduced in comparison to baseline levels, which were a peak concentric power of 6,100W, and relative peak concentric power of 58.5W/kg. 12 hours post-match, peak concentric power was reduced to 5,700W, and relative peak concentric power to 55W/kg. 36-hours post-match, peak concentric power was reduced to 5,750W, and relative peak concentric power to 55W/kg. However, the player's results returned to baseline levels ($p > 0.05$) 60 hours post-match, where peak concentric power was recorded as 6,000W, and relative peak concentric power as 57.5W/kg (West et al, 2014). Estimated values are used above due to only graphs and no values being shown. Although the group's results returned to baseline 60 hours post-match, seven of the fourteen players' peak power output had not returned to baseline level by this timepoint, and this shows the individual nature of recovery. A potential reason for this could be playing position, with several match variables being significantly different depending on this. It should be noted that due to baseline testing only taking place 36 hours prior to their match, high training load from prior in the week could have potentially affected jump performance due to neuromuscular fatigue. However, this is not known as no information is given regarding training leading up to the match used in the study. It should also be noted that the high level of collisions in rugby, also known as blunt force trauma, in comparison to soccer can have an effect on the recovery period of players.

Another team sport that has been studied in terms of neuromuscular fatigue is Australian Rules Football, with 15 male players performing CMJ testing prior to the season beginning and then in between each match of the 22-match season, ranging from 72 to 360 hours post-match. FT:CT was calculated using the CMJ and of the seven 72 hour post-match test days, four had a substantial decrease in FT:CT in comparison to pre-season, with magnitudes of change being classified as "a substantial increase or decrease when there was a ≥75% likelihood of the effect being equal to or greater than the smallest worthwhile change estimated as 0.2 x between-subject standard deviation". However, when tested at 96, 144 and 360 hours post-match there was often still a substantial reduction for the same variable (Cormack et al, 2008). A potential reason for this could be that overtraining took place, which is likely to result in extended periods of substantial reductions and less frequent returns to baseline performance, resulting in a longer time being required for recovery. Therefore, the reduction in FT:CT potentially should not be attributed to match fatigue alone. The issue of small sample sizes should be considered when considering the results from studies mentioned, with small sample sizes being associated with low statistical power, inflated effect size estimation and low reproducibility. Studies that are underpowered have been found to have an increased type 2 error rate, meaning that false null hypothesis is not rejected. Moreover, a greater proportion of statistically significant effects will be type 1 errors, which means that a true null hypothesis is rejected (Button et al, 2013).

One study, which tested elite male soccer player's CMJ pre- and post-match, and that had a similar cohort to the players used in this thesis, found that peak power during CMJ testing, which was recorded as 3,919 ± 538W pre-match, 3,977 ± 586W 30 min post-match, 3,934 ± 576W 24 hours post-match and 3,928 ± 577W 48 hours post-match was not significantly different ($p > 0.05$) during any of the post-match CMJs in comparison to pre-match. Moreover, the same was discovered for peak force during CMJ testing, with a pre-match peak force of 1,833 ± 181N. This is in comparison to 1,809 ± 234N 30 min post-match, 1,830 ± 209N 24 hours post-match and 1,824 ± 175N 48 hours post-match. The power recorded during CMJ testing for the soccer players in Romagnoli and colleague's study was far lower than the power recorded during CMJ testing for the rugby union players in West and colleague's 2014 study mentioned previously. Similar testing protocol was used, however the rugby union players were older. It should also be noted that this study's results were all from a single match. By testing players over the course of a season, like in this thesis, it gives more reliable and valid information in comparison to results from a single match. A potential factor in this finding is the different characteristics of athletes in varying studies, due to body mass being taken into account when calculating power. Markovic and colleague's study discovered that there was a moderate power-performance relationship (range: $0.55 < r < 0.64$) for CMJs, but that when controlled for body mass, the same values were higher (range: $0.61 < r < 0.82$; $p < 0.05$ for peak power). This finding indicates that body size can "confound the relationship between the muscle power output with the performance of maximum vertical jumps" (Markovic et al, 2014).

Often, active recovery is used in an attempt to speed up the recovery process following a match. This was used when Andersson and colleagues CMJ tested a group of female soccer players' pre- and post-match having used either passive or active recovery. The active recovery consisted of "a low-intensity training program (submaximal cycling at 60% $HR_{peak}$ and approximately 45% $\dot{V}O_{2peak}$) and low-intensity resistance training (< 50% 1 rep maximum) performed at 22 and 46 hours after the first match". The results showed that jump height was significantly reduced ($p < 0.05$) immediately (active recovery: 29.1 ± 1cm; passive recovery: 28.4 ± 1cm) and 69 hours (29.2 ± 1.1cm, 28.9 ± 1.2cm) post-match in comparison to pre-match (30.5 ± 1.2cm, 29.8 ± 1.2cm) jump height, and that there was no difference ($p > 0.05$) between the active and passive recovery groups (Andersson et al, 2008). Testing also took place 5, 21, 27, 45 and 51 hours post-match for both groups and both were decreased at all time points in comparison to baseline levels. This data is shown in a percentage change graph in the study.

Thorlund and colleagues produced results which showed that there was no significant difference ($p > 0.05$) in jump height when comparing post-match CMJ height (34.7 ± 1.5cm) to non-fatigued control state CMJ height (35.4 ± 1.6cm) (Thorlund et al, 2008). However, the non-fatigued control state CMJ testing was performed 3-5 days post-match, which is potentially within the period of time in which neuromuscular fatigue is still apparent due to match load, and this can affect jump height achieved during a CMJ.

In summary, CMJs have been used for decades to discover the performance levels of athletes in the hours and days following the completion of training and matches. The most frequent variable used when CMJs are performed is jump height, however recently many other variables have begun to be used either in conjunction with jump height or as a replacement, with many believing there to be other variables that can more accurately monitor fatigue (Gathercole et al, 2015). Different variables can take different lengths of time to return to baseline levels following the completion of exercise. Moreover, the length of time taken to return to baseline levels for jump height and other variables varies between studies, from hours to several days (Duffield et al, 2011; Fatouros et al, 2010; Nedelec et al, 2014). In an attempt to improve the detection of fatigue and find ways of streamlining the testing of large squads, other methods to test players other than CMJs have been researched. One of these is through the use of Kvert, which the next section will discuss.

Vertical Stiffness Findings

Kvert can be defined as the ratio of the maximal ground reaction force to vertical displacement (Girard et al, 2010). This maximal force is exerted on the ground when each foot comes into contact with the ground, and the term Kvert is used to describe the vertical motion of the centre of mass during contact with the ground (Farley and Gonzalez, 1996). In comparison to CMJ testing, there is little research looking into the effect that fatigue has on Kvert, hence why this thesis chose to attempt to discover more surrounding the area.

On the other hand, how velocity affects Kvert when running has been investigated more frequently, and it has been discovered that at higher running velocities, Kvert increases quadratically with velocity, meaning that as velocity increases, Kvert increases at a far higher rate (McMahon and Cheng, 1990). However, one study which investigated the effect fatigue has on Kvert was performed by Morin and colleagues in 2006. It consisted of eight male physical education students (age: 23 ± 4 years) performing four maximum effort 100m sprints on a synthetic track, with 2 minutes of passive recovery in between each sprint. It was discovered that as velocity decreased over the sprints, so too did Kvert ($p < 0.05$), by 20.6 ± 7.9% between the first and the last 100m (1st: 93.9 ± 12.4kN/m; 2nd: 81.4 ± 10.0kN/m; 3rd: 78.4 ± 13.5kN/m; 4th: 74.9 ± 14.2kN/m) (Morin et al, 2006). Another study, which was performed on grass, tested 13 male soccer players with each participant completing six 20m sprints interspersed with 20s of passive recovery. Plantar pressure distribution was recorded via an insole pressure recorder device divided into nine areas for analysis, and from this Kvert was calculated. It was discovered that Kvert decreased significantly ($p < 0.05$) over the course of the six runs (Girard et al, 2011). Each sprint had a mean Kvert score calculated, however this was only in a graph so only an estimation for each is given here. The 1st sprint was 120kN/m, 2nd was 112kN/m, 3rd was 110kN/m, 4th was 109kN/m, 5th was 101kN/m and the 6th and final sprint was 98kN/m. A similar study, which was also conducted by Girard, used force plates at 5-10m and 30-35m into each sprint to calculate Kvert during twelve 40m sprints interspersed with 30s of passive recovery, with 16 active participants involved in the study. It was discovered that Kvert decreased ($p < 0.05$) from the first to the last run, and that changes in Kvert were positively correlated with stride frequency (5-10m: Pearson Correlation: 0.74, $p < 0.05$; 30-35m: 0.72, $p < 0.05$) (Girard et al, 2010). Once again the Kvert data was only presented in a graph so an estimation is that the Kvert decreased from 86kN/m during the first sprint to 70kN/m during the final sprint. In both Girard studies aforementioned, reference is made to the spring mass model, which in this case is the leg functioning as a linear spring (Brughelli and Cronin, 2008). It has been discussed that in this spring it is possible for energy to be stored during the mid-step phase of running within stretched tendons and muscles contained within the leg (Cavagna et al, 1977). This storing of energy is described as an “elastic bounce” by Cavagna and colleagues, and provides energy when the motion of running takes place.

Prior to Morin and colleagues study, there was a 2002 study conducted by Dutto and Smith, during which 15 runners (11 males and 4 females) ran on a treadmill until exhaustion at a speed equivalent to 80% of their $\dot{V}O_{2peak}$. The treadmill measured vertical ground reaction forces, and allowed Kvert to be calculated from these forces. The results from an ANOVA revealed that 11 of the 15 runner’s Kvert scores decreased over the course of the run, and group analysis revealed significant decreases ($p < 0.05$) in Kvert (23.9 ± 3.2kN/m to 23.1 ± 2.8kN/m) over the run. However, one of the runners had no change for Kvert during the run and three showed an increase ($p < 0.05$) in Kvert over the run, therefore showing the individual nature of an athlete’s reaction to exercise in regards to Kvert (Dutto and Smith, 2002).

Several different methods are used to calculate Kvert, with force plates being the criterion method (Eggers et al, 2017). In the past few years, Global Positioning System (GPS) units and accelerometers have started to be used as an alternative as force plates are not a feasible option for assessing Kvert in team sports (Buchheit et al, 2015), and accelerometers embedded in GPS units are used in this thesis. A team sport player performed six runs at 10, 17 and 24 km/h with or without his right ankle taped, which aimed at creating a stride imbalance. With an accelerometer embedded in a GPS unit placed on his back, it was possible to calculate Kvert via the treadmill and the raw accelerometer data through the use of Athletic Data Innovations (ADI), a software which uses accelerometer data to discover a player's imbalances and Kvert amongst many other variables. It is also used in this thesis' study to calculate Kvert. In the study mentioned, a commercially available GPS unit was used that had an embedded 100-Hz triaxial accelerometer. Similar accelerometer data has previously been shown to have good reliability when collected during football specific activity (Boyd et al, 2011). It was stated that biases were small (-13.3%; 90% Confidence Interval (CI): -14.6, -11.9) and that the typical error of the estimate was small (6.3%; 5.5, 7.5) for Kvert, and nearly perfect correlations ($r = 0.98$; 90% CI: 0.97, 0.99) for Kvert were recorded via treadmill and accelerometer (Buchheit et al, 2015). The "Sine-wave" method for measuring Kvert during running was created by Morin in 2005, and this is what ADI uses. Based on the modelling of the force-time curve by a sine function, this method allows Kvert to be estimated from a few simple mechanical parameters: body mass, forward velocity, leg length, flight time, and contact time (Morin et al, 2005).

Another study, which performed similar testing but for over ground running as opposed to treadmill running discovered that the standardised mean bias was trivial (-0.14; 90% CI: -0.39, 0.12) for accelerometer derived Kvert versus force plate when the accelerometer was placed at the scapula (Accelerometer Kvert: 24.4 ± 3.8 kN/m; force plate Kvert: 24.9 ± 3.7 kN/m). However, reliability was moderate (Intraclass Correlation Coefficient (ICC): 0.71) for accelerometer derived Kvert when placed at the scapula, whereas the reliability was deemed good (ICC: 0.89) for Kvert when it was calculated using force plates (Eggers et al, 2017).

**Summary**

The measurement of fatigue in players is an important aspect of elite soccer, with match schedules becoming more hectic. It is therefore vital that reliable and efficient tests of measuring fatigue are available to clubs and practitioners. Although the CMJ has been used for several decades to measure performance and fatigue, it can be time consuming and does not always provide a complete picture of the recovery process when only using variables such as jump height. As a result, new methods of monitoring fatigue are being considered and researched, and Kvert is one of these. Although there has been some research regarding how fatigue affects Kvert, considerably less research has taken place in comparison to monitoring fatigue using the CMJ. Therefore, this thesis is taking place in order to discover more regarding how Kvert is affected by fatigue, and if it is viable form of measuring fatigue throughout the season.

# Methods

## Participants

The data was collected from 17 male youth soccer players (age: 18.4 ± 1.1, height: 179.8cm ± 6, weight: 74.7kg ± 6.5) who were all contracted to an elite Scottish full-time development/reserve squad during the 2018/19 season. The chosen players covered a range of outfield positions, with there being at least 1 player in each of the following positions: CB, CM, WM, ATT and FB.

Testing took place over a 6-month period between November 2018 and April 2019 at the club's training ground. For the Yo-Yo Intermittent Recovery Test Level 1, the surface used was a 4G artificial surface which was located outside. The temperature ranged from 1.8°C to 10.9°C, humidity from 60.9% to 84.4% and wind speed from 0.5m/s to 10.9m/s over the course of testing, with it occasionally raining during testing but usually being dry. All players wore their own studded football boots while completing the Yo-Yo test. The players participating in the testing were familiar with the pitch having trained and played matches on it prior to testing commencing. The players always ran on the same section of the pitch and wore the same boots during testing. During the course of the study, there were 8 matches that data was collected from. The original intention was to collect data from more matches than this, however during the course of testing only 12 matches took place for the reserve squad. For 4 of these matches the players were given days off on MD+2 and therefore testing did not take place, this was unfortunately out with my control. The players that played <60 minutes had minutes played ranging from 13 to 56 minutes, with 7 of the 15 data points consisting of players playing 21 minutes or less. A study which took data from 155, 172 and 158 games from the English Premier League, Serie A and La Liga discovered that the 1$^{st}$ substitution was made after the 57$^{th}$ minute on average, where as the mode was around the 60$^{th}$ minute (Myers, 2012). Due to this, the players that played >60 minutes were grouped together.

The purpose of each test was explained to the squad of players prior to the first week of testing, with an emphasis placed on the importance of performing to their maximum whenever tested. This included aiming to jump as high as possible at each CMJ attempt and matching the beeps during the Yo-Yo test. The players would be instructed throughout the Yo-Yo test to match the beeps and would also be encouraged throughout the CMJ testing.

| Match | Number of Players That Played >60 Minutes and Had Data Collected | Number of Players That Played <60 Minutes and Had Data Collected |
|---|---|---|
| **1** | 3 | 1 |
| **2** | 7 | 2 |
| **3** | 4 | 6 |
| **4** | 6 | 5 |
| **5** | 1 | 0 |
| **6** | 5 | 0 |
| **7** | 1 | 0 |
| **8** | 6 | 1 |

*Table 1 - Table displaying the number of players that had data collected for each match.*

**GPS Units**

GPSports EVO 10 Hz GPS units (GPSports, Australia) were worn in the pouch of vests designed by GPSports. Once placed in the pouch of the vest, the unit was located in the upper thoracic region of the spine between the scapulae. The device has a size of 68mm x 42mm x 18mm and inside has a 100 Hz accelerometers 3D, with 100 Hz for each plane, being vertical, lateral and longitudinal. The majority of players wore the same unit throughout the season but due to a shortage of units and some units becoming deficient, some players wore different units for different days of testing. The GPS units were worn for both training and matches, which allowed Kvert to be calculated during the 6-minute Yo-Yo test that took place prior to training commencing. This also allowed match data to be collected for each player.

**CMJ Protocol**

Prior to the Yo-Yo test taking place, on each day of testing the players would complete 3 CMJs in the gym of the training ground. To record the jumps that took place Pasco Portable PS-2141 PASPORT Force Platforms (Pasco, USA) were used, with ForceDecks (VALD Performance, UK) software being used to analyse the data collected from the force platforms. The squad had all completed CMJs prior to the start of the testing period and therefore were familiar with the methodology but it was explained to them before each day of testing. The players would arrive in the gym around 45~60 minutes prior to the Yo-Yo test taking place and once they were in the gym they would undertake a warm up consisting of cycling and static stretching. Once they felt comfortable to complete the jumps they would approach the force plates and using the laptop, the force plates would be set up for each individual player. Each player was told to complete 3 CMJs with maximum effort being put in for each jump. As well as this they were instructed to keep their hands on their hips throughout the jump, and that they should have a break of 15 seconds in between the jumps so that they felt prepared for each one. For the depth to which the player's dropped to before jumping, it was agreed that they could go to whatever depth they felt most comfortable with and the depth which they felt they could achieve the highest jump possible. The players were also told to maintain extension in the hip, knee and ankle joints following their jump in order for them to avoid bending their legs so as to avoid them achieving any additional flight time. Finally, they were also instructed to land in the same position on the force plates as they took off from.

**Yo-Yo Test Protocol**

The players completed a 6-minute sub-maximal Yo-Yo Intermittent Recovery Test Level 1, whilst wearing GPS units with embedded tri-axial accelerometers, on the pitch that was mentioned previously, for each day that testing took place. The Yo-Yo test took place after the CMJs, with the jumps taking place ~30-45 minutes prior to the Yo-Yo test commencing. After a 5-minute warm up consisting of a jog around the pitch and static stretching the players lined up in preparation for the test commencing. The Yo-Yo test consisted of the players running 20m in a straight line and then turning and running 20m in the opposite direction. They then walked 5m in the same direction and then turned and walked 5m in the opposite direction, meaning they were then back at the same position they began at, and then repeated these steps for a total of 6 minutes. The speed was set due to beeps indicating when the players should be reaching certain parts of the test. At the start of the test the players had to run at ~13km/h to cover the correct distance at the allotted time. The speed increased over the 6 minutes as the beeps had less time between them until the final stage when the players had to travel at ~17km/h. Figure 9 shows a diagram of the Yo-Yo test. Each player's Kvert during the Yo-Yo test was calculated as being their average Kvert over the 6 minutes. Following the completion of the Yo-Yo test the players would then begin their training session. After the training session was complete the GPS units were collected and downloaded. The 6-minute Yo-Yo test was separated from the warm up and training session and the data during the 6 minutes was exported to ADI. ADI then performed the necessary calculations with the data and produced a Kvert score for each player which was recorded in an Excel document along with the rest of the data. To attempt to mitigate the possibility that players were running at differing paces for each stage of the Yo-Yo test pre- and post-match and throughout the period of testing, the players were instructed that they should perform each test the same way and in line with one another. In addition to this, myself and an additional coach watched each test and instructed players to complete the test whilst running in a line alongside each other throughout the 6 minutes.

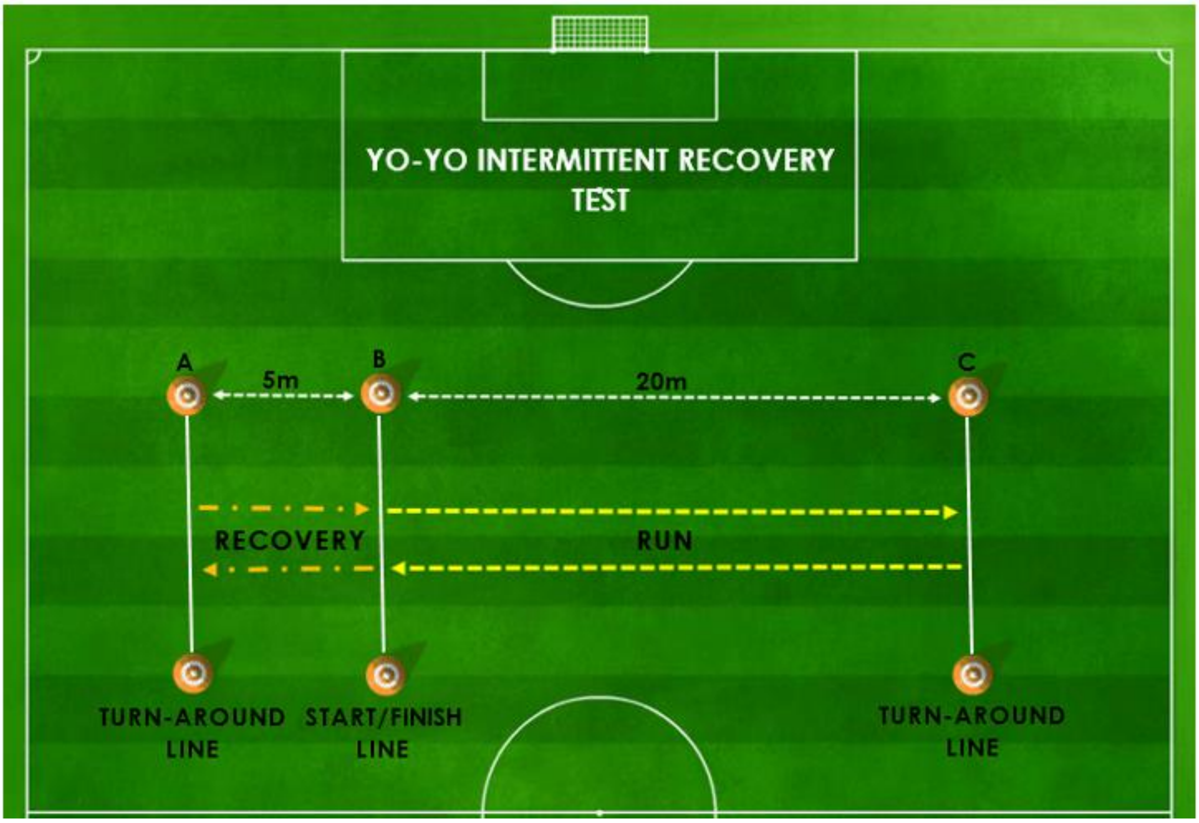


*Figure 9 - Yo-Yo Intermittent Recovery Test Level 1*

**Reliability Testing**

During the first month of testing there was an international break, resulting in several of the players going on international duty. Six players were available and reliability testing of the 6-minute submaximal Yo-Yo test took place using these players. The testing took place over three consecutive days, with the first day being 8 days after the most recent match. The players completed the Yo-Yo test using the same methods as were mentioned above. The test was completed prior to training commencing on these three days.

**Timeline of Testing**

| ~24 Hours Pre-Match → | Match Day → | ~48 Hours Post-Match |
|---|---|---|
| • CMJ Testing Pre-Training<br>• 6-minute Yo-Yo Test Pre-Training<br>• GPS Units Worn During Training | • GPS Units Worn During Match | • CMJ Testing Pre-training<br>• 6-minute Yo-Yo Test Pre-Training<br>• GPS Units Worn During Training |

**Data Analysis**

The data that was collected from the jumps for analysis was FT:CT.

The data that was collected from GPS units from match data for analysis was total distance, high intensity running distance, accelerations, and decelerations. After being downloaded, the matches were tagged from the beginning of the match to the end of the first half, and then from the beginning of the second half to the full time whistle, so that injury time was included at the end of each half. Therefore, the total distance, high intensity running distance, accelerations and decelerations all took place in the tagged time zones. High intensity running distance was calculated with "high intensity running" being defined as >21km/h. This was due to this value being used to define high intensity running for both the 1st team and reserve squad at Celtic, with this value being used for all players. This value was used as a result of several other studies also using similar values as a cut-off point to define high speed running (Rago, Pizzuto and Raiola, 2017; Izzo and Vardei, 2017). Accelerations and decelerations that were used in the statistical analysis were all accelerations and decelerations >3m/s$^2$. This value was used as values close to >3m/s$^2$ are often used as a threshold for accelerations and decelerations in various studies (Russell et al, 2016b; Russell et al, 2015; Tierney et al, 2016). This intensity of acceleration and deceleration imposes internal physiological and mechanical loading demands on players (Vanrenterghem et al, 2017), and when movements are performed at or above this intensity it is commonly associated with a reduction in neuromuscular performance (Gastlin et al, 2019).

Following the completion of the jumps, the laptop was used to export a CSV with all the jump variables. The necessary data was then copied into the Microsoft Excel 2016 (Microsoft, USA) database that was used to store all of the testing data.

For the data collected during the Yo-Yo test, the raw data from the GPS units that were worn were downloaded using the supplier's mass USB device in the charging box. The raw accelerometer data was then exported and ran through Athletic Data Innovations (ADI, Australia), with an Excel sheet being produced which had Kvert for each player that completed the Yo-Yo test. The Kvert variable was an average Kvert for the duration of the 6-minute Yo-Yo, with Kvert being calculated for each full phase of running.

Once testing had taken place, all the relevant data was collected from the necessary data sheets and pasted into various tabs on a single excel document. This document contained all the data that was then used to statistically analysis the results of the study.

For the reliability testing, the mean and standard deviation Kvert of the group during the three consecutive days of testing was used to calculate the CV.

**Statistical Analysis**

The statistical analysis aimed at discovering whether there was a significant difference between Kvert in comparison between MD-1 and MD+2 for the squad as a whole, certain positions and individual players. Another aim was to discover whether there was a correlation between the change in Kvert and CMJ variables from MD-1 and MD+2.

All results are presented as mean ± standard deviation. Data was analysed using SPSS statistics package (version 26). All data were assessed for normality of distribution according to Shapiro-Wilk's test. A majority of the data was found to have $p > 0.05$ for Shapiro-Wilks, meaning the data was normally distributed and therefore paired sample T tests were used to statistically compare the change in player's Kvert and FT:CT. Where a statistically significant difference was found, Cohen's D effect size was used to discover the magnitude of change, with 0.2 – 0.39 indicating a small change, 0.4 – 0.79 indicating a moderate change and 0.8 - 1 indicating a large change (Cohen, 1988). Pearson's correlation was used to discover whether there was correlation between the change in Kvert and FT:CT The rule of thumb for interpreting the size of a correlation coefficient used was taken from Hinkle, Wiersma and Jurs' 2003 study, which can be seen below. Significance was accepted at $p < 0.05$.

| **Size of Correlation** | **Interpretation** |
|---|---|
| .90 to 1.00 (-.90 to –1.00) | Very high positive (negative) correlation |
| .70 to .90 (-.70 to -.90) | High positive (negative) correlation |
| .50 to .70 (-.50 to -.70) | Moderate positive (negative) correlation |
| .30 to .50 (-.30 to -.50) | Low positive (negative) correlation |
| .00 to .30 (.00 to -.30) | Little if any correlation |

*Table 2 - Table displaying the rule of thumb for interpreting the size of a correlation coefficient (Hinkle, Wiersma and Jurs, 2003)*

## Results

### Reliability of Kvert Testing

During an international break where no games for the reserve squad took place, reliability testing took place with a reduced squad size of 6. The Yo-Yo test was performed prior to training for 3 days in a row. It was discovered that the mean Kvert of the group was 29.19 ± 4.76kN/m and that the CV of the group for interday Kvert during the 6-minute Yo-Yo test was 16.32 ± 4.5%, with players having similar CV values within ~3% of each other. Several studies state that a CV of <10% is a marker of a reliable test measure, with a CV of between 10 and ~15% showing marginal reliability (Gathercole et al, 2015; Cormack et al, 2008; Sheppard et al, 2008). Using the ranges mentioned would mean the method used to measure Kvert in this study shows marginal to low reliability.

### ICC and Typical Error of Measurement

When using the data that has been mentioned above, the ICC was calculated and found to be -0.007 when measuring Kvert during the 6-minute Yo-Yo test, and this ICC indicates very poor reliability (Koo and Li, 2016). The typical error of measurement for the same data set is 4.75kN/m. This is quite a large typical error of measurement when considering the mean of the group was 29.19 ± 4.76kN/m during the 3 days of reliability testing.

**Power Calculations**

Power calculations were performed after the data had been collected. The outcome of these are detailed in the table below. The sample size required had the power been 0.8 refers to the sample size required for there to be 80% likelihood of avoiding a type II error. It is generally accepted that power should be 0.8 or greater, hence why 0.8 has been used. A higher power, such as 0.9, would be preferable but would also result in higher sample sizes being required.

| Data Analysed | Power | Sample Size Required had Power Been 0.8 |
|---|---|---|
| Change in Kvert from MD-1 to MD+2 for players that played >60 minutes | 0.05 | 2,638 |
| Change in FT:CT from MD-1 to MD+2 for players that played >60 minutes | 0.07 | 1,291 |
| Change in Kvert from MD-1 to MD+2 for players that played <60 minutes | 0.19 | 225 |
| Change in FT:CT from MD-1 to MD+2 for players that played <60 minutes | 0.36 | 102 |

*Table 3 - Power calculations for data that has been analysed as part of results section*

**Training Load Leading into Matchday**

Figures 10 and 11 display the mean distance covered and mean distance covered at high speed respectively in the lead up to a match day for a week during the period of data collection. The lowest mean distance covered was MD-1 (3,430 ± 285m), with MD-4 having the highest mean (6,826 ± 1,380m) (Figure 10). The lowest mean high-speed distance covered was MD-5 (9 ± 11m), with MD-3 having the highest mean (466 ± 62m) (Figure 11).

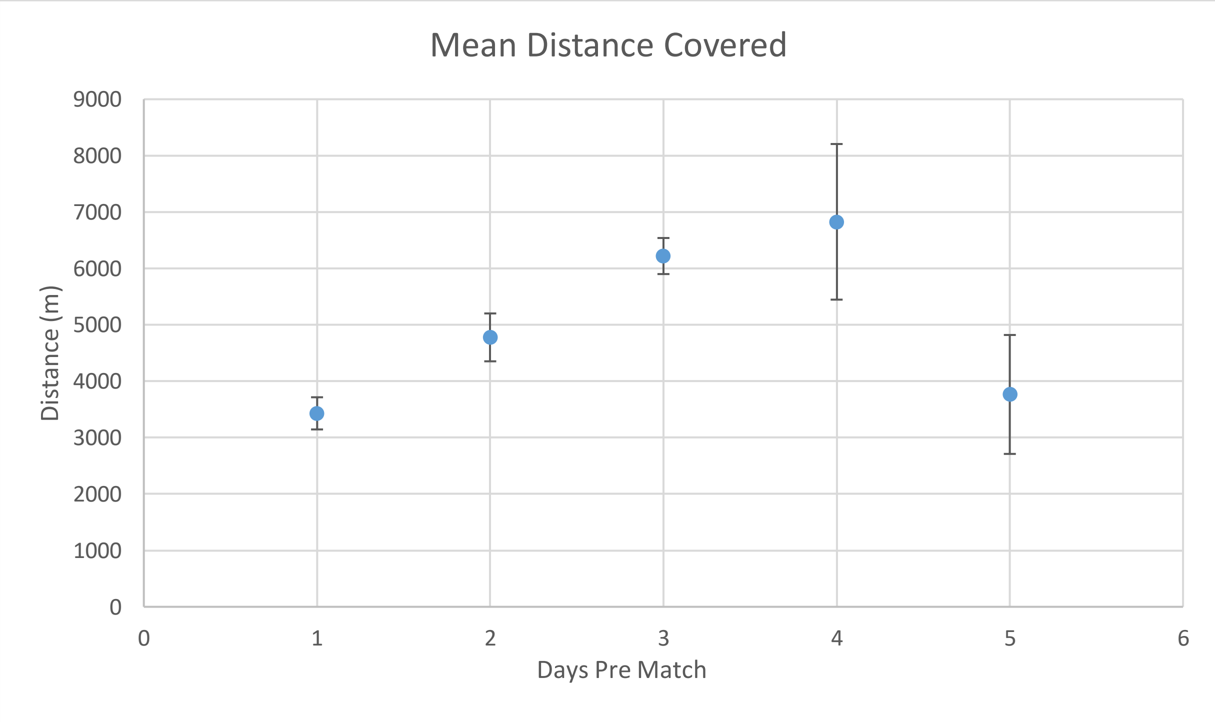


*Figure 10 – Total distance covered by squad during training in lead up to match. Mean data is shown and N=12. The error bars show standard deviation.*

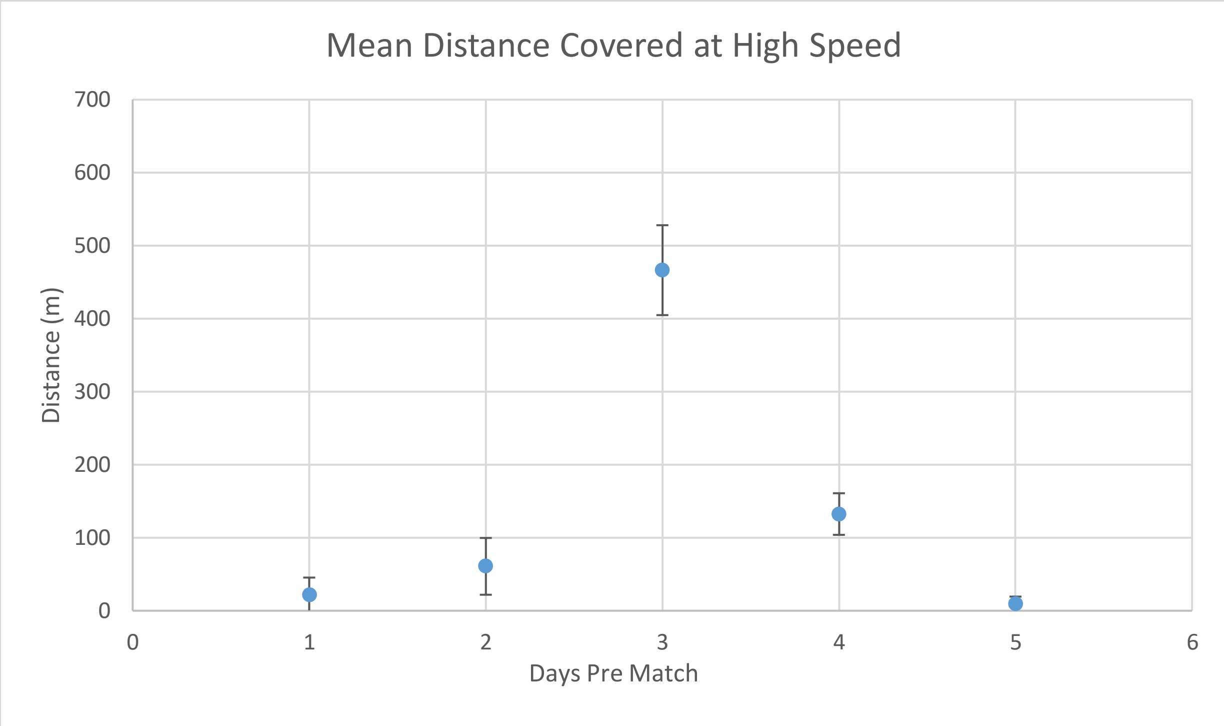


*Figure 11 – Total high-speed distance covered by squad during training in lead up to match. Mean data is shown and N=12. The error bars show standard deviation. High speed is classed as >21km/h.*

**Summary of Results**

The Kvert from MD-1 and MD+2 of each match was statistically analysed against each, as well as the jump data from MD-1 and MD+2 of each match being statistically analysed against each other. In addition, the change in Kvert from MD-1 to MD+2 was analysed against the change in FT:CT from MD-1 to MD+2. As well as this the match data from each match was also recorded and statistically analysed alongside the Kvert and jump data. There was no statistically significant differences between MD-1 and MD+2 for Kvert and FT:CT for players that played >60 minutes in matches. Moreover, there was no statistically significant correlation between the change in Kvert and FT:CT from MD-1 to MD+2 against the recorded match variables.

**Change in Vertical Stiffness From MD-1 to MD+2 Against Change in FT:CT from MD-1 to MD+2**

It was discovered that for players that played >60 minutes in matches, there was no correlation between the change in Kvert from MD-1 and MD+2 (31.75 ± 7.09kN/m and 31.23 ± 6.38kN/m) and the change in FT:CT (0.836 ± 0.126 and 0.821 ± 0.145) over this same time period, with there being a Pearson Correlation of -0.18, which indicates a neligible corelation ($p > 0.05$) (Figure 12). For players that played <60 minutes in matches there was also no correlation between the change in Kvert from MD-1 and MD+2 (29.51 ± 4.74kN/m and 28.34 ± 4.09) and the change in FT:CT (0.803 ± 0.126 and 0.753 ± 0.128) over this same time period, with there being a Pearson Correlation of 0.16, which indicates a neligible corelation ($p > 0.05$) (Figure 14). In figures 12 and 16, the games that are represented by the data points are from 05/11/2018, 16/12/2018, 10/01/2019, 18/01/2019, 24/02/2019, 04/03/2019, 13/03/2019 and 01/04/2019. 4 of the 13 players feature once in figures 12 and 14, with the 7 other players being represented by two or more data points each. In figure 14 the games that are represented by the data points are from 05/11/2018, 16/12/2018, 10/01/2019, 18/01/2019 and 01/04/2019. 5 of the 10 players feature once in figure 14 with the 5 other players being represented by 2 data points each.

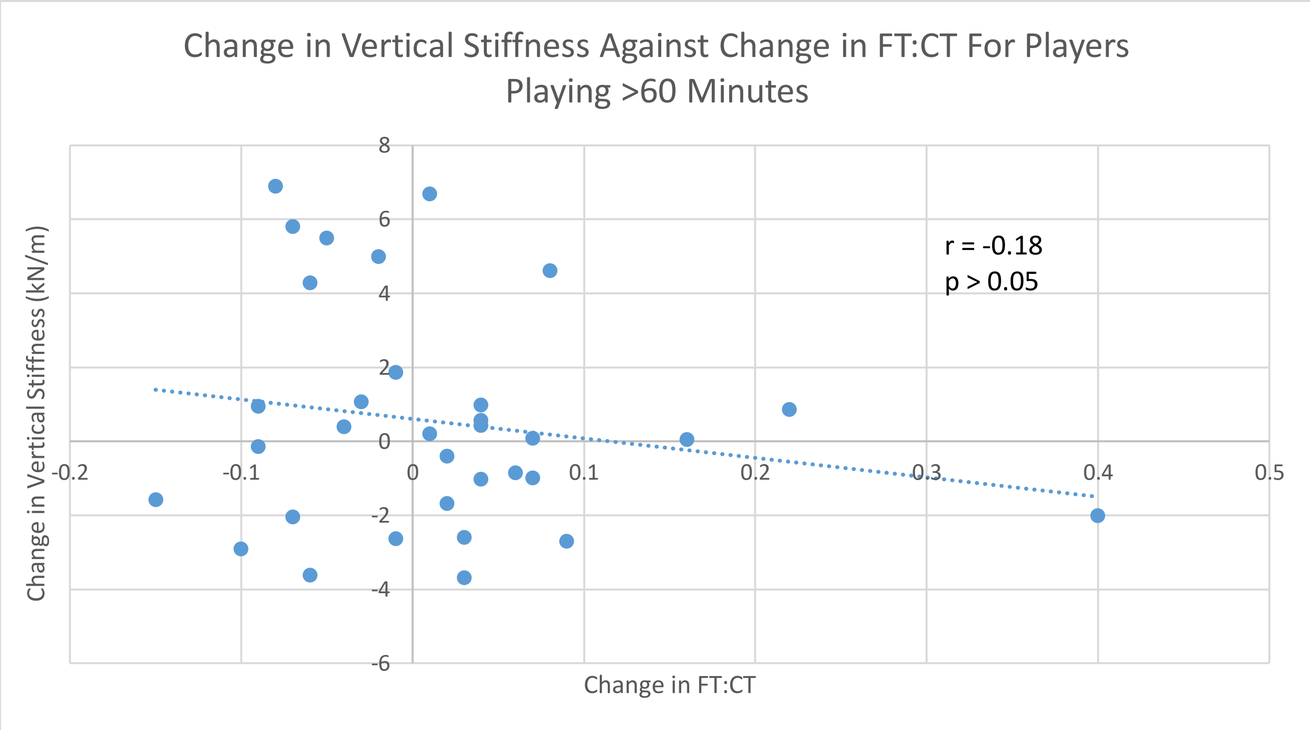


*Figure 12 – Graph displaying the change in vertical stiffness from MD-1 to MD+2 against the change in FT:CT from MD-1 to MD+2 for players that played >60 minutes in each match. The line featured is a linear trendline and there are 33 data points.*

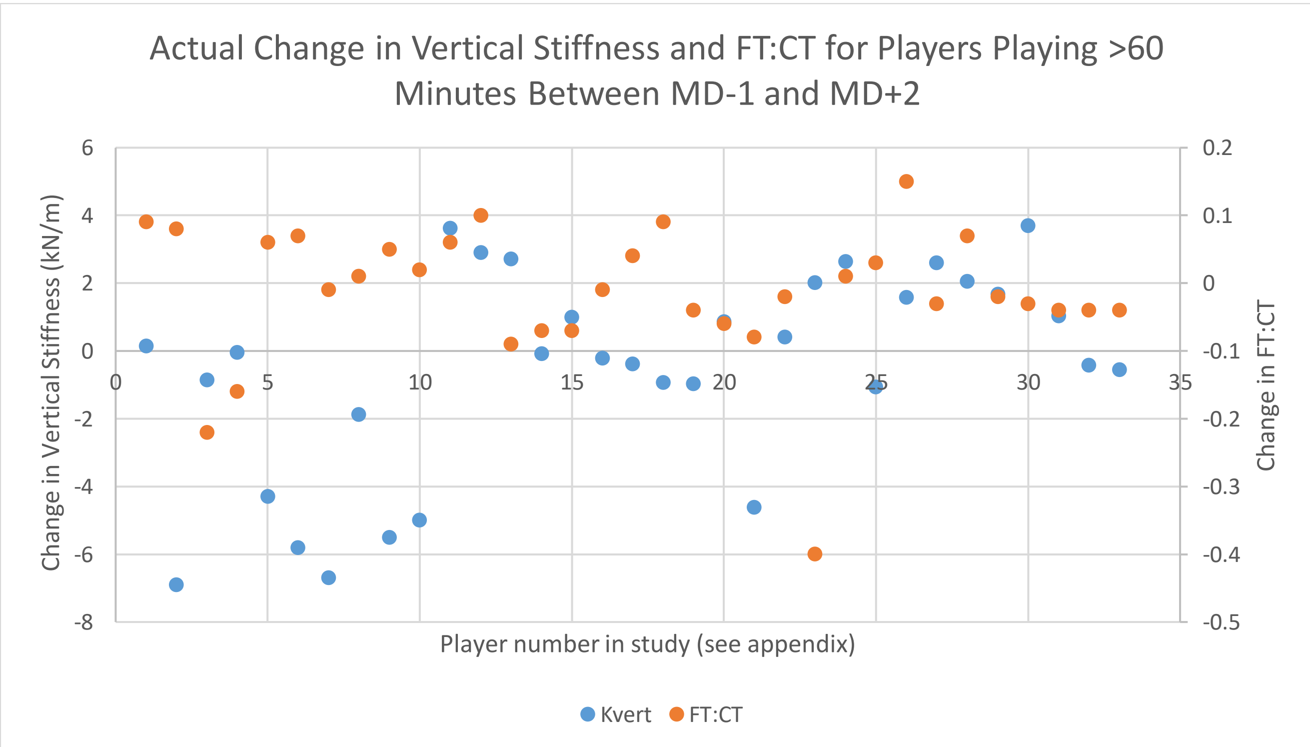


Figure 13 – Graph displaying actual change in vertical stiffness and FT:CT from MD-1 to MD+2 for players that played >60 minutes in each match.

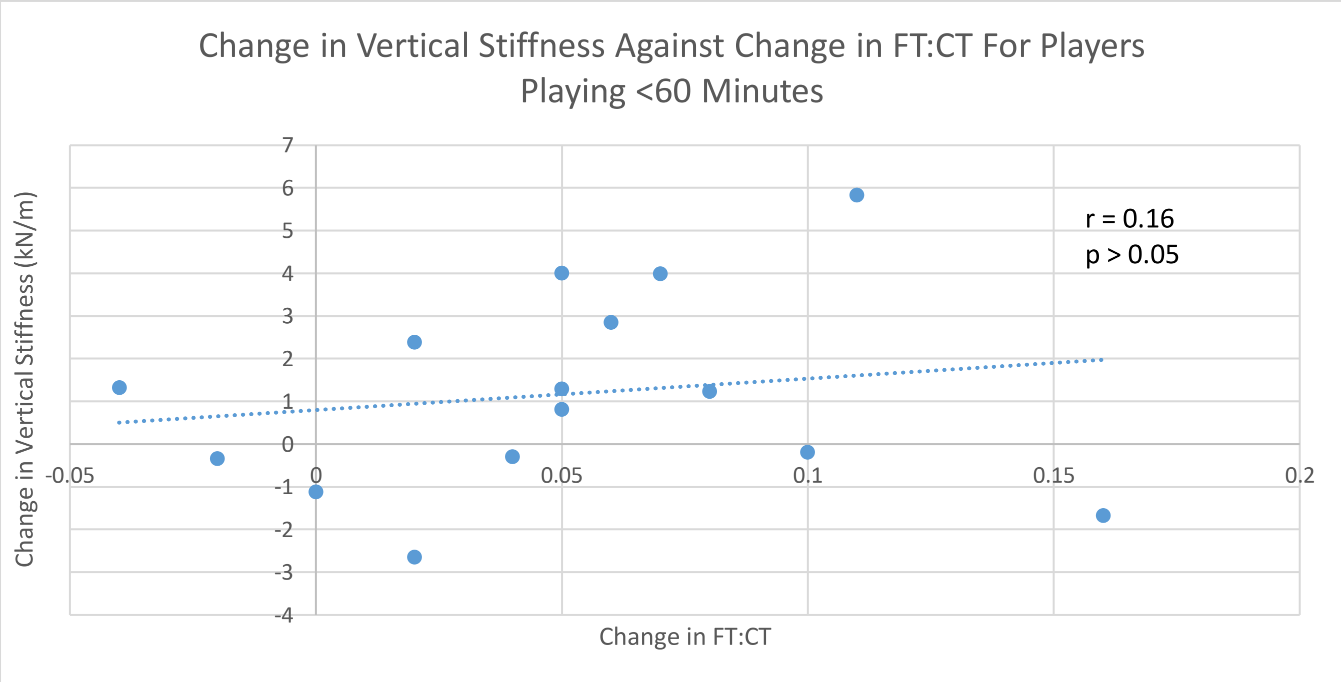


*Figure 14 - Graph displaying the change in vertical stiffness from MD-1 to MD+2 against the change in FT:CT from MD-1 to MD+2 for players that played <60 minutes in each match. The line featured is a linear trendline and there are 15 data points.*

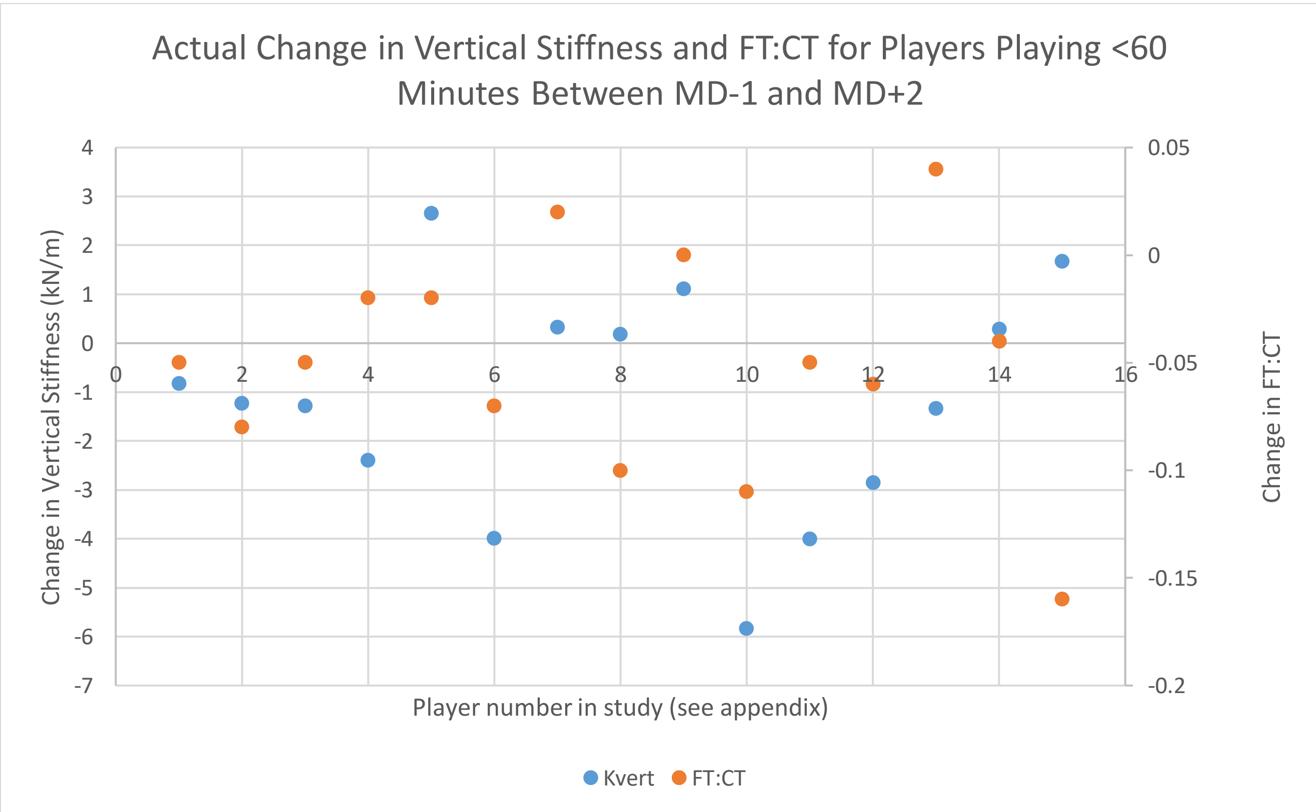


Figure 15 - Graph displaying actual change in vertical stiffness and FT:CT from MD-1 to MD+2 for players that played <60 minutes in each match.

**Change in Vertical Stiffness and FT:CT From MD-1 to MD+2**

When comparing the Kvert for players playing >60 minutes in matches, it was discovered that there was no statistically significant difference ($p > 0.05$) between MD-1 and MD+2 (31.75 ± 7.09kN/m and 31.23 ± 6.38kN/m), with a mean difference of -0.52 ± 3.02kN/m and 95% CI (-0.55, 1.6) (Figure 16). The same was found for players playing <60 minutes in matches, with no statistically significant difference ($p > 0.05$) being found for Kvert between MD-1 and MD+2 (29.51 ± 4.74kN/m and 28.34 ± 4.09kN/m), with a mean difference of -1.17 ± 2.33kN/m and 95% CI (-0.12, 2.46) (Figure 17).

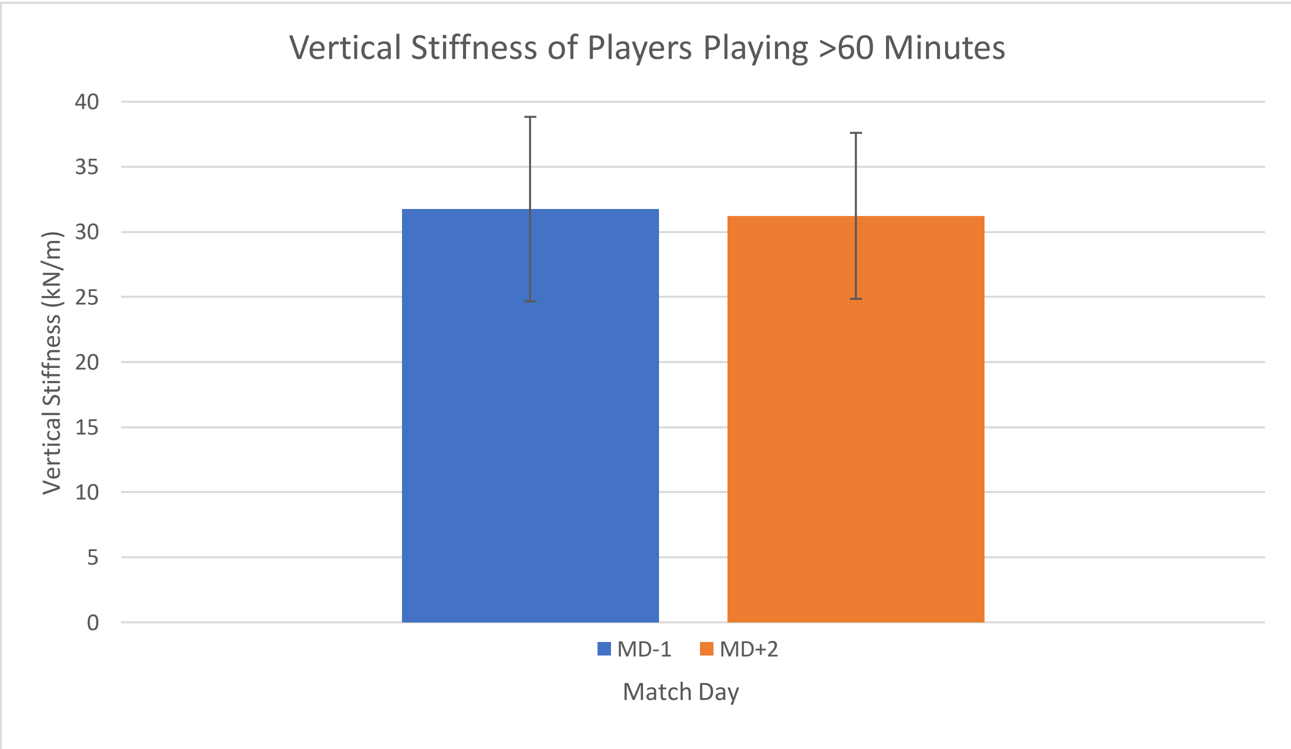


*Figure 16 – Graph displaying the mean vertical stiffness for MD-1 and MD+2 for players that played >60 minutes of each match. Error bars display standard deviation.*

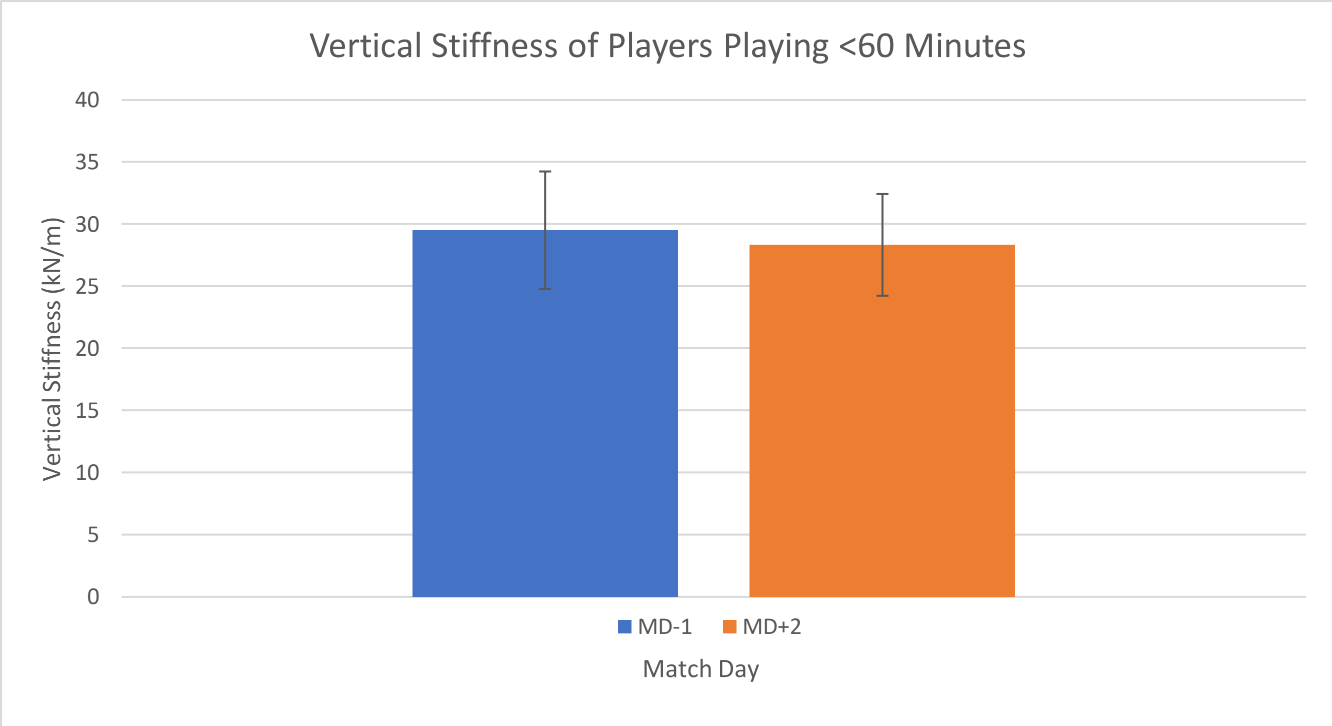


*Figure 17 - Graph displaying the mean vertical stiffness for MD-1 and MD+2 for players that played <60 minutes of each match. Error bars display standard deviation.*

When comparing the FT:CT for players playing >60 minutes in matches, it was discovered that there was no statistically significant difference ($p > 0.05$) between MD-1 and MD+2 (0.836 ± 0.126 and 0.821 ± 0.145), with a mean difference of -0.015 ± 0.103 and 95% CI (-0.021, 0.052) (Figure 18). For players playing <60 minutes in matches, it was discovered that there was a statistically significant difference ($p < 0.05$) for FT:CT between MD-1 and MD+2 (0.803 ± 0.126 and 0.753 ± 0.128), with a mean difference of -0.050 ± 0.051 and 95% CI (0.022, 0.078). The small sample size of the study results in an increased risk of type 1 and type 2 errors however, meaning that the statistically significant difference is possibly due to an error. There was a Cohen's D effect size of 0.4 present here, indicating a moderate change (Figure 19).

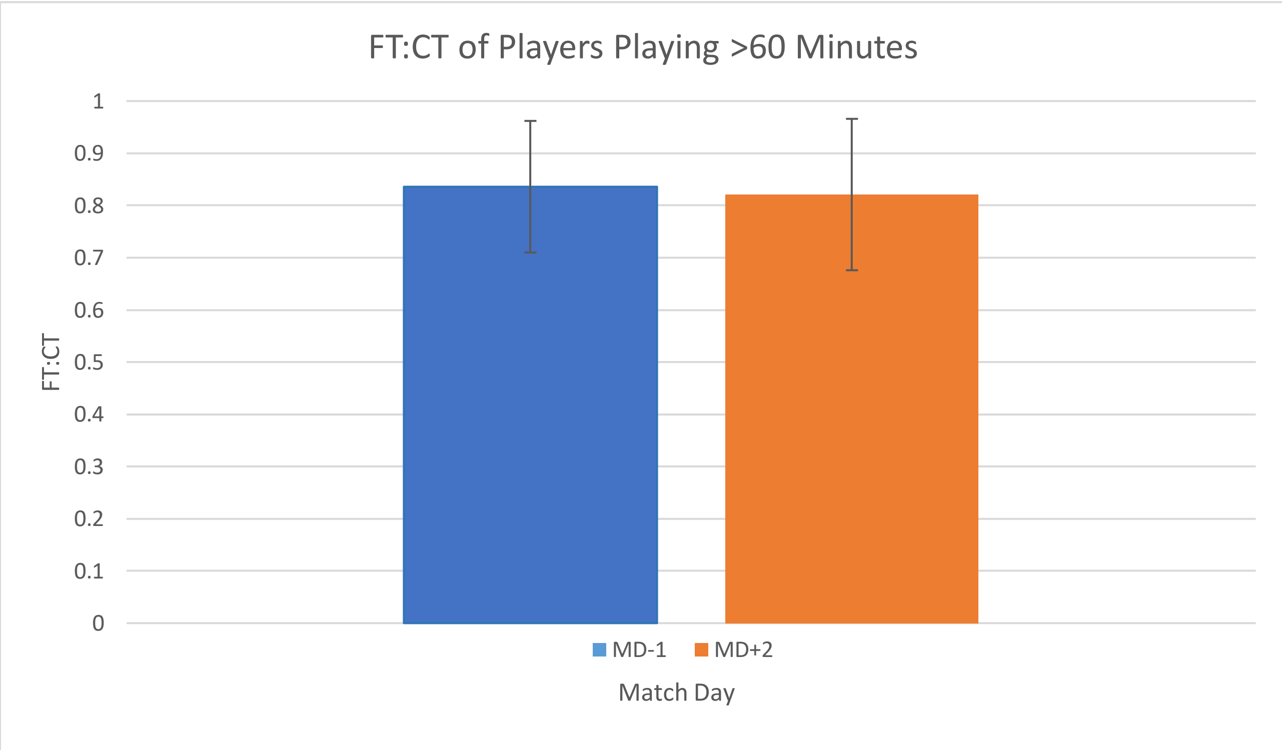


*Figure 18 - Graph displaying the mean FT:CT for MD-1 and MD+2 for players that played >60 minutes of each match. Error bars display standard deviation.*

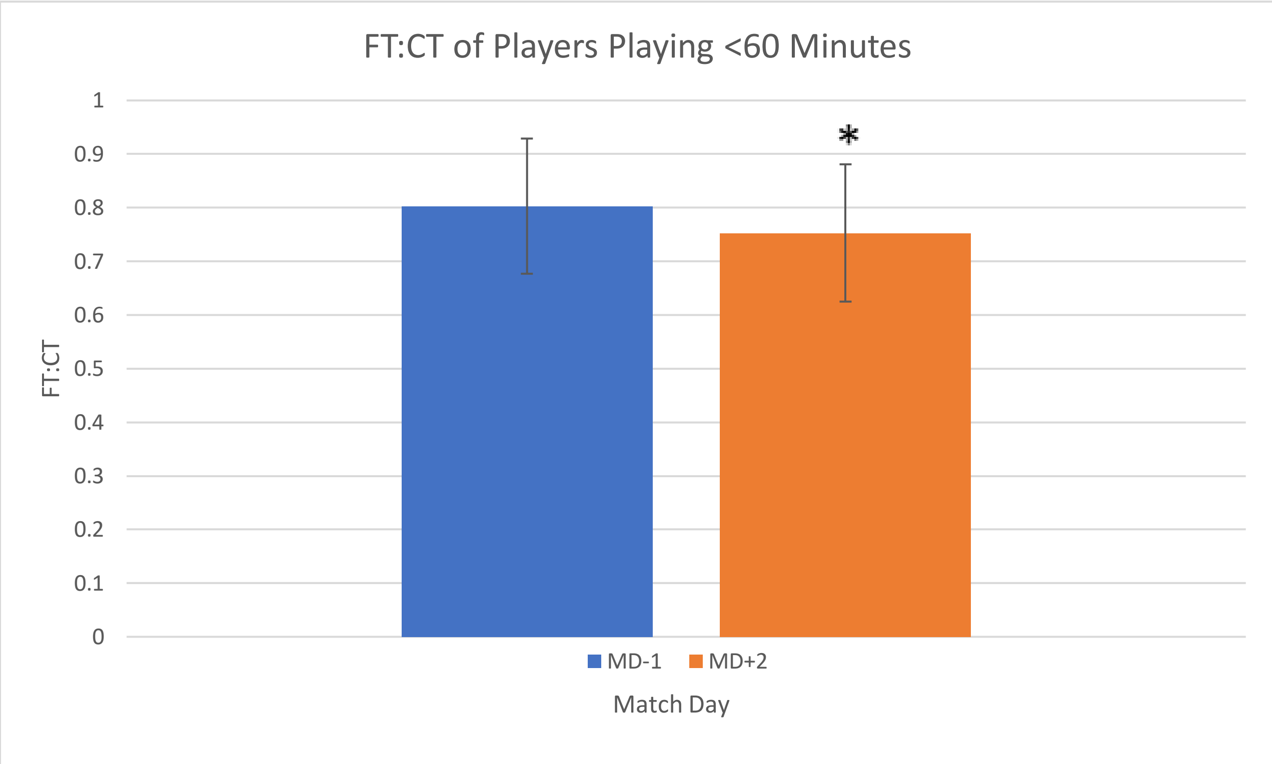


*Figure 19 - Graph displaying the mean FT:CT for MD-1 and MD+2 for players that played <60 minutes of each match, * denotes a significant difference (however, small sample size increases risk of type 1 and type 2 errors so this statistically significant difference could be due to an error). Error bars display standard deviation.*

# Discussion

## Main Findings

The main findings from this study were that when players played >60 minutes in matches, there was found to be no significant difference ($p > 0.05$) when comparing their Kvert during a 6-minute Yo-Yo test from MD-1 to MD+2 (Figure 16). In addition, it was also discovered that there was no significant difference ($p > 0.05$) between Kvert from MD-1 to MD+2 for players who played at CB, CM, WM, ATT and FB whilst playing >60 minutes Tables (4, 5 and 6). These results indicate that Kvert is not changed by the physical demands of soccer match play. It is suggested that in the future testing takes place on more days, such as MD and MD+1, as it could provide a clearer picture of the recovery process following matches and how Kvert is affected in relation to this. Different results could be obtained if the reason Kvert is not significantly changed from MD-1 to MD+2 is that players are fully recovered by MD+2. Therefore, testing on MD and MD+1 would provide further information regarding how the players Kvert is affected by match load. This is due to the possibility of players not having recovered during MD+1 but having recovered and not being fatigued by the time testing takes place on MD+2, such as in this thesis. Another possibility of what the results obtained show is that the measurement used to estimate Kvert is just too variable. This means that even if the match load aspect of the testing was taken away and the players were not fatigued, the measurement of Kvert may be too variable for any results to be valid. A possible test that could be done in the future to discover the variability of the measurement used to estimate Kvert is two pre match measurements taking place. Performing this test with the players would make it possible to look at the test – retest variation without any fatigue. The results of this test would provide further information on whether the estimate of Kvert using this method of testing is reliable and should be used in the future. Reliability of Kvert testing took place during the season, as mentioned in the methods, with data in the results section. It was discovered that the interday CV for Kvert was 16.32 ± 4.5%, which can be regarded as marginal to low reliability (Gathercole et al, 2015; Cormack et al, 2008; Sheppard et al, 2008). Taking these results into consideration, measuring Kvert via this method appears to be weak, however there were several limitations that will be discussed later that may have affected the results obtained. Findings from Morin and colleagues in 2006 and Girard and colleagues in 2011 and 2010 display that Kvert has potential to be used as a marker of fatigue, and as a result of the potential this form of testing has, I believe further research is warranted to discover more.

**Change in Vertical Stiffness for Whole Squad**

One of the aims of the study was to discover how Kvert was affected by match load, as well as how several jump variables were also affected by match load over the same time period. Several different discoveries have been previously made regarding how fatigue affects Kvert in athletes. For a group of 16 long distance runners, it was discovered that over the course of a 1-hour high intensity fixed pace run performed on a treadmill, the mean Kvert did not significantly change ($p > 0.05$). However, when analysing individual data, it was discovered that the Kvert of 8 participants significantly decreased from initial to final recording, whilst 7 remained the same and 1 significantly increased (Hunter and Smith, 2007). The results from Hunter and Smith's study display that inter-individual differences can occur between athletes when Kvert is being measured, with this result also displaying that there was no systemic and predictable effect. In this thesis' study it was discovered that no player that had played >60 minutes had a significant difference ($p > 0.05$) between their Kvert during MD-1 and MD+2 (Table 7).

As aforementioned, there was no change in Kvert for any players who played >60 minutes in matches from MD-1 to MD+2. In a further study by Dutto and Smith in 2002, it was discovered that during a run to exhaustion, Kvert decreased for a group of 15 trained runners ($p < 0.05$). However, similar to the Hunter and Smith study already mentioned, when looking at individual data, 11 participants had a significant reduction, 3 had a significant increase and 1 had no change in Kvert, once again displaying that inter-individual differences can occur (Dutto and Smith, 2002). Although the result of Kvert remaining unchanged for all players from MD-1 to MD+2 was not expected, there are some potential reasons why this was observed. One of these potential reasons is that athletes can adapt their movement strategies in order to maintain their Kvert at optimum performance levels after fatiguing exercise (Padua et al, 2006). This was shown as Kvert remained unchanged during a hopping protocol when comparing before and after fatiguing exercise, but peak hamstrings and anterior tibialis activation was reduced. This was in addition to gastrocnemius and soleus peak activity increasing and quadriceps-hamstrings and gastrocnemius/soleus-anterior tibialis coactivation ratios also increasing. This process, which leads to an ankle dominant control strategy, rather than relying on the knee musculature, has been hypothesised to lead to an increase in risk of knee injuries due to a lack of knee stability (Padua et al, 2006).

Different findings have been obtained in another study, however, where results were presented which involved 13 youth soccer players performing six 20m sprints with 20s of passive recovery in between. This study found there to be a significant reduction in Kvert ($p < 0.05$), however surface electromyographic activity was monitored for vastus lateralis, rectus femoris and biceps femoris muscles and changes in activity in these muscles were found to not be significant (Girard et al, 2011). It should be noted that the Padua and colleague's 2006 study consisted of hopping protocols however, as opposed to the Girard and colleague's 2011 study which consisted of sprints that took place on grass. It was addressed in Padua and colleague's 2006 study that although 2-legged hopping is not as relevant an exercise in soccer as other forms of movement, it is a form of testing that can be highly controlled and allows the neuromuscular response to fatigue to be analysed.

Another potential explanation for there being no change in Kvert from MD-1 to MD+2 for players that played >60 minutes is that the collection of data on MD-1 did not occur when the players were in their peak physical condition. This could be a result of the players being affected by fatigue due to the acquisition phase of the training week, which consists of building the training load up each day until MD-3, which is regularly the training session with the highest load, before the training load is reduced between MD-3 and MD (Los Arcos, Mendez-Villanueva and Martínez-Santos, 2017). The players would be closer to peak physical condition on MD prior to their match commencing, therefore potentially leading to a higher Kvert in comparison to MD+2. An example of the training load in a standard week can be seen in figures 10 and 11, which display the average distance and high-speed distance covered in the days leading up to a match. MD-3 and MD-4 have the highest figure for both parameters as expected, with this high load potentially impacting the physical condition of the players on MD-1.

It should also be considered that there was simply no effect and that is why the results show that there was no change in Kvert between MD-1 and MD+2. The possibility of this is supported by the rationale that several parameters return to baseline within 48 hours of the completion of a match and/or fatiguing exercise (Silva et al, 2013; McLellan, 2012). This theory could indicate that testing on MD+2 was too late for the Kvert measurement and that testing on MD+1 could have provided data that was more appropriate. However, testing of Kvert via the chosen method would not have been possible for MD+1 throughout the season due to players having the day off or players that played >60 minutes not being on the pitch on MD+1, therefore ruling out the possibility of the 6-minute Yo-Yo test. Had the players been available on MD+1, and with the Yo-Yo test not an option on this day, in future research another form of measuring Kvert should be considered. This would be a possibility due to Kvert being able to be calculated through the use of a force platform (Ryu and Murray, 2016). If this were to happen however, the problem of testing a whole squad of players on force platforms would arise again. A key advantage to measuring Kvert via the 6-minute Yo-Yo is the efficient use of time by being able to test a whole squad at the same time.

If a player's Kvert was shown to increase or decrease between MD-1 and MD+2, it should be noted that this result would not be as simple as stating that either of these outcomes would be completely good or bad, as it is considered by some that either too much or too little stiffness may lead to injury, however there is too little evidence to definitively confirm this (Butler, Crowell and Davis, 2003). This view stems from findings from a variety of studies, with one study consisting of assessing male and female athlete's ground reaction force data and kinematics. Over the course of the following year injuries were recorded for the group and although stiffness was not noted, the ground reaction force of the participants was recorded. It was discovered that the injured group had a greater ground reaction force than the uninjured group, leading to the suggestion that Kvert may have been higher in the injured group, due to a greater ground reaction force resulting in an increased Kvert (Hewett et al, 1996). In addition to this, it was also discovered that stress fractures were present in runners that exhibited increased peak ground reaction forces, which possibly led to increased Kvert, however due to vertical displacement of the centre of mass not being recorded during this study it is not possible to definitively confirm this (Grimston et al, 1991).

Some believe that there is no "optimal" Kvert for athletes and/or soccer players. This is a result of the specific demands of each position changing, as well as the limb length and body mass changing from player to player, and therefore affecting the Kvert that will be recorded from them during the completion of testing or in match play. It is however thought that an increase in Kvert is a positive, with an increase being associated with an increase in running economy (Dutto and Smith, 2002). Usually, athletes will adopt a stride rate that reduces oxygen cost at a given running speed, and this is the optimal stride rate due to it minimising the metabolic cost of running (Cavanagh and Williams, 1982). Therefore, if changes in stride rate are recorded, it can be considered that this can lead to a move away from optimal running strategy. In Dutto and Smith's study it was discovered that "decreased stiffness was accompanied by a decrease in stride rate", indicating that a lower stiffness would lead to a decreased running economy.

From the data that has been collected, the variation in the results is an issue and leads onto the discussion of how this could be reduced. In order for the measurement of Kvert to result in less variation there are several approaches that could be taken, with one possible option consisting of a more standardised pre-test routine. Although the players followed a similar pre-test routine for each Yo-Yo test, consisting of a jog and then static stretching which lasted 5 minutes in total, there could be an even further standardised approach. For example, the distance of the jog could be set to be the same for each pre-test warm up, as well as the exact same static stretches being performed, each lasting for the same length of time for each warm up. This could reduce the variation in the data due to the players not performing a slightly different warm up prior to each test. However, one study that recorded vertical stiffness via the sine wave method whilst participants ran on a treadmill discovered that vertical stiffness was not changed ($p > 0.05$) following participants performing three different stretching conditions. The study consisted of fourteen males performing 30s running bouts at 4.44m/s following static stretching, dynamic stretching, or no stretching. Running after dynamic stretching did however result in a significant increase ($p < 0.05$) in vertical ground reaction force. These findings display that a different warm up can influence lower-limb force production (Pappas et al, 2017). Pappas and colleague's study highlights the importance of having a set warm up as mentioned before for the whole squad to reduce variation in the testing. Using the Yo-Yo test as a method to record Kvert for a whole squad at once is a key advantage to this method of testing, with a whole squad of players being able to have data collected at once, rather than one at a time with testing such as the CMJ. It should be noted however that even if variations in the warm up prior to testing are a cause of variation in the data, it may not be productive to constrain the warm up that is performed prior to testing. If this type of testing is to take place regularly throughout the season with a set warm up being used in every instance prior to testing, this restricts the potential usefulness of the warm up for the players. The players may become disinterested by a warm up that is predictable, rather than not knowing what to expect before each training session.

Another option to reduce the variation of the data would be to change the test being performed to obtain Kvert to a more standardised test than the Yo-Yo, such as performing a drop jump from a set height onto a set of force platforms. This would take away the variation in how the players perform the test, as despite the players having guidelines to follow for completing the Yo-Yo test, they will inevitably run at different speeds at the same time points of the Yo-Yo test over the course of testing. In addition to changing the testing from a Yo-Yo test to a more standardised test such as a drop jump from a set height, another aspect that could be changed is removing footwear for the players. It was discovered that peak vertical ground reaction force was significantly different ($p < 0.05$) when performing two consecutive CMJs when performed wearing minimalist shoes and cushioned shoes. 21 physically active and healthy men performed this study, with a mean ± standard deviation score for the group being 36.2 ± 7.0N/kg when wearing minimalist shoes and 31.6 ± 5.4N/kg when wearing cushioned shoes (Malisoux et al, 2017). Although the participants of this study were not barefoot, the results obtained display how different footwear may affect jumping performance, and therefore by performing testing with no footwear this could reduce the possible variation caused by player's wearing different footwear.

A further change that could be made to the testing during the Yo-Yo test in order to obtain Kvert is moving the test indoors. This would reduce the variation in surface characteristics when comparing how outdoor surfaces will change throughout the year and even day to day, with changing temperatures and weather. By moving the testing to an indoor pitch, there would be no variation in the amount of water on the surface, whereas for outdoor pitches the amount of water will range and could affect the running mechanics of some players.

**Change in CMJ Variables and Correlation with Change in Vertical Stiffness**

The CMJ has been used for decades as a physical test of the lower extremities when assessing strength, power and/or fatigue, and has been shown to have a good reliability (Gathercole et al, 2015). It is a relatively easy and quick test to undertake, however when attempting to test a squad of 20+ players it can become quite time consuming. As a result of this, Yo-Yo testing of players to obtain a Kvert score on MD-1 and MD+2 was considered a potential replacement to the CMJ, with a full squad of players able to be tested in a far quicker way. This has the potential to save well over half an hour, as well as saving even more time by incorporating the Yo-Yo test into part of the warm up before the training session commences. Collecting Kvert and using this to monitor a player's level of fatigue would be strengthened by a correlation between CMJ variables and Kvert over the same time period.

In a study involving a similar cohort to this study, it was discovered that CMJ height was decreased for a group of 15 under-19 male elite soccer players when comparing their CMJ height 2 hours pre-match (36.31 ± 3.83cm) and then 48 hours post-match (34.11 ± 4.05cm), with an effect size indicating a moderate change (Hoyo et al, 2016). It has also been discovered that fatigue reduces Kvert in a group of 16 active males. When tasked with completing twelve 40m sprints with 30s of passive recovery, it was found that the Kvert was significantly decreased from the first to the last repetition ($p < 0.05$) (Girard, Micallef and Millet, 2011). During the 1st sprint, at the force plate which was placed 5-10m into the run, the mean Kvert was ~86kN/m for the group. This had a ~19% reduction to a mean Kvert of ~70kN/m for the group during the final sprint, once again recorded at the force plate which was placed 5-10m into the run. The results from Girard and colleague's study were presented in a graph with no exact figures reported, therefore rough mean values has been used when being discussed above. Although the participants from Girard and colleague's study were only tested on the same day as the fatiguing exercise, as opposed to being tested 2 days post-fatiguing exercise in Hoyo and colleague's study, it could still be conceivable that there would be a correlation between the reduction in both CMJ height and Kvert from MD-1 to MD+2 due to the match load experienced by players playing >60 minutes in the match. However, as stated earlier this did not occur.

The results of this study had differing results from the Hoyo and colleague's study. A significant reduction was observed for CMJ height in Hoyo and colleague's study, with CMJs being performed 2 hours pre-match (36.31 ± 3.83cm) and 48 hours post-match (34.11 ± 4.05cm). When CMJs were performed in this study 1 day pre-match (38.92 ± 2.6cm) and then 2 days post-match (38.6 ± 3.04cm), there was no significant difference between the CMJ heights. However, there are many varying recovery time periods for athletes in regards to CMJ height post-fatiguing activity. The CMJ height of elite youth soccer players who competed in an under 21 division 1 league in Greece was found to significantly decrease 24 hours post-match in comparison to optimum performance level, but when recorded 48 hours post-match there was no significant difference (Fatouros et al, 2010). This was also the case when 14 elite youth players competed in a match and had their optimum CMJ height from a week prior compared with their 24 and 48 hour post-match value. Once again it was discovered that there was a significant decrease 24 hours post-match, but no significant difference between optimum value and 48 hours post-match (Ispirlidis et al, 2008). The results from these two studies are comparable with this study.

Of all the results obtained and statistically analysed in this study, there was only one figure where a statistically significant change occurred. This can be seen in figure 19, where a significant decrease in FT:CT is present from MD-1 to MD+2 for players playing <60 minutes in matches, with an effect size of 0.4 indicating that this was a moderate change. This result was not expected, especially when considering the players that played >60 minutes showed no change in FT:CT when comparing their CMJs from MD-1 and MD+2 (Figure 16). It was mentioned in the results section however that this could be due to the small sample size of the study, with a far larger sample size being required to reduce the risk of type 1 and type 2 errors occurring.

There are a number of potential reasons for this finding. Firstly, the players who played <60 minutes, on occasion, trained on MD+1 and therefore the training load from this training session may have affected their jump performance. Flight time has been shown to decrease following soccer related activity for youth soccer players whilst contact time was shown to be unchanged (Oliver, Armstrong and Williams, 2008). This is likely due to the submaximal and maximal SSC exercise undertaken, as well as frequent acceleration and deceleration throughout the exercise which is present in the training and matches of the players in this study. However, it should be noted testing took place directly after the completion of exercise in Oliver and colleague’s study. On occasion, the players that had played <60 minutes in the match completed a training session the following day to elicit a training load that would be similar to participating in >60 minutes of a match. This meant that all the players would then be in their taper phase the following day following the completion of a large training or match load in the previous days.

Another potential factor as to why this result occurred is that there was a far lower number of players who played <60 minutes in matches in comparison to the number of players who played >60 minutes.

This led to a lower number of participants being included in the statistical analysis when comparing MD-1 and MD+2 FT:CT. This meant that there was a larger possibility of a single player distorting the results in the <60 minutes group, as well as the statistical outcome not having as much power as the finding regarding the players playing >60 minutes.

A crucial factor in the study relates to the players performing to their maximum each time they were tested, with this being explained to the players prior to the first week of testing. This is important for both the Yo-Yo test and the CMJ, however it is more relevant to the CMJ. For the Yo-Yo test the players were expected to hit the target points on the beep. They were observed and if any were not seen to be doing this, it would be communicated to them throughout the test. This unfortunately does not give certainty that the players were completing the test in a fully standardised way. Even if players were reaching the line at the required time of the beeps, they may have used a different style of running to reach the line in time for the beep. For example, a player may accelerate sharply at the start of the 20m run and then run at a constant speed until decelerating, where as another player may accelerate at a slower rate and not reach a constant speed before decelerating.

A 6-minute Yo-Yo test was used when recording the Kvert as the players in the squad were familiar with this test from pre-season training in the season of data collection and in the season prior to that. Because the test was familiar to the players, it was decided it would be used for analysing their running mechanics. However, for future testing it may be beneficial to use a single 40m shuttle with just one 180-degree change of direction, rather than the Yo-Yo test which includes several 180-degree changes of direction. The changes of direction have an impact on the running mechanics of the players and hence the single shuttle with just one change of direction would eliminate the impact this has on the Kvert recorded for each player.

**Variation in Data**

As can be seen in figures 10 and 11, the variation in some of the data is large for certain training days and small for others. In figure 10, analysing the mean distance covered during training, the standard deviation is large for MD-5 and MD-4, whereas for the remaining training days the variation is small. In figure 11, analysing the mean high-speed distance, the standard deviation is large on MD-3 and small for the remaining training days. A possible reason for these differences is the type of training drills being performed by the players. On a MD-3 the players would usually accumulate the highest high-speed distance, with a common drill contributing to this being small sided games but played in a large area of the pitch. The high-speed distance covered would be affected by the position being played in these small sided games, with FBs covering more distance at higher speed thresholds than CBs. This would agree in part with the results obtained by Oliveira and colleagues who collected GPS data throughout an in-season period from 19 elite soccer players. They discovered that during the 1st mesocycle, FBs covered a significantly higher distance at high speed (>19km/h) in comparison with CBs ($p < 0.05$). Regarding distance covered, in the same mesocycle the results showed that FBs and CMs covered a significantly further distance than WMs ($p < 0.05$) (Oliveira et al, 2019). It should be noted however that in the remaining 9 mesocycles there was no significant difference between player positions for distance covered and high-speed distance covered.

Another explanation of the large variation in data is that the test-retest reliability was low. Some measurements are intrinsically more variable than others, with this applying to the measurement of Kvert via the 6-minute Yo-Yo test. The low reliability means that a far larger data set would have been required for there to be the possibility of statistically significant results to occur. Power calculations were performed after the data had been collected and are included in the results section (Table 3). The power calculated in reference to the change in Kvert from MD-1 to MD+2 for players that played >60 minutes was 0.05, which displays that a far larger sample size would have been required for the probability of avoiding a type II error to be reduced. The large increase in sample size would create a significant amount of additional testing, with a far longer time period being necessary or for multiple squads to be tested. Taking this into account, the additional info that could be obtained does not justify the extent of the additional testing that would be necessary to achieve this.

**Limitations**

There were some limitations that should be noted when considering the results obtained. One of these limitations, that has been referred to earlier, is that players were tested on MD-1 over 24 hours prior to their matches, as opposed to being tested on the MD in the hours leading up to each match. The MD-1 data collection was as close as possible to recording the players in their optimum physical condition, as data collection on MD was unfortunately not possible. Moreover, it would have been beneficial to collect the same data as MD-1 and MD+2 on each MD in the hours after the completion of each match and also on MD+1, giving a clearer picture of the player's recovery timeline. However, the players usually had a day off on MD+1, and when they were in on MD+1 all players that had participated in >60 minutes of the match were based solely in the gym. This meant that there was no possibility of performing the Yo-Yo test with them and therefore Kvert could not be recorded as a result. This combination of reasons resulted in there being no possibility of testing taking place on MD+1 consistently throughout the season and timeframe of the study.

In addition to this, testing was not possible on MD as mentioned previously, due to equipment not being able to be transported to matches and coaches not allowing the submaximal Yo-Yo test to take place in the hours leading up to matches or the in the hours following each match. Without any data collection on MD, both before and after the match, and on MD+1, only estimations can be made as to what the data would have shown. The results that are obtained in this study either indicate that CMJ testing and recording of Kvert on MD-1 and MD+2 in the format used are not able to monitor the level of neuromuscular fatigue in elite youth soccer players, or that the players have fully recovered by the time of testing on MD+2. Unfortunately, MD+1 testing, which did not occur, would have given a clearer picture of the recovery process of the players and could have provided evidence that the players were potentially recovered once MD+2 testing took place.

Another issue was the lack of any control subjects in the study, but as a result of the data collection taking place in an elite sporting environment there was no possibility of there being a control group. Due to the study taking place within an elite sporting environment, it also meant that the study size was fairly small, especially when analysing data for certain positions. Preferably, there would have been a greater number of participants resulting in the statistical power of the results being stronger, but this was not possible. In addition, the study would have been aided by further data collection but due to the constraints of when the season took place for the squad in question this was not possible. The study would have been aided by matches taking place on a weekly basis and therefore allowing more data to be collected, however matches were more infrequent than each week for the majority of the season. As a result of this, there was a lack of data for individual players as many only played >60 minutes in one game or in many cases just two or three games which led to weak statistical power when statistical analysis took place in regard to individual players.

In terms of technological limitations, it would have been beneficial to have used the same GPS unit for each player for the length of data collection. Due to a lack of units being able to be assigned to individual players in the reserve squad that were involved in the study, as well as units malfunctioning and having to be sent away to be repaired, it meant that some players did not have the same GPS units for the whole study. As there was a lack of GPS units, every match and day of data collection consisted of usually around 1-4 players using a spare 1st team player's GPS unit. The units that were switched for players were given to players that usually played <60 minutes. The units were set up in the exact same way and had the same threshold values for all variables, however this does not necessarily mitigate all errors. Unfortunately, this issue was outwith my control and may have had an impact on the results, with the results of identical GPS units being found to be different despite having travelled at the same speed and distances as one another, as was discussed earlier (Buchheit et al, 2014).

Some studies have discovered that intra unit reliability of GPS units is good, such as Castillo and colleague's study which contained results that showed an ICC of between 0.935 and 0.984 when GPS units were used to measure velocity during linear, circular and zig-zag movements at walking and sprint speed (Castillo et al, 2018). These ICC values indicate excellent reliability (Koo and Li, 2016). However, in another study which consisted of female soccer players completing a 20m shuttle run test, it was discovered that in the second and third stage of the test the intra unit reliability of the GPS units was moderate, with an ICC of 0.718 (Nikolaidis et al, 2018). Certain GPS units malfunctioning also led to a loss of data for some parts of the study which led to data being lost that could have been used in the statistical analysis and resulted in greater statistical power for certain results.

Another limitation of the study was that any change of player's mass was not included. This is an issue due to the study period being 6 months and therefore the player's mass may have changed during this time. In future this information should be collected on a more regular basis as body mass is included in the equations that are used to calculate Kvert through the use of ADI. In addition to this, during the 6-minute Yo-Yo test, Kvert for each player was calculated as their average Kvert during the 6 minutes, which included whenever they turned. The turning mechanics will have had an effect on their average Kvert during the test and therefore in future when this test takes place, the average Kvert of each player should only include the periods of the test where they are running in a straight line. Another limitation that was briefly discussed during the introduction is the varying extent to which the submaximal 6-minute Yo-Yo test is actually "submaximal" for players. As players have different max speeds, the ~17km/h top speed during the Yo-Yo test will be a different percentage of max speed for players as a result. In the current study, the lowest max speed of the squad was 30.8km/h in comparison to the highest being 33.4km/h. When comparing these two speeds, it would mean a player is running at 55.2% or 50.9% of their max speed respectively if running at 17km/h.

**Future Directions**

A further limitation of the study was that the amount of data collected was limited, both in terms of the number of players and the time points, with less data being collected by the end of the season than was originally planned. This was a result of there being an unexpectedly reduced number of matches for the squad in the season that data was collected. Unfortunately, there were often only matches once every three weeks, as opposed to the 1st team who would regularly have two and sometimes even three matches in a week. Prior to the study commencing it was expected that the squad would have several friendly matches to add to their league and cup matches, however this did not occur to the extent that was expected, resulting in the time points included in study being reduced.

Having a smaller sample of matches means that it becomes more difficult to distinguish between significant change and non-significant change. It is not possible to change the playing schedule of a team to suit testing such as the testing that has taken place in this study, and the testing must be designed to work around the playing schedule. Therefore, the frequency of matches during the period of data collection was far less than anticipated. As has been mentioned previously with the power calculations, the amount of data that was collected was far less than what was required for any statistically significant results to be found with the methods of data collection that were in place. A consequence of this reduced data set means that less reliance can be placed on the results of the study. A possible direction that could be taken in future would be to perform another study with various age groups throughout the academy of a club, which would therefore increase the volume of data that could be collected, and to ensure that a full season of data is collected rather than data collection commencing after the season had already begun.

Looking forward, it should be considered whether the Yo-Yo test is a worthwhile test to perform with a squad of players several times a week to obtain a Kvert score. Although the test is submaximal, towards the end of the test the speed is increased to around ~17km/h, and around 800m is covered by the players during the test. It may be considered that the load placed upon the players as a result of this test happening throughout the season is unnecessary. The application of the testing in the real world of sport needs to be considered in great detail, with keeping players satisfied and avoiding unnecessary load during testing being a priority. If the 800 metres that is covered during each test is added up over a whole season, this becomes a significant distance that the players are covering.

In an ideal world, there are several key components of the study that I would have performed differently. Firstly, I would have collected the heart rates of the players performing the Yo-Yo test, as this metric has been shown to have good reliability when being collected during the submaximal Yo-Yo test (Owen, Jones and Comfort, 2017). The results from Owen and colleague's study showed that the HR at the end of the 6-minute test was the most reliable metric, with an ICC of 0.93. Unfortunately, the heart rate monitors that were used by the reserve squad were not reliable enough to be used, with it being highly unlikely that enough quality data would have been collected during the study due to malfunctioning HR monitors.

An issue with relying on the submaximal 6-minute Yo-Yo test to collect Kvert data is that this method of data collection has not been confirmed as being reliable previously, regarding the collection of Kvert. The gold standard measure of Kvert is to use force plates within treadmills, however this was not possible when collecting data from a squad of elite youth soccer players. Looking forward, a more valid and reliable test than the Yo-Yo should be utilised when collecting the Kvert data.

## Conclusion

In conclusion, the aim of this study was to discover how the Kvert of elite youth soccer players was affected during a 6-minute sub maximal Yo-Yo test by match load, with a comparison being made between MD-1 and MD+2. In addition to this, there was an aim to discover if there was a correlation between the change in Kvert from MD-1 to MD+2, and the change in FT:CT whilst performing a CMJ over the same time period.

It was discovered that there was no significant change in Kvert from MD-1 to MD+2 for the group of players tested, as well as there being no significant change when players played >60 minutes. Moreover, there was no correlation between the change in Kvert from MD-1 to MD+2 and the change in FT:CT on the same days of testing. The results from this study indicate that measuring Kvert as a direct replacement of CMJ testing would not be recommended. There were limitations that have been mentioned previously that affected the study, with a key factor being the lack of data collected over the time period of testing due to multiple different reasons. Unfortunately, this resulted in weak power when statistically analysing the results, and a far larger group of data would have been beneficial. Due to the limitations of the study and the results from various other studies such as from Morin and colleagues in 2006 and Girard and colleagues in 2011 and 2010 which discovered Kvert is affected by level of fatigue, I believe further research is warranted due to the potential of using Kvert to monitor neuromuscular fatigue of large groups of players simultaneously. It is however recommended that further research focuses on obtaining Kvert in another method than during the 6-minute Yo-Yo test, due to the significant load this places on a squad of players over the course of a season if performed multiple times per week.

# Appendix

| Player Number | Game Number | Kvert MD-1 | Kvert MD+2 | FT:CT MD-1 | FT:CT MD+2 |
|---|---|---|---|---|---|
| **1** | 1 | 24.38 | 24.53 | 0.97 | 1.06 |
| **2** | 1 | 44.26 | 37.36 | 0.7 | 0.78 |
| **3** | 1 | 42.32 | 41.46 | 0.96 | 0.74 |
| **1** | 2 | 25.12 | 25.08 | 1.03 | 0.87 |
| **4** | 2 | 40.18 | 35.89 | 0.85 | 0.91 |
| **5** | 2 | 36.05 | 30.24 | 0.61 | 0.68 |
| **6** | 2 | 37.63 | 30.94 | 0.68 | 0.67 |
| **7** | 2 | 28.56 | 26.69 | 0.89 | 0.9 |
| **3** | 2 | 42.61 | 37.11 | 0.85 | 0.9 |
| **8** | 2 | 25.73 | 20.74 | 0.84 | 0.86 |
| **6** | 3 | 32.12 | 35.74 | 0.75 | 0.81 |
| **2** | 3 | 34.43 | 37.34 | 0.74 | 0.84 |
| **9** | 3 | 39.02 | 41.73 | 0.76 | 0.67 |
| **8** | 3 | 22.91 | 22.82 | 0.87 | 0.8 |
| **1** | 4 | 22.99 | 23.98 | 1 | 0.93 |
| **6** | 4 | 32.7 | 32.49 | 0.81 | 0.8 |
| **9** | 4 | 38.87 | 38.48 | 0.68 | 0.72 |
| **7** | 4 | 26.88 | 25.94 | 0.88 | 0.97 |
| **3** | 4 | 38.45 | 37.47 | 0.99 | 0.95 |
| **8** | 4 | 21.94 | 22.8 | 0.82 | 0.76 |
| **6** | 5 | 37.74 | 33.12 | 0.79 | 0.71 |
| **1** | 6 | 22.16 | 22.56 | 0.99 | 0.97 |
| **4** | 6 | 37.09 | 39.1 | 0.75 | 0.35 |
| **6** | 6 | 29.48 | 32.11 | 0.96 | 0.97 |
| **3** | 6 | 37.09 | 36.03 | 1 | 1.03 |
| **10** | 6 | 24.64 | 26.22 | 0.6 | 0.75 |
| **11** | 7 | 24.24 | 26.84 | 0.78 | 0.75 |
| **1** | 8 | 21.69 | 23.74 | 0.9 | 0.97 |
| **12** | 8 | 27.13 | 28.81 | 0.64 | 0.62 |
| **4** | 8 | 33.39 | 37.08 | 0.89 | 0.86 |
| **6** | 8 | 31.78 | 32.81 | 0.87 | 0.83 |
| **13** | 8 | 24.99 | 24.57 | 0.71 | 0.67 |
| **3** | 8 | 39.24 | 38.68 | 1.03 | 0.99 |

*Table 4 - Data for players that played >60 minutes*

| **Player Number** | **Game Number** | **Kvert MD-1** | **Kvert MD+2** | **FT:CT MD-1** | **FT:CT MD+2** |
|---|---|---|---|---|---|
| **14** | 1 | 26.69 | 25.87 | 0.81 | 0.76 |
| **2** | 2 | 36.37 | 35.14 | 0.88 | 0.8 |
| **13** | 2 | 27.56 | 26.27 | 0.63 | 0.58 |
| **1** | 3 | 26.66 | 24.27 | 0.95 | 0.93 |
| **14** | 3 | 25.78 | 28.43 | 0.82 | 0.8 |
| **15** | 3 | 29.84 | 25.85 | 0.55 | 0.48 |
| **16** | 3 | 28.65 | 28.98 | 0.81 | 0.83 |
| **7** | 3 | 26.05 | 26.23 | 0.96 | 0.86 |
| **10** | 3 | 25.07 | 26.18 | 0.74 | 0.74 |
| **4** | 4 | 40.71 | 34.88 | 1.03 | 0.92 |
| **17** | 4 | 26.12 | 22.11 | 0.83 | 0.78 |
| **2** | 4 | 35.93 | 33.07 | 0.86 | 0.8 |
| **16** | 4 | 28.77 | 27.44 | 0.74 | 0.78 |
| **10** | 4 | 25.86 | 26.15 | 0.71 | 0.67 |
| **15** | 8 | 32.61 | 34.28 | 0.73 | 0.57 |

*Table 5 - Data for players that played <60 minutes*

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