The association and differences of various lower body athletic performance metrics in adolescent male football and volleyball athletes

by

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ABSTRACT

The countermovement vertical jump (CMVJ) is considered a primary indicator of lower body muscular power producing capability and has strong positive relationships with field and court sport performance. Performance in the CMVJ is influenced by multiple physiological and anthropometric factors. The aim of this study was to examine the relationships between CMVJ height, peak lower body force production (Fmax), resisted sled sprint power output (RSS) and fat free body mass (FFM) among male football (FB) and volleyball (VB) players aged 16-18. The study (n=68) included two participant groups (FB group n=33, VB group n=35) all being assessed on CMVJ height (cm), lower body Fmax (N) via isometric back squat test, peak power production (W) via RSS, and FFM (kg) via bioelectric impedance analysis. Participants groups were examined for significant between-group differences with an independent t-test while Pearson product moment correlations between CMVJ height, Fmax (N, N/kg, and N/kg FFM), RSS (W, W/kg, and W/kg FFM) and FFM were calculated. FB group means for body mass and FFM (87.02 ± 17.02 kg; 68.27 ± 8.61 kg, respectively) were significantly higher ($p < 0.05$) than the VB group (73.95 ± 5.71 kg, 63.84 ± 4.92 kg, respectively). CMVJ height (cm) was significantly higher in the VB group compared to the FB group (52.40 ± 11.28 cm vs. 34.03 ± 8.23 cm; $p < 0.05$). Significant positive relationships between CMVJ height and Fmax (N/kg) were present among both participant groups (FB: r=0.67; $p < 0.05$) (VB: r=0.52; $p < 0.05$). FFM had a significant negative relationship with CMVJ among FB group participants (r=-0.46; $p < 0.05$), there were no significant relationships between CMVJ height and RSS performance ($p > 0.05$). The results of this study suggest that relative lower body maximal force producing capabilities have a strong, significant correlation with CMVJ performance among FB and VB athletes. Further, findings suggest that relative Fmax scores by FFM in lieu of body mass does not strengthen the relationship with CMVJ height.

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Chapter 1 – Scientific Framework

1.1 Introduction

The ability to perform maximum effort bouts of sprinting and jumping in multiple planes are crucial to performance in field and court sports such as football and volleyball (Montalvo et al., 2021). Countermovement vertical jump (CMVJ) ability has been identified as an accurate indicator of future success among football athletes (Daugherty et al., 2021), as this movement occurs frequently in field sports (Montalvo et al., 2021). The CMVJ is a commonly used measurement for lower body vertical power production, and is considered by both researchers and practitioners to be a necessary skill in developing both jump and sprint performance (Montalvo et al., 2021). Vertical jump performance is also considered a key indicator of success across all levels for both male and female volleyball players (Sattler et al., 2015). This indicates that using the CMVJ is a valid means of identifying potential sport performance in both football and volleyball athletes.

Work by (Thompson et al., 2013) has shown that relativizing lower body peak force values resulted in significantly improved relationships with CMVJ performance when compared to absolute lower body peak force values among collegiate male football players. This coincides with findings by Ferreira et al. (2010) that higher levels of relative strength can induce increased power output leading to a positive increase on CMVJ performance. Work by Tønnessen et al. (2011) has shown a significant positive relationship between CMVJ and sprint performance. Findings from this study show that improvements in 40m sprint performance (decreased time to complete a 40m maximal sprint) were accompanied by significant improvements in the standing CMVJ among young male soccer players. This implies a reciprocal relationship between CMVJ and sprint ability, in that improvement in one may positively impact performance in the other. In a study by (Daugherty et al., 2021) vertical impulse (the product of the force exerted vertically in to the ground, or ground reaction force and the duration of the force application which leads to upward propulsion of the body) was found to be a valid predictor of CMVJ ability when relativized to body mass. Further, positive associations between vertical impulse and sprint ability have been reported in previous investigations (Kirby et al., 2011). These findings demonstrate evidence of a positive relationship between CMVJ and sprint ability and can therefore be described as complementary physical traits. Research by Ferreira et al. (2010) has shown that high body fat levels have a negative impact on CMVJ performance. This is due to increased body mass that lacks contractile function decreasing lower body relative strength and power output. Additionally, body fat levels have demonstrated a negative relationship with CMVJ performance, while fat free body mass has shown a small positive relationship with CMVJ height (Bosak & Carver, 2020).

Multiple studies have examined the relationship between sprint performance and other markers of lower body power such as the CMVJ. However, there is less known about resisted forms of sprinting and how these compare to CMVJ performance. When the resisted sled sprint exercise (RSS) is performed with lighter loads, notably those equal to 10-30% bodyweight, it is reflective of the speed-strength portion of the force velocity curve (Cahill et al., 2020). This differs from the low-force high-velocity profile of unresisted sprinting and can provide further insight to the power output ability of an athlete (Cahill et al., 2020). Limited research exists comparing speed-strength movements in the horizontal plane (such as RSS) to vertical plane (CMVJ) performance.

Studies by Asmundson (2019) and Peterson et al., (2006) have examined the relationship between lower body relative strength and CMVJ performance, however these studies involved the isometric mid-thigh pull and barbell back squat, respectively. Previous work by Weiss et al., (2006) examined the relationships between multiple markers of lower body strength and power as well as body composition and standing CMVJ. Recommendations of this study suggested further inquiry into the individual differences in CMVJ performances, however this study only involved resistance trained men, and did not factor in any discrepancies in athletic backgrounds. Research by (Bosak & Carver, 2020) has shown relationships between body fat levels and CMVJ performance, however these relationships were relatively low and it was suggested by the authors to further investigate the individuals differences that may lead to altered CMVJ performance. Further, this study only examined female volleyball athletes and did not include any multisport disciplines. Given that power output and body composition are two critical variables to athletic performance (McDowell, 2021), the relationships between these and CMVJ must be explored and compared. Therefore, the aim of this present study is to examine the correlations between both physiologic and anthropometric variables, specifically lower body peak force production, resisted sprint performance, and fat free mass and how they relate to CMVJ performance in male volleyball and football athletes.

1.2 Review of Literature

1.2.1. Acute Neuromuscular Response to Exercise. The maximal force producing capabilities of a muscle can be augmented significantly through lengthening or shortening of the muscle's fibres. Research suggests this is related to the amount of overlap between actin and myosin filaments in the muscle fibre (Cudicio et al., 2022). This principle, referred to as the sliding filament theory (Huxley & Niedergerke, 1954) states that the shortening of the fibers during muscular contractions are a result of myosin filaments binding to actin filaments pulling them together. This theory has been since challenged in research, however, is widely accepted as the primary mechanism of skeletal muscle contraction.

1.2.1.2. Motor Unit Recruitment. Motor unit recruitment is the ability of the central nervous system (CNS) to activate contractile units of the muscle during a voluntary contraction (Del Vecchio et al., 2019). This is often viewed as one of the first adaptations to occur from resistance training, as opposed to structural change within the muscle fibre. Increases in motor unit recruitment leads to increased force producing capabilities as well as the muscle's rate of force development. This is notable for performance of dynamic movements such as jumping and sprinting, as they require the muscles to produce high levels of force in relatively short time periods. Performance of these dynamic movements involves recruitment of predominately type II motor units, as these motor units are involved in higher velocity and intensity muscle contractions (Houtman et al., 2003). Further, when examining muscle damage following high intensity plyometric exercise - most damage occurs within type II muscle fibres, implying that those muscle fibers were recruited to perform the requisite contractions (Macaluso et al., 2012).

1.2.1.3. Length-Tension Relationship of Skeletal Muscles. The force producing capabilities of skeletal muscle is dependent on the length of its fibres. As per the sliding filament theory, as a muscle contracts and shortens, the actin and myosin filaments begin to slide and overlap each other. While this overlap initially aids in force production as a muscle moves from a lengthened position, a point occurs in the shortened fibre where there is so much overlap that force production subsequently decreases. This forms a force-length curve in both a single muscle fibre as well as a whole muscle. While they have similar principles, the force-length curves of muscle fibres and whole muscles do differ. Where the force-length curve of a muscle fibre is entirely influenced by myosin cross-bridges, whole muscle force curves are influenced by other factors such as contractile properties, fibre type, fibre pinnation and tendon properties (Brughelli & Cronin, 2007).

1.2.1.4. Types of Muscle Contractions. There are three main types of muscle contractions. 1) eccentric – where the muscle fibres are being lengthened and resisting some degree of force, 2) isometric – where the muscle fibre length remains constant while resisting force; and 3) concentric – where the muscle fibres shorten against a load. The force producing capabilities of the muscle at any point throughout these contraction types is dependent on factors such as the force-length curve as well as the force-velocity relationship of the muscle. The force-velocity relationship of a muscle describes the inverse relationship between the velocity of a muscular contraction (m/s) and the amount of force (N) that is produced by the muscular contraction (Cahill et al., 2020).

1.2.1.5. Exercise Induced Neuromuscular Fatigue. Participation in maximal effort exercise can elicit high amounts of fatigue both locally within the active muscles (peripheral fatigue) as well as a reduction in the ability of the central nervous system (CNS) to recruit active muscles (central fatigue) (Carroll et al., 2017). After high intensity exercise, there is a restoration of CNS ability due to dissipation of central fatigue in about two minutes, while decrease in peripheral fatigue and restored muscle function may take upwards of three to five minutes (Carroll et al., 2017). It should be noted that complete muscular recovery may not occur for several hours due to prolonged impairment of intracellular Ca^{2+} release or sensitivity (Carroll et al., 2017). Given this information, maximal effort plyometric exercises such as sprinting and jumping should be followed by a full recovery of at least three to five minutes when being assessed as a measure of power producing capability.

1.2.2. Plyometric exercise. Plyometric exercises refer to movements that utilize the stretch-shortening cycle (SSC) of a muscle or muscle group. The SSC involves a rapid eccentric lengthening phase, followed immediately by a rapid concentric contraction of the same muscles. The SSC results in increased levels of power and force production in the activated muscles. A crucial aspect of plyometric exercise and the SSC is the deliberate effort to have the amortization phase (the time between eccentric and concentric contractions) as brief as possible. This ensures that the increased power and force producing capabilities elicited by the SSC are present. The CMVJ and sprinting are two commonly used plyometric exercises.

1.2.2.1. Countermovement Vertical Jump. In a CMVJ, the jumper starts in a standing upright position and begins the preliminary portion of the movement by flexing at the hip, knee and ankle joint. This is followed by a vigorous triple extension movement at each joint to propel the body's centre of mass in an upward direction. The CMVJ movement is an example of the SSC, where the desired motion is preceded by movement in the opposite direction. During the CMVJ, the jumper must overcome the combined forces of their bodyweight and downward acceleration of their centre of mass eccentrically before concentrically propelling themselves upward. The CMVJ is considered an example of a slow SSC movement (>250 milliseconds). The amortization phase of a CMVJ is similar to that of maximum velocity sprinting, and the two variables have been shown to be related (Cronin, 2005). It is by this SSC profile as well as the ground reaction forces involved with a CMVJ that make it a more relevant test for measuring athletic performance, as these variables more closely mimic the movements performed in a sport environment - sprinting, jumping, and cutting (Linthorne, 2001). Due to this, the CMVJ is one of the most widely utilized tests for monitoring and assessing athletic performance.

Testing of the CMVJ as a means of measuring physical performance dates back to the early twentieth century with the Sargent Test, named after its creator Dudley Allen Sargent – a prominent figure in the United States' physical education system during this time. The initial protocol for this test involved the participant performing a CMVJ and touching a cardboard disk with the top of their head at the highest possible point. The calculated difference between the participants standing height and the maximum height achieved on the test was their CMVJ score (Sargent, 1921). This test was implemented into physical testing curriculum as it was believed that the ability to overcome the gravitational forces of one's own bodyweight was a prime marker of physical fitness (Sargent, 1921). More recently, the CMVJ has been identified as a fundamental motor skill, and the ability to perform such a test serves as a standard for measuring physical development of children and young adolescents (Gallahue & Ozmun, 1998). Over one hundred years later, the CMVJ is still utilized as a tool for evaluating athletic performance – though numerous alternative testing procedures have since emerged in research.

Multiple means of CMVJ performance measurement exist in the literature, ranging from those set forth by Sargent (1921), to more advanced methods utilizing kinematic calculations, motion capture and force plate measurement (Montalvo et al., 2021). Among the most common methods are the flight time method, the vertical reach method, and force platforms. The force platform is considered by many the "gold standard" of CMVJ measurement due to its direct kinematic analysis, though these platforms are often only found in laboratory settings and may lack accessibility in practical settings for many strength and conditioning practitioners. The Vertec Vertical Jump Tester (Sports Imports, Columbus OH) is one of the most common used pieces of equipment for CMVJ field testing among collegiate and commercial fitness facilities. This system involves having the participant perform the jump while reaching up and swiping the highest point possible in a series of plastic swivel vanes. The participants maximum standing reach is then subtracted from the highest point touched, and jump height is calculated (Whitmer et al., 2015). Equipment such as a vertical jump mat have become more prevalent in CMVJ testing, this is due to the fact that similar to a force platform, the jump mat systems calculate CMVJ height using flight time as opposed to a standing reach. This method allows for quicker feedback on CMVJ performance as the device provides the participants score immediately upon completing the jump. CMVJ from both the jump mat and Vertec have shown to be favorably comparable (Forsythe, 2012; Whitmer et al., 2015), however both the Vertec and jump mat method display a tendency to overestimate CMVJ height when compared to the force platform, suggesting that the force platform method may be the most precise means of measuring CMVJ performance (Whitmer et al., 2015).

1.2.3 Rate of Force Development The rate of force development (RFD, $N \cdot s^{-1}$) describes the time it takes a muscle to reach peak torque values following the onset of a muscular contraction (Thompson et al., 2013). This development of maximal force in minimal time is often measured and used as an index of explosive strength (McLellan et al., 2011). In a study measuring RFD and peak lower body force production (Fmax) during CMVJ tests among physically active adult males, McLellan et al. (2011) found that both RFD and Fmax have a significant positive relationship with CMVJ height scores ($r=0.68$, $p<0.001$; and $r=0.51$, $p<0.05$ respectively). Results of this study illustrate a bi-directional relationship between RFD, Fmax and CMVJ performance, wherein higher levels of performance in both RFD and Fmax contribute to improved CMVJ performance, and vice versa. The authors also include that incorporating an arm swing action to the CMVJ movements increased relevancy to sport movement. Given that both volleyball and football include dynamic movement of the lower and upper limbs, CMVJ tests among athletes in these sports may benefit from inclusion of an arm swing.

Research findings have shown RFD to be significantly related to performance of dynamic lower body movements such as sprinting, jumping and change of direction and therefore can have implications on CMVJ performance. Improvements in RFD are believed to be a contributing factor to improved sprint performance as discussed in a previous study by Boone et al., (2021). As RFD is described as one of the primary indicators of CMVJ performance (Daugherty et al., 2021), it can be assumed that improvements in RFD in the lower limbs will lead to improvements in both sprint and CMVJ performance. RFD can be measured in multiple ways, however when measuring it within the context of the CMVJ, a force plate is often used. In order to calculate the RFD, the peak ground reaction force must be determined. From there, peak RFD can be calculated by dividing the peak ground reaction force over the derivative of the force-time curve of the concentric portion of the CMVJ (McLellan et al., 2011). Time to peak force in the CMVJ has shown to be as low as 239 ms, with RFD values being 10 278 $(\pm 4014)\ N \cdot s^{-1}$ among active adult males. Physiological factors such as age, strength and body composition will have a significant impact of RFD, and improved levels of RFD is considered an important factor for athletes by researchers and coaches due to its implications for improved performance in dynamic activities such as sprinting, jumping and cutting (Miller et al., 2022).

1.2.4. Lower Body Strength and CMVJ Performance. In a study performed on collegiate athletes by Sullivan et al. (2019), results demonstrated a strong positive relationship between lower body Fmax in Watts/kilogram (W/kg) and single leg CMVJ values (r=0.82, p<0.05). The Fmax test performed in this study was done on a Keiser Air420 leg press machine, which measures force output in a horizontal direction. To most accurately compare lower body Fmax and CMVJ, the force test should be performed in a vertical plane at a knee angle similar to the CMVJ test, as explained in the study by Moir et al. (2011). These findings coincide with findings from Farrell et al. (2017) in a study performed on male high school football players examining the relationships between 3RM back squats at varying knee flexion angles, CMVJ and 36.6m sprint time. Findings from this study found a moderate positive correlation between CMVJ height and maximum effort back squat load at both 45- and 90-degrees knee flexion (r=0.33, p<0.001). This study incorporated a knee joint angle similar to the CMVJ, however back squat loads were measured as absolute and no relativization was done on scores. Incorporation of a relative strength index for each participant could potentially strengthen the relationship between the two variables (Ferreira et al., 2010). This notion is reinforced by the fact that relationships between all back squat values and maximum effort sprint times were strengthened when sprint time was compared to a back squat/body mass ratio.

A study by Bonnette et al. (2011) performed on male high school football players comparing CMVJ height, 1RM back squat and a relative lower body power index demonstrated a significant positive correlation between 1RM back squat and power index values ($r=0.48$, $p<0.001$). Given that the power score provides a relative measure of lower body power output, results show that lower body Fmax and relative lower body power are positively correlated. The 1RM squat values in this study were not relativized for participant body mass, however based on previous research by (Ferreira et al., 2010), measuring lower body Fmax in Newtons/kilogram can strengthen its relationship with CMVJ.

Research has suggested that the degree of knee flexion used in any lower body maximal force production (Fmax) test should match that which is attained in a CMVJ in order to accurately compare the two variables (Moir et al., 2011). This was demonstrated in a study on female collegiate volleyball players that determined the knee angle in any Fmax test must coincide with CMVJ knee angle to accurately predict CMVJ performance.

1.2.4.2. The Back Squat Isometric Test. The isometric squat, specifically when performed on a force platform is an often-used field test to measure lower body strength. The test involves the participant performing a maximum effort isometric contraction at a pre-determined knee-joint angle, most often with an immovable barbell loaded on their upper back. The isometric squat test is strongly related to both the 1RM back squat, isometric mid-thigh pull as well as more dynamic measures of physical performance such as CMVJ and RFD (Bazyler et al., 2015). In past research, isometric tests have been critiqued in their ability to assess dynamic sport performance, due to the differences between isometric and dynamic muscle contractions (Abernethy et al., 1995; Murphy & Wilson, 1996). These findings have been addressed in studies involving multi-joint isometrics at a specific joint angle, such as the isometric back squat. For these isometric tests to best correspond with dynamic movements, the joint angles involved must feature a high degree of specificity to the corresponding dynamic movement, notably the point in the movement where force output about the joint is the highest (~120 degree knee angle for the CMVJ) (Bazyler et al., 2015). Further, performing these isometric strength tests on a force plate provides insight on specific strength qualities such as peak ground reaction force and rate of force development. Research by Miller et al., (2022) suggests that peak ground reaction force may be a stronger predictor of variance in CMVJ height than RFD values among NCAA division 1 athletes, Utilizing the back squat isometric test allows the researcher to gain further insight to these peak ground reaction force values at a controlled joint angle that closely matches those attained during the CMVJ. Arguably the most important benefit of utilizing isometric strength testing is that these tests are relatively easier to standardize than dynamic 1RM testing. The ability to pre-determine joint angle for the tests lends to greater test-retest reliability (Bazyler et al., 2015), whereas guaranteeing identical joint angles and ranges of motion for repeated trials of a 1RM back squat may be accompanied by extraneous factors such as variance in participant mobility and proficiency in an exercise such as the back squat. Lastly, isometric back squat tests take much shorter to complete on average versus 1RM back squat tests. From a practical approach, this allows strength and conditioning professionals to test more athletes in a given time period while still ensuring the safety of the participant and reliability of data collection.

1.2.5. Sprint Ability and CMVJ Performance. CMVJ test scores have demonstrated a strong relationship with sprint ability. CMVJ scores among teenage male soccer and basketball athletes demonstrate a significant negative relationship with 10-metre maximal sprint times ($r=-0.61$, $p<0.05$) (Rodríguez-Rosell et al., 2017). Additionally, results from this same study showed a significant positive relationship between CMVJ and back squat 1RM scores ($r=0.62$, $p<0.05$). This data suggests that both sprint ability and lower body maximal force production may be predictors of CMVJ performance among male teenage field and court sport athletes.

1.2.5.2. RSS and CMVJ Performance. Within resistance training for athletes, there are multiple methods used to develop specific movement patterns such as sprinting and jumping. Given the high demand of sprint performance in field sports, resisted sled sprint (RSS) training is a useful method in developing lower body power, sprint ability, and motor unit recruitment among athletes (Bachero-Mena & González-Badillo, 2014). Research by Harrison & Bourke (2009) has shown that RSS training improved sprint performance greater than normal sprint training. When utilizing RSS training for developing sprint performance, the existing body of research recommends a decrement of less than 10% maximum sprint velocity (Cahill et al., 2020), therefore load on the sled must be prescribed accordingly. This is typically achieved with a load equivalent to 10-30% of the participant's bodyweight (Bachero-Mena & González-Badillo, 2014). Using a lighter relative percentage of the athlete's body mass will also help to avoid any deceleration throughout the course of the repetition. This methodology coincides with the maximum resisted sled load protocol set forth by Petrakos et al. (2019). Field studies on young adult female field athletes have shown the maximum resisted sled load to have moderate relationships with fat free mass ($r=0.593$, $p<0.05$), and CMVJ ($r=0.589$, $p<0.01$), suggesting that increased performance on the RSS exercise was favorable to those with higher levels of fat free mass as well as higher results on the CMVJ test.

Much of the existing research on RSS training involves the effects of RSS training methods on sprint performance times following a training intervention. Two studies by Spinks et al., (2007) and Prieske et al. (2018) have involved examination of both RSS programs and their effect on vertical jump performance, however neither of these have included any form of quantitative values for the RSS performance. It has been established in these studies that RSS training has a significant effect on vertical jump performance, however the degree of performance improvement on the RSS exercise is unknown. Small to moderate relationships (r= 0.30-0.34) have been displayed in the literature between second-step sprint power and CMVJ force (r= 0.30-0.34) (Boone et al., 2021) among collegiate football players (n=73).

Results of a study by Wong et al. (2017) on athletic males showed that acute performance of the RSS exercise had a significant negative effect on 5m sprint acceleration time. Research suggests that the physiologic demands of the CMVJ closely mimic the acceleration phase of sprinting. This is due in part to the increased demand of knee extensor force development and decreased reliance on sprint mechanics compared to maximum velocity sprinting (Rodríguez-Rosell et al., 2017). Given this information, it is hypothesized that performance in the RSS may demonstrate a relationship with CMVJ performance. Coinciding with these results, Ferreira et al. (2010) found that peak relative power output in a loaded squat jump with light resistance - 20% participant BM – was a strong predictor of CMVJ performance ($r=0.82$, $p<0.001$) among resistance trained young adults. Given that an individual's lower body power production capacity, relative to their bodyweight can predict CMVJ performance, it can be implied that peak relative power on a resisted sled sprint performed with similar resistance – 25% of body mass – will share a similar relationship with CMVJ.

Measuring sprinting power may be a more accurate predictor of on-field success in football than sprint time (Vincent et al., 2019). However, using extrapolative measures to calculate power output in a sprint using a participant's body mass may not be sufficient, so obtaining direct kinematic measures during a maximal effort sprint is recommended to provide greater insight on sprint performance.

1.2.6. Fat-Free Mass and CMVJ Performance. Fat free mass has demonstrated multiple relationships with factors of CMVJ height among male children aged 12.1 (±1.1). These include CMVJ RFD ($r=0.636$, $p<0.05$), CMVJ peak power ($r=0.872$, $p<0.05$), and CMVJ concentric impulse ($r=0.965$, $p<0.05$) as per research by Gillen et al. (2022). Conversely, FFM lacked any significant relationship with CMVJ height among adult male elite badminton players, however FFM did demonstrate significant relationships with repeated sprint ability ($r=0.756$, $p<0.03$). This implies that this body composition metric does bear a significant effect on explosive movements (Akdogan et al., 2022). Other research by Bosak & Carver, (2020) has demonstrated a low, non-significant relationship between FFM and CMVJ performance among female volleyball athletes. This suggests that further exploration in to the intersecting relationships of FFM and other physical performance metrics is warranted.

The relationship between anthropometric values and physical performance among elite youth rugby players aged between 15.1 (±0.3) to 17.0 (±0.3) has been analyzed, where body fat percentage and FFM correlate with performance in the 20m sprint and CMVJ. Strong positive relationships ($r=0.55$-0.75) have been demonstrated between FFM and predicted lower body vertical power, which was calculated using body mass and CMVJ height (Waldron et al., 2014). Similarly, the relationship between FFM and CMVJ ability among both young and older adults shows that FFM explains a significant portion of the variance in CMVJ scores among all ages, and that FFM had a significant positive relationship with CMVJ (Buehring et al., 2010). The relationships between body mass, lower body force production and CMVJ performance metrics among male collegiate football players have been examined – with results suggesting that athletes with a higher body mass, such as offensive and defensive linemen will display greater momentum values when performing a CMVJ (Norford et al., 2019). This difference implies that relativizing lower body force production values may aid in providing more consistent comparisons between position groups with significantly different body mass. The higher values of CMVJ momentum (the product of participant body mass and peak velocity of the concentric portion of the CMVJ) in this study did not equate to higher absolute CMVJ height, however when these higher momentum values are relativized by body mass it may provide more practical comparisons and rankings of CMVJ performance and lower body power output.

Relative strength levels have been shown to be positively associated with CMVJ performance, with body fat levels conversely being negatively associated to CMVJ performance (Ferreira et al., 2010). This is due to higher proportions of musculature, specifically in the lower body leading to increased capability of the body to propel itself upwards, while higher proportions of adipose tissue leads to decreased contractile function (Ferreira et al., 2010). Granted this information, it may be expected that controlling for these variable may strengthen relationships with CMVJ performance. Therefore, relativizing lower body strength and power measures (Fmax and RSS) by FFM (kg) may lead to stronger relationships with CMVJ height compared to relativizing scores by total body mass (kg).

1.2.7. Normative Anthropometric Values on Volleyball and Football Athletes.

1.2.7.2. Anthropometric Profile of Volleyball Athletes. Next, the anthropometrics among male volleyball players aged between 15.6 (±0.1) to 17.5 (±0.5) years based on position will be discussed. The mean heights (m) can range from 1.87 (±0.04) to 1.95 (±0.05) for centres to hitters, respectively (Duncan et al., 2006; Gabbett & Georgieff., 2007). Body mass (kg) can range from 71.2 (±9.3) to 81.8 (±1.7) for centres to hitters, respectively (Duncan et al., 2006, Gabbett & Georgieff., 2007). These relatively small ranges demonstrate similar anthropometrics among volleyball players in this age range. Additionally, lean body mass (kg) measurements among this group ranged from 43.4 – 50.9kg (4.4-7.1). Interestingly, data from Duncan et al., (2006) showed no significant differences in height, weight, or muscle mass between position groups in this study (n=25), however the data collected by Gabbett & Georgieff (2007) showed significant differences in height between skill levels of novice provincial and national level athletes, respectively.

1.2.7.3. Anthropometric Profile of Football Athletes. Normative data on the anthropometric measurements of high-school football players (n=7478) in the United States was examined by McKay et al. (2020). Mean (SD) height (m) values for all positions age 15-17 ranged from 1.71(±0.06) to 1.85 (±0.07) for running backs and offensive linemen, respectively. Body mass (kg) ranged from 68.2 (±9.3) to 121.5kg (±17.0) for defensive backs and offensive linemen, respectively. It should be noted that the increased range in values – notably in the body mass, among football players should be considered when examining CMVJ performance among all position groups.

1.2.8. CMVJ as a Predictor of Success in Sport

1.2.8.2. Football Scouting Combines. National Scouting Combines are the primary evaluation tool used for prospective players in the Canadian Football League and National Football League. These combines involve athletes participating in a battery of physical tests used to measure their athletic performance. These tests are also used as a primary assessment tool for football players in high school and collegiate settings. The CMVJ is one of the primary lower body power tests included, as it is frequently used as a primary assessment of an athlete's power producing capabilities. In a study examining the relationship between National Scouting Combine scores and game performance among Canadian Football League players, Pincivero & Vandeweerd, (2021), found that performance in the CMVJ test was a significant predictor for both draft order and total tackles for linebackers and defensive linemen. This relationship suggests that improved performance in the CMVJ resulted in athletes being drafted in a more optimal position as well as improved statistical performance in competition. These finding were supported further by McGee & Burkett, (2003) examining relationships between scouting combine scores and draft order. The authors found a significant difference in CMVJ scores and draft order, in that player's who performed better in the CMVJ had a tendency to be drafted in earlier rounds and yielded significantly higher sacks, tackles and performance accolades. Examination of similar data revealed positive relationships with CMVJ performance and yards per rushing attempt ($r=0.429$, $p<0.05$) and sacks ($r=0.207$, $p<0.05$) among quarterbacks and linebackers, respectively (Vincent et al., 2019).

A study by Robbins, (2010) examined whether normalized data from the NFL combine was a better predictor of performance in the subsequent NFL draft. The results from this study revealed multiple significant correlations between performance in the CMVJ and draft order. CMVJ score among the running back (r= -0.47), offensive tackle (r= -0.29), outside linebacker (r= -0.30), and tight end (r= -0.35) positions all demonstrated a significant ($p < 0.05$) negative relationship with draft order – meaning that improved absolute scores in the test led to a higher draft position. A further finding in this study was that the raw CMVJ scores had a stronger relationship with draft order compared to CMVJ scores that were scaled allometrically to reflect body composition. This suggests that examining a predictive outcome variable as raw data may be beneficial over allometrically scaled data.

1.2.8.3. CMVJ as a Skill Level Predictor in Volleyball. In a review of observational and experimental studies performed on CMVJ among male and female volleyball players (n=32), Ziv & Lidor, (2010) found that among multiple physical performance characteristics, skill level had the most significant relationship with CMVJ performance. These findings coincide with those by Sattler et al. (2015). This indicates the CMVJ as a valid marker of success in volleyball and should be both trained and evaluated accordingly.

1.2.9. Similar Study Design. Swinton et al., (2014) conducted a study examining regression models for both anthropometric and physiologic variables as they relate to CMVJ performance. This study was conducted on adult male rugby union players (n=30, age:24.2 ±3.9 years). The participants' ability to jump, sprint and change direction were measured by testing CMVJ, 30m sprint and the 5-0-5 agility test. Regression variables were collected through testing maximum strength in the 1RM back squat and deadlift exercise. Anthropometric data was collected on multiple variables including body mass and body segment lengths. Sprint test data was collected on participants' maximum 5m, 10m, and 30m sprint time (seconds). Only total time taken to complete each distance was recorded, with no kinematic data regarding power output during the sprint being collected. Regarding the measurement of lower body Fmax in this study design, the 1RM back squat and deadlift tests were used. Dynamic strength tests such as these have been shown to bear relationships with CMVJ performance, however they also have a tendency to display larger degrees of variance when compared to a maximum effort isometric test (Bazyler et al., 2015).

Results of this study demonstrated a significant positive relationship between 1RM back squat and CMVJ performance ($r=0.80$, $p<0.05$) as well as relative peak power during the back squat exercise and CMVJ ($r=0.67$, $p<0.05$). Additionally, strong negative relationships ($r=0.52$, 0.75, 0.82, $p<0.01$) were found between 5m, 10m, and 30m sprint times, respectively. It should be noted that there was a training effect present in this study, in that the current block of training that all subjects were currently participating in included frequent exposures to high-load resistance training. This exposure stimulus may serve as a confounding variable for maximum strength test data.

Anthropometric data collected in this study design included multiple measures of body mass, segment length and girth. A significant, strong negative relationship ($r=-0.68$, $p<0.01$) was discovered between body mass (kg) and CMVJ performance, there was no consideration of fat free body mass in this calculation which has shown to have stronger relationships with CMVJ performance than total body mass (Waldron et al., 2014). More advanced body composition modeling including proportionality and segmental masses may provide data that combine more effectively with the force- and velocity-related variables identified in the present study.

1.3 Statement of the Problem

There exists a need to further examine the complex relationships between lower body maximal strength, power, as well as anthropometrics and CMVJ performance. Literature exists on the relationship between these values and CMVJ performance, however there is little data that explores and compares all these variables between two different sport groups. Therefore, the aim of this present study was to examine the correlations between both physiologic and anthropometric variables, specifically lower body peak force production, resisted sprint performance, and fat free mass and how they relate to CMVJ performance in male volleyball and football athletes.

1.4 Hypotheses

1.4.1. Primary Hypothesis. It is hypothesized that lower body Fmax in the isometric back squat test, specifically when relativized to N/kg fat free body mass, will have the strongest relationship with CMVJ performance height for both participant groups. This is due to the strong positive relationship between lower body relative strength and CMVJ performance (Bonnette et al., 2011; Ferreira et al., 2010; Moir et al., 2011).

1.4.2. Secondary Hypotheses. It is hypothesized that relativizing both Fmax and RSS scores by fat free mass will result in stronger correlation values with CMVJ height than relativizing scores by total body mass. This is extracted from the findings in the literature on the strong positive relationship between fat free mass and CMVJ height (Buehring et al., 2010).

It is further hypothesized that both total body mass and fat free body mass will be significantly higher in the football group. This hypothesis is rooted in existing normative anthropometric data on football and volleyball athletes that demonstrate a noticeable difference between groups. Additionally, based on the existing normative data it is hypothesized that VB group participants will test significantly higher than FB group participants in the CMVJ test.

Chapter 2 – Methods

2.1 Experimental Design

The present study used a cross-sectional correlational design. Prior to participation in this study all participants were required to complete the Get Active Questionnaire, which was used to screen for any possible contraindicators of participation in the activities required of this study. All sessions took place at Testify Performance (57 South Landing Dr, Oak Bluff, Manitoba). Before performing any physical tests, anthropometric values were collected on body mass, and fat free body mass (Tanita BC-554, Tanita Corporation, Tokyo, Japan). All testing sessions were preceded by a general dynamic warmup delivered by a Certified Strength and Conditioning Specialist through the National Strength and Conditioning Association. Following a general warmup, a test-specific warmup was performed by each participant for each test, including the CMVJ, RSS and lower body Fmax test. Upon completion of the specific warmup, participants were instructed on the procedures of testing and data collection. The tests were administered in a specific order, with each participant performing the CMVJ test first, followed by the Fmax test and concluding with the RSS test. All participants were subject to identical warm-up and testing procedures. All test data was collected and exported to a secure Excel spreadsheet. CMVJ and lower body Fmax tests were performed on a force plate with results being examined on a tablet. RSS scores were collected on a TechnoGym Skill Run machine and immediately exported to an Excel spreadsheet. All anthropometric values were collected and immediately exported to the same Excel spreadsheet. All participant data was collected by the present author.

2.2 Participants

70 participants were included in the study for data collection. Participants were split into a football (n=35) or volleyball (n=35) group based on their sport. Participants were selected from the active membership of the facility, with additional participants being recruited from a convenience sample of eligible athletes from a high school football program. It should be noted that these additional participants all had previous experiences at the facility prior to participation in the study. Recruitment of these participants was accomplished by passing on the study information to their respective coaches. Sample size for this study was determined by using the sample size calculation software GPower (Faul et al., 2007). Effect size of 0.325 was determined by using previous data from Laffaye et al., (2014) for the CMVJ parameter. Alpha was set at 0.05 and beta was set at 0.20 on a two-tailed test.

2.3 Equipment

2.3.1. Anthropometric Measurements. Body mass and fat free mass was calculated using bioelectrical impedance (Tanita BC-554, Tanita Corporation, Tokyo, Japan).

2.3.2. CMVJ Assessment. Participants performed the CMVJ test on Vald ForceDeck force platforms (Vald ForceDecks FD4000, Vald Performance, Newstead, QLD, AUS), with data being exported to and processed on a laptop computer (MacBook Pro A1502, Apple, CA, USA)

2.3.3. Lower Body Fmax Assessment. Participants performed the lower body Fmax test with an Intek Olympic Barbell (20kg) in a Keiser squat rack with the barbell set to a height corresponding with 120 degrees of knee flexion, determined using a joint goniometer. Once the desired height was found, the barbell was loaded against inverted J-Hooks to prevent any concentric movement (Spieszny et al., 2022). Data during this test was collected via participants standing on a Vald force platform (Vald ForceDecks FD4000, Vald Performance, Newstead, QLD, AUS), with data being exported to and processed on a laptop computer (MacBook Pro A1502, Apple, CA, USA)

2.3.4. Resisted Sled Sprint (RSS) Assessment. The RSS test was performed on a Technogym SKILLRUN machine (Technogym SKILLRUN, Technogym, Cesena, Italy). Biometric feedback was processed and displayed on the treadmill display and recorded and exported to a laptop computer (MacBook Pro A1502, Apple, CA, USA).

2.3.4.2. Technogym Skillrun. The Technogym Skillrun (TGSR) is a programmable treadmill with features designed to mimic RSS in a closed setting. The TGSR has the capability to set specific loads of resistance that replicates the resistance provided by a weighted sled on a smooth surface. For the purpose of this research, the TGSR Sled mode was used specifically to mimic a sled push on ground (Martínez-Serrano et al., 2021), where resistance is higher during the initial acceleration portion and decreases proportionately as velocity increases. The subjects pushed the track as hard as possible while holding on to handles located at the front of the treadmill. This positioning closely mimics that of an RSS on a standard weight sled. The starting position for the test involves the subject in a staggered stance with their dominant foot placed forward and hand on the treadmill handles. From there, subjects begin the test at their own volition and are instructed to exert a maximum effort throughout the whole tests. Distance, time, velocity, and power output are all tracked automatically on the TGSR, and a large display screen notifies the subject when the test is complete.

2.4 Procedures

2.4.1 Demographic Assessment. Participants were required to complete a brief questionnaire including date of birth, biological sex, sport participation (football or volleyball, for the purpose of this study), and resistance training experience (in years).

2.4.2 Anthropometric Assessment. Body mass and fat free body mass (kg) was assessed via bioelectrical impedance (Tanita BC-554, Tanita Corporation, Tokyo, Japan). The participants stood on the scale and had their height, age and sex entered into the scale by the investigator. Participants were then instructed to stand in a static position for approximately ten seconds while the scale assessed body mass, fat free body mass, and body fat percentage via BIA. All requisite data was then recorded by the investigator and exported to a secure spreadsheet on a laptop computer.

2.4.3 CMVJ Assessment. Prior to commencement of the tests, the force plate was calibrated to ensure accuracy and reliability. As a baseline, the force platform sampled at 1000Hz. The CMVJ test began with the participant standing upright on the force platform. Participants were instructed to perform three maximum effort CMVJ repetitions with arm swing permitted (McLellan et al., 2011). The only instruction provided on the repetitions was to ensure that the participant landed safely on the force platform. A self-selected countermovement depth was chosen by the participant. Each participant performed three repetitions, with 20 seconds rest between each trial as suggested by Cuk et al., (2016). CMVJ height (cm) was determined using the impulse-momentum method, as this method of measuring CMVJ height on a force platform has been shown to be more reliable than simpler methods such as the flight-time method, especially when including an arm swing (Linthorne, 2001). All CMVJ height data was immediately exported to a laptop computer.

2.4.4. Lower Body Fmax Assessment. Prior to commencement of the tests, the force plate was calibrated to ensure accuracy and reliability. As a baseline, the force platform was sampled at 1000Hz. Proper positioning for the test involved the athlete standing on the force plate with a barbell across their upper back and at as close to 120 degrees of knee flexion as possible. The barbell height was set corresponding to this position and loaded against inverted J-Hooks to ensure that no concentric movement of the barbell was possible (Spieszny et al., 2022). Participants made two attempts at 50 and 75% of maximal effort followed by three-minutes of complete rest. The participants then completed two maximal six second efforts with three minute rest intervals (Bazyler et al., 2015). To minimize any jerk with the movement, participants were instructed to maintain constant tension on the barbell prior to commencement of each rep, however the six second time interval for each rep only began once maximal effort had commenced. Fmax was calculated as the maximal force recorded from each trial, and the data was immediately exported to a laptop computer.

2.4.5 RSS Assessment. The RSS test began with the participant standing on the static treadmill. The administer of the tests programmed the test variables - weight, repetitions, and resistance – into the treadmill display. Resistance on the sled was set to 25% of participant bodyweight, as per Cahill et al., (2021). Participants completed two repetitions with the distance of each repetition set to 15 metres, with 3 minutes of complete rest in between each repetition (Martínez-Serrano et al., 2021). The starting position was determined individually, with participants being instructed to begin the repetition with their dominant leg forward. The repetitions began volitionally; however, participants were instructed to begin the first repetition at their own perceived readiness, and all following repetitions immediately upon completion of the rest interval. Kinematic feedback for each repetition was provided on the unit display immediately upon completion of each repetition, and participants were verbally encouraged to maximally exert themselves during each repetition. Data values were recorded after each rep, tracking peak power output that is calculated and displayed on the monitor. Immediately upon completion of the test, the peak power values for each repetition were exported to a laptop computer.

2.5 Statistical Analysis

Statistical analysis was conducted on IBM SPSS Statistical software (SPSS Statistics 27.0, IBM Corp, Armonk, NY, USA). The primary purpose of this analysis was to discover any significant relationships between CMVJ height and lower body Fmax, RSS power output and fat free body mass. A Shapiro-Wilk test was performed on the data to test for normality. A Pearson correlational test was performed to establish the correlations between CMVJ height and lower body Fmax, RSS power output and fat free body mass. Independent t-tests were performed to evaluate whether there were significant differences between any of the dependent variables between the two participant groups. The α-value for significance was set at $p \leq 0.05$.

The following thresholds will be used for describing the degree of correlation, based on widely used interpretations or correlations regarding athletic measures such as the CMVJ and lower body strength (Hopkins, 2000; Wallace et al., 2014):

Correlation (r)	**Interpretation**
<0.1	Trivial
0.1 – 0.3	Weak
0.3 – 0.5	Moderate
0.5 – 0.7	Strong
0.7 – 0.9	Very Strong
>0.9	Almost Perfect

Chapter 3 – Results

3.1 Participant Characteristics

Descriptive statistics of all participants are depicted in Table 1. A total of 68 male athletes (n= 33 FB Group, n= 35 VB Group) completed the study. Two participants from the FB group were lost to attrition, as participant anthropometric measurements were deemed statistical outliers via standard deviation rule of ± 3 SD.

Table 1 Descriptive characteristics from all participants, FB Group, VB Group; t-values and p-values from independent t-test between FB and VB athletes.

Variable	All (n=68)	FB (n=33)	Linemen (n=15)	Skill (n=18)	VB (n=35)	t-value	p-value
	Mean ±SD					**df (66)**	
Height (cm)	180.43 ± 6.65	179 ± 6.90	181± 4.41	177.33 ± 8.19	181.77 ± 6.21	1.74	0.09
BM (kg)	80.29 ± 14.08	87.02 ± 17.02	100.85 ± 13.75	75.50 ± 8.96	73.95 ± 5.71	4.29	<0.01
BF (%)	16.82 ± 7.30	20.23 ± 8.63	26.36 ± 7.75	15.13 ± 5.49	13.60 ± 3.59	4.18	<0.01
FFM (kg)	65.99 ± 7.26	68.27 ± 8.61	73.60 ± 7.74	63.83 ± 6.66	63.84 ± 4.92	2.63	<0.01
CMVJ (cm)	43.49 ± 13.51	34.03 ± 8.23	29.46 ± 8.62	37.84 ± 5.70	52.40 ± 11.28	7.63	<0.01
Fmax (N)	2719.07 ± 569.63	2791.27 ± 563.62	2850.40 ± 574.60	2742.00 ± 566.05	2651.00 ± 574.98	1.01	0.31
Fmax1 (N/kg)	34.36 ± 7.42	32.84 ± 7.64	28.37 ± 4.54	36.56 ± 7.79	35.80 ± 7.02	1.66	0.10
RSS (W)	876.63 ± 112.43	916.97±118.41	915.60±103.69	915.61±134.88	838.60±92.98	3.05	<0.01

RSS1 (W/kg)	11.14 ± 1.97	10.89 ± 2.47	10.30 ± 1.62	11.47 ± 2.90	11.38 ± 1.33	1.02	0.31

Note: p≤ 0.05 denotes a significant difference between group means

Note: t-value and p-value denotes relationship between FB and VB groups

Note: BM = Body mass, BF = Bodyfat percentage, FFM = Fat free body mass, FM = Fat mass CMVJ = Countermovement vertical jump, Fmax = Lower body maximal force output, Fmax1 = Lower body maximal force output relative to body mass, RSS = Resisted sled sprint power output, RSS1 = Resisted sled sprint power output relative to by body mass.

Table 2 Shapiro-Wilk test of normality for all participant data (n=68)

Variable	**df**	**p-value**
Height (cm)	68	0.47
BM (kg)		<0.01
BF (%)		<0.01
FFM (kg)		<0.01
CMVJ (cm)		0.26
Fmax (N)		0.23
Fmax1 (N/kg)		0.51
RSS (W)		0.33
RSS1 (W/kg)		<0.01

Note: p≤ 0.05 denotes that data was not normally distributed between all participants (n=68)

Note: BM = Body mass, BF = Bodyfat percentage, FFM = Fat free body mass, CMVJ = Countermovement vertical jump, Fmax = Lower body maximal force output, Fmax1 = Lower body maximal force output relativized by body mass, RSS = Resisted sled sprint power output, RSS1 = Resisted sled sprint power output relativized by body mass

3.2 Correlation Values for CMVJ Performance Among All Participants

There were no significant relationships between CMVJ and absolute Fmax (N) when all participants (n=68) were analyzed as one whole group. Conversely, significant positive relationships were found between CMVJ and Fmax (N/kg) (r=0.55, p≤0.05), and Fmax (N/kg FFM) (r=0.37, p≤0.05) Entire group (n=68) RSS peak relative power (W/kg) and peak velocity (m/s) both had significant positive relationships with CMVJ RFD ($N \cdot s^{-1}$) (r=-0.42, p≤0.05, and r=-0.37, p≤0.05) respectively.

3.3 Correlation Values for CMVJ Performance Among Volleyball Athletes

Correlations for all anthropometrics, lower body force production, lower body power production and CMVJ performance within the VB group are depicted in Table 3. When the VB group was analyzed individually, CMVJ height was significantly correlated with Fmax (N) (r=0.48, p≤0.05), Fmax1 (N/kg) (r=0.52, p≤0.05), and Fmax2 (N/kg FFM) (r=0.52, p≤0.05).

Within the VB group, CMVJ height produced non-significant correlations with RSS (W) (r=0.27, p>0.05), RSS1 (W/kg) (r=0.23, p>0.05), and RSS2 (W/kg FFM) (r=0.27, p>0.05). Participants in the VB group showed a significant positive relationship between RSS (W) and Fmax (N/kg) (r=0.35, p≤0.05). The results of the correlational analysis between anthropometric factors and CMVJ performance did not produce any significant correlations in the VB group (all p>0.05).

3.4 Correlation Values for CMVJ Performance Among Football Athletes

Correlations for all anthropometrics, lower body force production, lower body power production and CMVJ performance within the FB group are depicted in Table 4. When the FB group was analyzed individually, CMVJ height was negatively correlated with FFM (kg) (r= -0.46, p≤0.05), and positively correlated with Fmax1 (N/kg) (r=0.67, p≤0.05) and Fmax2 (N/kg FFM) (r=0.45, p≤0.05).

Within the FB group, CMVJ produced non-significant correlations with RSS (W) (r= -0.14, p>0.05), RSS1 (W/kg) (r=0.16, p>0.05), and RSS2 (W/kg FFM) (r= 0.23, p>0.05). RFD scores on the Fmax test among FB group participants displayed a significant positive relationship with CMVJ height (r=0.36, p≤0.05).

Table 3 Pearson correlation coefficients for all test variables among VB group (n=35)

	CMVJ (cm)	**FFM (kg)**	**Fmax (N)**	**Fmax1 (N/kg)**	**Fmax2 (N/kg FFM)**	**RSS (W)**	**RSS1 (W/kg)**	**RSS2 (W/kg FFM)**
CMVJ (cm)		0.001	**0.48***	**0.52***	**0.515***	0.27	0.23	0.27
FFM (kg)	0.001		0.30	-0.01	-0.08	0.21	**-0.37***	**-0.45***
Fmax (N)	**0.48***	0.30		**0.93***	**0.92***	**0.42***	0.10	0.20
Fmax1 (N/kg)	**0.52***	-0.01	**0.93***		**0.98***	**0.35***	0.26	0.33
Fmax2 (N/kg FFM	**0.52***	-0.08	**0.92***	**0.98***		**0.35***	0.23	**0.38***
RSS (W)	0.27	0.21	**0.42***	**0.35***	**0.35***		**0.77***	**0.78***
RSS1 (W/kg)	0.23	**-0.37***	0.10	0.26	0.23	**0.77***		**0.94***
RSS2 (W/kg FFM)	0.27	**-0.45***	0.20	0.33	**0.38***	**0.78***	**0.94***	

*Note: * = significant at p≤0.05*

Note: CMVJ = countermovement vertical jump, FFM = fat-free body mass, Fmax = absolute lower body maximal force output, Fmax1 = Fmax relativized by body mass, Fmax2= Fmax *relativized by fat-free body mass, RSS = absolute resisted sled sprint power output, RSS1 = RSS relativized by body mass, RSS2 = RSS relativized by fat-free body mass*

Table 4 Pearson correlation coefficients for all test variables among FB group (n=33)

	CMVJ (cm)	**FFM (kg)**	**Fmax (N)**	**Fmax (N/kg)**	**Fmax (N/kg FFM)**	**RSS (W)**	**RSS (W/kg)**	**RSS (W/kg FFM)**
CMVJ (cm)		**-0.46***	0.14	**0.68***	**0.45***	-0.14	0.16	0.23
FFM (kg)	**-0.46***		**0.36***	**-0.42***	-0.29	0.19	0.04	**-0.62***
Fmax (N)	0.14	**0.36***		**0.56***	**0.78***	-0.70	0.03	-0.30
Fmax1 (N/kg)	**0.67***	**-0.42***	**0.56***		**0.88***	-0.15	0.12	0.23
Fmax2 (N/kg FFM	**0.45***	-0.29	**0.78***	**0.88***		-0.17	0.01	0.12
RSS (W)	-0.14	0.19	-0.07	-0.15	-0.17		**0.49***	**0.65***
RSS (W/kg)	0.16	-0.04	0.03	0.12	0.01	**0.49***		0.33
RSS (W/kg FFM)	0.23	**-0.62***	-0.30	0.23	0.12	**0.65***	0.33	

*Note: * = significant at p≤0.05*

Note: CMVJ = countermovement vertical jump, FFM = fat-free body mass, Fmax = absolute lower body maximal force output, Fmax1 = Fmax relativized by body mass, Fmax2= Fmax relativized by fat-free body mass, RSS = absolute resisted sled sprint power output, RSS1 = RSS relativized by body mass, RSS2 = RSS relativized by fat-free body mass

Table 5 Pearson correlation coefficients for all test variables among Lineman positions in FB group (n=15)

	CMVJ (cm)	**FFM (kg)**	**Fmax (N)**	**Fmax (N/kg)**	**Fmax (N/kg FFM)**	**RSS (W)**	**RSS (W/kg)**	**RSS (W/kg FFM)**
CMVJ (cm)		-0.43	-0.10	**0.54***	0.12	-0.30	0.12	0.65
FFM (kg)	0.43		0.38	-0.17	-0.18	0.39	0.21	**-0.54***
Fmax (N)	-0.10	0.38		**0.67***	**0.84***	0.30	0.39	-0.27
Fmax1 (N/kg)	**0.54***	-0.17	**0.67***		**0.80***	-0.18	0.49	0.05
Fmax2 (N/kg FFM	0.12	-0.18	**0.84***	**0.80***		-0.16	0.26	0.06
RSS (W)	-0.30	0.38	0.30	-0.18	-0.16		-0.05	**0.57***
RSS (W/kg)	0.12	0.20	0.38	0.49	0.26	-0.05		-0.22
RSS (W/kg FFM)	0.65	**-0.54***	-0.27	0.05	0.06	**0.57***	-0.22	

*Note: * = significant at $p \leq 0.05$*

Note: CMVJ = countermovement vertical jump, FFM = fat-free body mass, Fmax = absolute lower body maximal force output, Fmax1 = Fmax relativized by body mass, Fmax2= Fmax relativized by fat-free body mass, RSS = absolute resisted sled sprint power output, RSS1 = RSS relativized by body mass, RSS2 = RSS relativized by fat-free body mass

Table 6 Pearson correlation coefficients for all test variables among Skill positions in FB group (n=18)

	CMVJ (cm)	**FFM (kg)**	**Fmax (N)**	**Fmax (N/kg)**	**Fmax (N/kg FFM)**	**RSS (W)**	**RSS (W/kg)**	**RSS (W/kg FFM)**
CMVJ (cm)		0.40	**0.64***	**0.69***	**0.68***	-0.05	0.02	-0.04
FFM (kg)	0.40		0.37	-0.17	-0.17	0.14	0.25	**-0.50***
Fmax (N)	**0.64***	0.37		**0.80***	**0.85***	-0.14	-0.09	-0.31
Fmax1 (N/kg)	**0.69***	-0.17	**0.80***		**0.96***	-0.18	-0.15	-0.01
Fmax2 (N/kg FFM	**0.68***	-0.17	**0.85***	**0.96***		-0.19	-0.21	-0.01
RSS (W)	-0.05	0.14	-0.14	-0.18	-0.19		**0.69***	**0.78***
RSS (W/kg)	0.02	0.25	-0.09	-0.15	-0.21	**0.69**		0.41
RSS (W/kg FFM)	-0.04	**-0.50***	-0.31	-0.01	-0.01	**0.78***	0.41	

*Note: * = significant at p≤0.05*

Note: CMVJ = countermovement vertical jump, FFM = fat-free body mass, Fmax = absolute lower body maximal force output, Fmax1 = Fmax relativized by body mass, Fmax2= Fmax relativized by fat-free body mass, RSS = absolute resisted sled sprint power output, RSS1 = RSS relativized by body mass, RSS2 = RSS relativized by fat-free body mass

Table 7 ANOVA comparison of VB, Lineman and Skill participant groups

	df	F	p-value	Effect Size
Height (cm)	2	2.87	0.06	0.81
BM (kg)		51.74	<0.01*	0.61
BF (%)		32.30	<0.01*	0.50
FFM (kg)		14.98	<0.01*	0.32
CMVJ (cm)		36.61	<0.01*	0.52
Fmax (N)		0.66	0.52	0.20
Fmax (N/kg)		7.56	<0.01*	0.19
RSS (W)		4.57	<0.01*	0.12
RSS (W/kg)		14.11	<0.01*	0.30

*Note: * = significant at p≤0.05*

Note: CMVJ = countermovement vertical jump, FFM = fat-free body mass, Fmax = absolute lower body maximal force output, Fmax1 = Fmax relativized by body mass, Fmax2= Fmax relativized by fat-free body mass, RSS = absolute resisted sled sprint power output, RSS1 = RSS relativized by body mass, RSS2 = RSS relativized by fat-free body mass

Table 8 Significant results of Tukey's HSD Post Hoc comparisons of all participant groups

	Group	Mean Difference	Sig.	Standard Error
Height (cm)	VB vs Skill	4.43*	0.05	1.87
BM (kg)	VB vs Lineman	-26.90*	<0.01	2.74
	Lineman vs Skill	25.35*	<0.01	3.10
FFM (kg)	VB vs Lineman	-9.76*	<0.01	1.88
	Lineman vs Skill	9.76*	<0.01	2.13
CMVJ (cm)	VB vs Lineman	22.94*	<0.01	2.95
	VB vs Skill	14.56*	<0.01	2.77
	Lineman vs Skill	-8.38*	0.04	3.34
Fmax1 (N/kg)	VB vs Lineman	7.42*	<0.01	2.10

	Lineman vs Skill	-8.19*	<0.01	2.37
RSS (W)	VB vs Lineman	-79.80*	0.04	32.90
	VB vs Skill	-77.18*	0.04	31.00
RSS1 (W/kg)	VB vs Lineman	2.14*	<0.01	0.52
	Lineman vs Skill	-3.02*	<0.01	0.58

*Note: * = significant at $p \leq 0.05$*

Note: CMVJ = countermovement vertical jump, FFM = fat-free body mass, Fmax = absolute lower body maximal force output, Fmax1 = Fmax relativized by body mass, Fmax2= Fmax relativized by fat-free body mass, RSS = absolute resisted sled sprint power output, RSS1 = RSS relativized by body mass, RSS2 = RSS relativized by fat-free body mass

Chapter 4 - Discussion

The primary purpose of this study was to examine the relationships between FFM, lower body maximal force production, lower body maximal power production, and CMVJ height among football and volleyball athletes. It was hypothesized that lower body Fmax when relativized by fat free body mass (Fmax2) would have the strongest positive relationship with CMVJ height. Additionally, it was hypothesized that relativizing Fmax and RSS by fat free body mass as opposed to total body mass would strengthen correlation values with CMVJ height.

In alignment with the primary hypothesis, the results of the analysis show significant positive relationships between both Fmax1 and Fmax2 and CMVJ height among both participant groups. However, these relationships were not strengthened when relativizing scores by fat free body mass versus total body mass, which is not in compliance with the secondary hypothesis. The results of this study illustrate that participants with higher levels of relative lower body force producing capabilities displayed a tendency to have a higher CMVJ height. These findings also show that within the present testing parameters, neither FFM nor BM demonstrated superiority in relativizing Fmax scores pertaining to their relationship with CMVJ performance. There were no significant correlations between RSS scores and CMVJ performance. Participants in the football group demonstrated a significant negative relationship between FFM and CMVJ height, there were no significant correlations between FFM an CMVJ among volleyball group participants.

4.1 Lower Body Fmax and CMVJ Performance

CMVJ performance was positively related to multiple markers of lower body force production across all participants in the study. This aligns with the study's primary hypothesis.

The study produced significant positive relationships between CMVJ height and lower body Fmax when relativized by both total body mass and fat free body mass among both participant groups. Further, absolute lower body Fmax had a significant positive relationship with CMVJ height among participants in the VB group. Absolute Fmax scores had no significant relationships with CMVJ performance. This may be attributed to the fact that body mass was not normally distributed within the FB group, and the FB group participants (87.02 ± 17.02 kg) had higher variation in body mass than the VB group participants (73.95 ± 5.71 kg). Findings from this study are consistent with those of previous research examining the relationships between lower body Fmax and CMVJ performance (Asmundson, 2019; Ferreira et al., 2010; Peterson et al., 2006; Thompson et al., 2013). Among all participants, CMVJ performance and its relationship with lower body Fmax was strengthened when Fmax was made relative to total body mass. This coincides with work by Bonnette et al. (2011) in which 1RM back squat scores among high school football players had a stronger positive relationship with CMVJ height when scores were made relative by BM. The significant positive relationship between relative lower body Fmax and CMVJ height support the primary hypothesis of this study. These findings add to the existing literature in that when seeking to improve CMVJ height, relative lower body strength qualities are an important physiological trait to develop, notably in a vertical plane of motion such as the squat pattern.

In previous work, lower body Fmax measured via an isometric back squat test has demonstrated strong positive relationships with CMVJ performance (Bazyler et al., 2015). It is suggested that for the back squat isometric test to best correlate with CMVJ height, the present joint angle about the knee should be highly specific to the biomechanics of a CMVJ. This is shown to be ~120 degrees (the point at which force output through the knee is said to be the highest) (Bazyler et al., 2015). It should be noted however, that participants in this study were not instructed to attain a specific joint angle during the eccentric portion of the CMVJ, but rather perform a self-selected countermovement motion that would subjectively elicit the best result in CMVJ height. While the results of the present study did demonstrate significant positive relationships, these correlations may have been strengthened if conditions were controlled to match all joint angles and respective muscle fibre lengths. This is based on the work of Tillin et al., (2018) in which the authors suggest that isometric test joint angles that do not correspond precisely with that of dynamic movement may have an impact on muscle fibre lengths and agonist muscle activation and may convolute the relationships between movements. Despite any critiques of using isometric strength tests and their relationship with dynamic movements such as the CMVJ, the finding of this study does support a positive relationship between lower body isometric strength and CMVJ height. Given these findings and in accordance with previous work by (Asmundson, 2019; Bazyler et al., 2015; Ferreira et al., 2010), it may be suggested that both isometric and dynamic strength, such as that tested in the 1RM back squat test (Bonnette et al., 2011) can be valid correlates of CMVJ performance. It must also be considered that isometric strength tests are often viewed as a more practical, safer and time efficient means of strength assessment (Spieszny et al., 2022).

RFD is a physiologic trait that has been shown to be closely related to Fmax, CMVJ and sprint performance (McLellan et al., 2011). Within this study RFD was calculated and collected as a biproduct of the Fmax test procedure. Fmax RFD among FB group participants displayed a significant positive relationship with CMVJ height. These results are in alignment with findings that higher RFD levels lead to increased CMVJ performance among athletes across multiple age groups and sport domains (Boone et al., 2021; Daugherty et al., 2021; Miller et al., 2022). Fmax test RFD among VB group participants did not demonstrate any significant relationship with CMVJ performance. It should be mentioned that to accurately measure RFD within an Fmax test, participants should be instructed to reach peak torque values as quickly as possible (Boone et al., 2021). The participants of this study were instructed to attain maximal force output gradually over the course of the repetition as RFD was not a primary measurement variable, so this gradual increase in effort was instructed to reduce any jerk within the movement and maximize comfort and safety for the participants.

4.2 RSS and CMVJ Performance

Data collected from the RSS test in the present study had a lesser tendency to demonstrate a relationship with CMVJ performance. Among the FB group, no significant relationships were found between RSS power output and CMVJ or Fmax test scores. Participants in the VB group showed a significant positive relationship between RSS (W) and Fmax (N/kg), however the data failed to establish any significant relationships with CMVJ. Conversely, maximum velocity (m/s) on the RSS test had a significant positive relationship with CMVJ height. Though maximum velocity was not one of the primary variables collected in this study design, the TGSR provides this information after each repetition. This relationship is aligned with research suggesting that higher levels of sprint performance (decreased 10m sprint time, higher velocity attained during sprint) is associated with increased CMVJ height (Rodríguez-Rosell et al., 2017). Results from both participant groups demonstrated a significant negative relationship between FFM and RSS (W/kg FFM) . These results contradict the findings of previous research on RSS performance and FFM, where it was found that RSS performance had a significant positive relationship with FFM (Petrakos et al., 2019). This discrepancy may be attributed to slight differences in study design, wherein the work by Petrakos et al. (2019) was focused on calculating the maximum resisted sled load to elicit peak power output, whereas the methods set forth in the present study prescribed a set load based off of participant body mass. It is typically suggested that RSS load should be between 10-30% of participant BM when using the RSS to improve sprint performance (Bachero-Mena & González-Badillo, 2014). Given that the protocols of the present study utilized a load at the higher of this range (25% BM) it is possible that a velocity decrement of greater than 10% occurred among participants, thus decreasing the relationship with sprint performance (Cahill et al., 2021). This decrement in velocity and increase in relative force output may potentially place the RSS test on a different portion of the force-velocity curve and further differ from the low force, high velocity profile of sprinting and jumping. This may explain why RSS scores for participants in the VB group had a significant relationship with Fmax test scores and not CMVJ scores. The RSS specifically mimics the acceleration phase of sprinting, putting a higher demand on the knee extensor group than upright sprinting mechanics at maximal velocity. The vertical torso and dorsiflexed ankle position of the Fmax test also biases loading of the knee extensor group, suggesting that success in both of these tests requires the participant's ability to utilize those specific muscle groups. The similar musculoskeletal demands of these tests may also explain the significant relationship between them.

When analyzed as an entire group (n=68) RSS peak relative power (W/kg) and peak velocity (m/s) both had significant positive relationships with CMVJ RFD ($N \cdot s^{-1}$). These findings are concurrent with much of the research on higher levels of RFD being attributed to increased performance in sprint and jumping related tasks (McLellan et al., 2011). Unlike the Fmax test in the present study, wherein participants were not instructed to complete the test in a manner that is harmonious with accurately measuring RFD, the CMVJ test can be an accurate measurement of RFD as participants were instructed to perform the concentric movements as explosively as possible. There was a very small, non-significant positive relationship between CMVJ RFD and Fmax RFD, implying that it may not be appropriate to consider these two tests comparable.

4.3 FFM and CMVJ Performance

Within the present study there were significant differences between the FB group and VB group in both FFM and BM measurements, with the FB group being significantly higher than the VB group in both parameters. These findings align with normative anthropometric data collected on the same demographics (Duncan et al., 2006; McKay et al., 2020).

Participant FFM measurements in the FB group had a significant negative relationship with CMVJ scores. Among VB group participants, there was no significant relationship between FFM and CMVJ scores. When analyzed as an entire group FFM displayed a significant negative relationship with CMVJ. Positive relationships between FFM and markers of CMVJ performance such as RFD, concentric impulse and peak power have been discovered among similar populations (Gillen et al., 2022). Despite this, definitive relationships between FFM and CMVJ are less prevalent. This may be explained by the idea that while higher FFM levels may entail a larger amount of skeletal muscle, it also entails a higher amount of total body mass that gravity is acting on and must therefore be overcome during the CMVJ. Additionally, when analyzed as an entire group, body fat percentage had a significant negative relationship with CMVJ. This is in alignment with findings on body composition metrics and their impact on CMVJ performance from Ferreira et al., (2010) and Waldron et al., (2014). The results from this study also show a significant negative relationship between body fat percentage and Fmax (N/kg) which may imply that within the selected demographic, lower body fat percentage may be related to higher levels of relative lower body strength. These findings coincide with much of the existing research on CMVJ, relative strength levels and body composition. Among FB group participants, FFM also has a significant positive relationship with Fmax (N), however when Fmax scores were made relative to body mass (N/kg) the relationship became negative. This may be explained by larger athletes in the group having higher absolute maximal force output, while those with a smaller body mass and, therefore lower FFM, displaying higher levels of relative strength. No significant relationships between FFM and lower body force output were found among VB group participants. It should be noted that when each participant group was analyzed individually via Shapiro-Wilk test, body mass was not normally distributed among the FB group or VB group.

When analyzing all participants as one group, there were significant negative relationships between CMVJ RFD and FFM, and body fat percentage. These findings contradict those by Gillen et al., (2022), however do suggest that individuals with lower total body mass as well as decreased proportions of fat mass display increased RFD levels in the CMVJ test, which conform to findings by Ferreira et al., (2010) and Waldron et al., (2014).

4.4 Observed Between-Group Differences

Participants in the FB group had a significantly higher mean body mass compared to the VB group. These findings align with existing normative data on similar populations, wherein football athletes tended to have higher body mass scores than volleyball athletes (Duncan et al., 2006; McKay et al., 2020). The FB group participants also displayed significantly higher scores in body fat percentage when compared to the VB group. Measured bodyfat percentage among FB groups is consistent with findings in previous work examining and comparing skinfold measurement accuracy among collegiate football athletes (Oliver et al., 2012). Bodyfat percentage scores for VB group participants is very comparable to normative data collected on volleyball athletes by Duncan et al., (2006). FB group participants had significantly higher FFM and fat mass values compared to VB group participants. Individual findings align with existing normative values, however there is minimal existing work directly comparing athletes from each sport to identify a statistically significant difference.

FB group participants had a significantly lower group mean CMVJ score compared to the VB group. Mean CMVJ scores for the FB group in the present study were notably lower than those collected in work by previous authors (Bonnette et al., 2011; Dupler et al., 2010; McKay et al., 2020). This may be attributed to the equipment used in the study. Participants in this study completed the CMVJ tests on a set of force plates with jump height being calculated via impulse-momentum method. This method has shown to be the most punitive and accurate means of measuring CMVJ height (Linthorne, 2001) and leads to lower observed scores when compared to other measurements means such as the Vertec or jump mat methods. VB group participants scored significantly higher on the CMVJ test, and mean jump height values are closer aligned with data from previous authors (Duncan et al., 2006).

There were no significant differences between participant groups in Fmax (N) or relative Fmax (N/kg). It is noted that the absolute Fmax mean value for the FB group was higher than that of the VB group, however when Fmax was made relative to body mass (N/kg), the VB group had a nearly significant increase compared to the FB group. This can likely be attributed to the VB group having higher levels of relative strength compared to the FB group. The FB group scored significantly higher on the RSS test in terms of absolute peak power. However, this can likely be attributed to the FB group having significantly higher body mass scores compared to the VB group. Because the load for the RSS test was prescribed as a percentage of body mass, FB group participants would have performed the test on average with more resistance on the sled, and when factored into the calculation for peak power output will tend to lead to higher scores. However, when RSS scores were made relative to body mass (W/kg), the VB group had a non-significant increase compared to the FB group. This can again likely be attributed to VB group participants displaying heightened levels of lower body relative strength and power when compared to the FB group.

4.4.1. FB Group Within-Group Differences FB group participants were further broken up in two separate groups based on position. The Lineman group were classified as any athlete who identified as an offensive or defensive lineman on participant questionnaires. The Skill group were classified as any athlete who identified as one of the following positions: receiver, defensive back, linebacker, running back, quarterback. When data was analyzed in separate groups, all relationships were strengthened between CMVJ, Fmax, Fmax1, and Fmax2 when the Skill position group was analyzed independently compared to the Lineman group and FB group as a whole. The strengthening of these relationships may be explained by findings that improved performance in the CMVJ and relative strength measures are typically present among high school football athletes with lower BM and bodyfat percentage (Bonnette et al., 2011). These findings also suggest a higher level of variance in test scores among the Lineman position group when compared to the Skill position group.

4.5 Limitations of the Current Study

The findings of the present study must be viewed in context of certain limitations. Primarily, the analysis was correlational in nature and therefore can not establish any cause and effect or predict performance in any capacity. Any practical implication derived from the present study must be extrapolative.

Another limitation of the study design was the absence of control for participant fatigue within the experimental sessions. Specifically, researchers were unable to control for any strenuous activity or resistance training before completing the experimental sessions. Previous strenuous exercise or sport participation may serve as a confounding variable and have an effect of participant scores during assessments such as CMVJ, Fmax and RSS. Further, researchers were unable to quantify participant familiarity with the required physical tests. Given the novelty of the Fmax test to many of the participants, it may be reasonable to expect greater variance in the data on account of this. In addition, there was no quantification of skill in the CMVJ test. Given that the vertical jump is a much more prevalent movement in game play for volleyball compared to football, it is reasonable to assume a higher level of skill and economy of movement among VB group participants. This discrepancy would have an effect on examining the relationships between tests and the outcome variable.

A third limitation of this study may have been selecting FFM as a primary correlate of CMVJ performance. While literature exists stating the relationships between FFM and CMVJ performance, the two-compartment model used in the present study may likely does not hold as strong of a relationship with CMVJ as a metric such as percent lean body mass or bodyfat percentage. Selecting an anthropometric measure that more accurately depicts body composition may have been a stronger correlate with the primary outcome of the study.

A final limitation of the present study is the lack of application for female athletes. Due to the stated physiological differences between male and female athletes, the findings may not be relevant for females. Female participants were excluded from this study as female tackle football participants within the specified age range are extremely limited in Canada, and recruitment for equal participant groups was not feasible.

Chapter 5 - Conclusion

The primary findings of this study conform with previous research stating that lower body maximal force production holds a strong positive relationship with CMVJ performance. Additionally, these findings support that relative force production capabilities are more closely related to CMVJ performance than absolute values. Secondary findings from this study illustrate that FFM relative strength scores did not amount to a stronger correlation with CMVJ performance when compared to body mass relative scores. While the results of the present study may not support this, it has been previously well defined that metrics of body composition such as FFM have shown strong relationships with CMVJ performance in adjunct with physiological markers such as relative lower body strength. Tertiary findings from the present study show multiple significant between-group differences when comparing football and volleyball athletes of the same age. Most notably that football players tend to have significantly higher body mass, fat free body mass and body fat percentage, meanwhile volleyball athletes score significantly higher in CMVJ performance and tend to display higher levels of lower body relative strength. In addition, it has been shown that further stratifying football athletes by position group can yield a more accurate insight to the relationships within the present study. It must be stated however that despite any between-group or within-group differences, lower body relative strength consistently held the strongest correlation with CMVJ. The findings of the present study are applicable to strength and conditioning practitioners who are looking to identify physiological traits to measure and train when aiming to assess performance in the CMVJ. Secondly, the results of this study can provide context to strength and conditioning practitioners working with athletes across multiple sport domains on the assessment of between-group differences and their impact on metrics such as lower body force production and the CMVJ.

5.1 Recommendations for Future Research

A direction for future research based off these findings should be to observe how longitudinal changes in Fmax scores over the course of a training intervention impact CMVJ performance. Additionally, findings over the course of a longitudinal study can be more powerful than those from a cross-sectional design such as the present study. If these cause and effect relationships are quantified over time, specific training interventions can be developed aimed specifically to improve performance in Fmax and CMVJ tests that are supported by research findings. This can provide athletes aiming to improve performance in these tests with a better understanding of how to specifically train for the required physiological adaptations, as well as provide practitioners with exercise prescription guidelines for best practice.

Further research can be done analyzing different methods of relativizing lower body force production. While the present study used BM and FFM, using other metrics such as fat mass or bodyfat percentage to relativize Fmax may lead to stronger relationships with CMVJ performance. This information can be relevant for strength and conditioning practitioners looking at different means of improving CMVJ performance outside of traditional training interventions.

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