Comparing vertical jump height measurement methods

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ABSTRACT

Vertical jump height is a method of assessing muscle strength and power in the lower body, and is used to assess athletic ability. The gold standard in measuring vertical jump height is the measurement of vertical centre of mass (COM) displacement from three-dimensional (3D) video analysis. Vertical jump height is ultimately affected by takeoff COM velocity, as greater takeoff velocity results in greater jump height. The current study explored the use of takeoff versus maximum COM velocity by examining the relationships and differences between 3D video analysis and 3D force platform analysis when predicting vertical COM displacement. Use of the Vertec, and correction of takeoff COM velocity using takeoff position, was explored through methods proposed by Aragon-Vargas (2000) and Moir (2008). Measurements were taken simultaneously on a single countermovement jump trial for 13 female varsity volleyball players. Centre of mass displacement from video analysis revealed the strongest correlation with jump height from maximum COM velocity, r=0.907, p=0.000. Use of repeated measures analysis of variance (ANOVA) revealed statistically significant differences between jump heights computed by each of the explored methods, $F(1,12)$=1073.421, p=0.000. Linear regression suggested that, of the explored methods, maximum COM velocity explained the greatest proportion of the variance in vertical COM displacement from video analysis (R^2=0.822) and the lowest mean square error (0.023m), when compared to conventional methods of jump height determination. Use of maximum COM velocity in computing vertical COM displacement therefore showed evidence of concurrent validity with 3D video analysis. The outcome of this study will allow future assessments of vertical COM displacement to be computed with greater ease and with less measurement error. This will have implications for researchers and sport organizations to better measure athletes' performance from force platform analysis alone.

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CHAPTER 1

Introduction

Vertical jump is widely used as a means of assessing muscular strength and power in the lower body, with the goal of predicting athletic potential (Markovic & Jaric, 2007). Due to the importance of explosive strength in the leg muscles, sports including weightlifting, football, basketball, volleyball and track often use the vertical jump test as a means of performance prediction (Moir, 2008). The standing countermovement vertical jump (CMVJ) is widely used because it is simple to perform and closely related to movements made during sport (Vanezis & Lees, 2009). Although a number of methods of examining vertical jump exist, vertical jump height is the most commonly used variable in tests examining the vertical jump. A great deal of importance is placed on vertical jump height because of its relative ease of determination (Aragon-Vargas, 2000).

Vertical jump proficiency is also determined by strength, speed, and segment coordination (Dowling & Vamos, 1993; Harman, Rosenstein, Frykman, & Rosenstein, 1990). Specifically, it is suggested that higher jumps are faster, with all movement phases (countermovement through force production) occurring in less time, or temporally closer to takeoff (Harman, Rosenstein, Frykman & Rosenstein, 1990). Furthermore, peak positive COM velocity occurs not at takeoff, but instead, before takeoff (Harman, Rosenstein, Frykman & Rosenstein, 1990). Based on this information, there is a need to examine the use of maximum COM velocity versus takeoff COM velocity to better estimate jump height measures during vertical jump performance.

Vertical jump performance can be assessed through a number of different approaches and methods. Some of these methods include anthropometric, kinetic and kinematic variables that are sometimes used as predictors to explain vertical jump performance (Dowling & Vamos, 1993; Hara, Shibayama, Takeshita, Hay, & Fukashiro, 2008; Riggs & Sheppard 2009; Vanezis, & Lees, 2009; Voigt, Simonsen, Alkjaer, Bojsen-Moller, & Klausen, 1999). In research, anthropometric factors, including limb length and body composition have been shown to influence power production in both men and women during vertical jumps. For instance, participants with greater limb length, greater muscular development, and lower body fat percentage, produce greater power (Riggs & Sheppard 2009). Similarly, kinematic analysis allows information to be gained in terms of segment velocities, centre of mass (COM) velocity and jump height, calculated from the distance traveled by the COM (Hara, Shibayama, Takeshita, Hay, & Fukashiro, 2008; Vanezis, & Lees, 2009; Voigt, Simonsen, Alkjaer, Bojsen-Moller, & Klausen, 1999). Finally, force-time curves contain kinetic and temporal information that can be used to evaluate athletic movements (Dowling & Vamos, 1993). Although the chosen methodology has implications on the type of information that can be drawn to explain vertical jump performance, each method of inquiry sheds a unique light on the ability to assess characteristics of the movement, determining the variables that can be assessed and the associated sources of measurement error (Atkinson & Nevill, 1998).

Determining vertical jump height through calculation of COM displacement, from standing height to peak flight height, is considered the gold standard in evaluating jump performance (Aragón-Vargas, 2000). Precise measurement of COM displacement is usually calculated through digitized video footage and the most valid technique is considered 3D kinematic analysis (Yeadon, Trewartha, & Knight, 2004). In general, the fundamental objective of the vertical jump is to achieve the greatest vertical velocity at takeoff. Measures of takeoff velocity can be used in conjunction with uniform acceleration equations to determine ones' jump height, as outlined in equation 1 (Dowling & Vamos, 1993; Harman, Rosenstein, Frykman, & Rosenstein, 1990; Moir, 2008).

$$h = \frac{v_{toff}^2}{2g} \tag{1}$$

where:

g: is the acceleration due to gravity (a constant 9.81ms^{-2} down)

v_{toff}: is vertical takeoff velocity of the COM

Flight time from takeoff to landing during the vertical jump can also be used to determine vertical jump height using equation 2 (Aragón-Vargas, 2000).

$$h = \tfrac{1}{2} g \left(\frac{t}{2}\right)^2 \tag{2}$$

where:

h: is vertical jump height

g: is acceleration due to gravity

t: is flight time

Determining jump height from flight time, however, relies on the assumption that the time from takeoff to peak height, and the time from peak height to landing are equal (Aragón-Vargas, 2000). This is only true if the participant takes off and lands in the same body position. For example, if the knees are bent during landing, jump height will be overestimated (Aragón-Vargas, 2000; Dowling & Vamos, 1993). As a result, this method creates a threat to validity during the interpretation of vertical jump test results.

The use of takeoff velocity relies on mechanically correct assumptions, from particle dynamics equations for conditions of uniform acceleration (Young, Wilson & Byrne, 1999). It is assumed in equation 1 that gravitation is a constant, which is a generally accepted assumption in particle dynamics equations (Young, Wilson & Byrne, 1999). Unfortunately, when applying equation 1 to human motion, a gap is observed between the jump heights from the particle dynamics equation versus actual vertical jump height; this is an issue that deserves attention (Aragon-Vargas, 2000). During human movement, takeoff velocity is used to calculate jump height, however, body position at takeoff is not taken into account. Based on these concerns, Aragón-Vargas (2000) suggested the use of equation 3 (Aragón-Vargas, 2000).

$$h = \frac{v_{toff}^2}{2g} + h_{toff} - h_{stnd} \tag{3}$$

where:

h: is vertical jump height

v_{toff}: is vertical takeoff velocity of the COM

h_{toff}: is vertical COM takeoff height

h_{stnd}: is vertical COM standing height

Here, jump height is corrected for body position at takeoff. Calculation of jump height using this method is valid, however, actual measurement of the required variables ideally requires the synchronized use of both force plate and kinematic data from video digitization (Aragón-Vargas, 2000). The use of digitized video footage by Aragón-Vargas (2000) involved 3D motion analyses at a sampling frequency of 60Hz, or 60 frames per second, which is the standard in sampling frequency of video recording. An insufficient frame rate has the potential for measurement error, due to the necessity to interpolate between acquired data points (Aragon-

Vargas, 2000). As a result, takeoff position may be incorrectly identified. Higher sampling frequency allows more accurate identification of the instant of takeoff. Specifically, the force platform in the analysis by Aragon-Vargas (2000) collected data at 300Hz, in contrast to the video data, sampled at 60Hz. It is also suggested that an error of 16.7ms (one video frame sampled at 60Hz) would cause a discrepancy between measured and actual takeoff position of 44mm, which is then added into the calculation of jump height (Aragón-Vargas, 2000). The jump height equation using takeoff velocity, for corrected body position, requires both digitized video and force platform data. If kinematic analysis of the COM is being carried out from digitized video then precise determination of the vertical displacement of the COM can be measured without this equation.

Previous research suggested that a method of calculating jump height with decreased measurement error should be examined in relation to takeoff velocity (Aragón-Vargas, 2000; Moir, 2008). For example, Moir (2008) proposed the use of the same takeoff velocity correction formula, using takeoff position, though the calculation of COM takeoff height is carried out through integration of COM velocities measured using force platform analysis. This method of correction avoids the reliance on video footage at lower sampling frequency, and does not rely on synchronization between video and force platform data (Moir, 2008).

Determining takeoff velocity is generally carried out through measurement of ground reaction forces and integration, using force platform data and associated computer software (Robertson, Caldwell, Hamill, Kamen & Whittlesey, 2004). The use of force platform data in measuring COM velocity is the result of a reliance on sound mechanical concepts and strong validity and reliability associated with the instrument (Robertson, Caldwell, Hamill, Kamen & Whittlesey, 2004). It is proposed that the use of force platform data alone may provide a means of calculating vertical jump height that does not require the use of digitized video, and corrects for underestimation of jump height from takeoff velocity alone. Examining changes in COM velocity from maximum to takeoff may provide this opportunity.

Examining the use of maximum COM velocity during the countermovement vertical jump is worthwhile, as there is a need to provide other means of calculating vertical jump height. This research furthers the work of Aragón-Vargas (2000) and Moir (2008) in offering a new method of jump height determination using force platform data alone. This study also compares jump height determination for laboratory versus field tests.

Purpose

The purpose of this study was to examine the relationships and differences between two laboratory methods used for vertical jump height determination, 1) jump height measured from a 3D video analysis based on COM displacement 2) jump height calculated using maximum COM velocity during the takeoff phase of a vertical jump, measured by a 3D force platform system, in combination with equation 4 (Aragon-Vargas, 2000).

$$h = \frac{v^2}{2g} \tag{4}$$

where:

h: is vertical jump height

v: is vertical velocity of the COM

g: is acceleration due to gravity

Further laboratory methods included the use of takeoff COM velocity in equation 4, as well as the Aragon-Vargas (2000) and Moir (2008) methods of correcting takeoff COM velocity with takeoff position. Predicting jump height measured from 3D video analysis was also explored using linear regression. Finally, relationships and differences between laboratory measurement techniques were compared to field test measurements from the Vertec apparatus.

Significance of the study

The aim of this research was to examine differences between calculation of jump height from maximum and takeoff COM velocities, measured from 3D force platform analysis, when compared to use of the gold standard of jump height assessment, 3D video analysis. This study contributes to the current body of literature, furthering the work of Aragón-Vargas (2000) and Moir (2008). Both Aragon-Vargas (2000) and Moir (2008) used equation 3 to correct COM takeoff velocity with COM takeoff position in attempting to better predict 3D video vertical COM displacement. Aragon-Vargas (2000) combined force platform and 3D video analyses, while Moir (2008) explored the sole use of force platform data in equation 3. Despite each of these methods demonstrating evidence of validity, the use of maximum COM velocity in equation 4 employs a previously unexplored method of jump height determination. Here, equation 4 takes the form:

$$h = \frac{v_{\max}^2}{2g} \tag{5}$$

where:

h: is vertical jump height

$v_{\max}$: is maximum vertical velocity of the COM

g: is acceleration due to gravity

Overall, seven methods of vertical jump height determination were examined. These methods included the use of the Vertec, 3D video analysis vertical COM displacement, and computations using equations 1, 5, 3, and an adjusted equation 5 from linear regression. Equation 3 was utilized twice, once by the Aragon-Vargas (2000) method, and once by the Moir (2008) method.

The implication of better predicting 3D video vertical COM displacement using maximum COM velocity alone from a force plate, provides a new method of measuring jump height. This method provides a better representation of vertical COM displacement, allowing data to be acquired with decreased measurement error, and with greater ease when compared to the gold standard (3D video vertical COM displacement).

Limitations

1. The Vicon Motus software screen resolution is fixed at 656x492 pixels, limiting the accuracy of subsequent measurements from the field of view of the camera during filming. Appendix E shows the calculation, converting field of view measurements to the screen resolution, representing the number of centimetres per pixel.
2. The spacing of the Vertec vanes limits the accuracy of vertical jump height values measured from this apparatus. The spacing of the vanes on the Vertec apparatus used in this analysis was 1.6cm.

Delimitations

1. The study was delimited to female participants from the Lakehead University women's varsity volleyball team. As a result, participant age was delimited from 18 to 22 years.
2. Only female participants were included, due to anthropometric differences between male and female participants, which may require the evaluation of each gender separately.

3. The data acquisition rates of the force platform and cameras being used were delimited to 1000Hz for force platform data and a sampling frequency of 100Hz for video footage.
4. The selected methodologies delimit the results to the kinetic and kinematic data, and the subsequent methods of calculating jump height. Though other methods exist, jump height determination from the gold standard (3D video analysis) was compared to the use of a Vertec apparatus, and calculation of jump height from equations 3 and 4.
5. Though numerous protocols exist in terms of the type of jump that can be assessed, the countermovement jump was specifically examined in this study. This jump was chosen due its similarity to techniques used in sport settings.

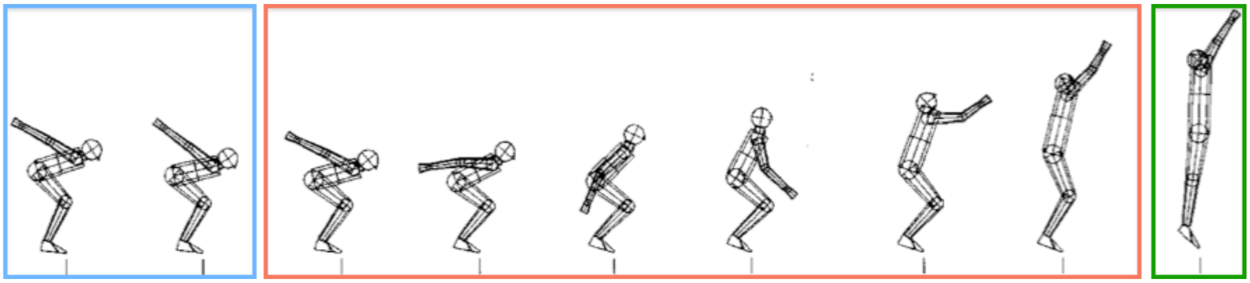
CHAPTER 2

Review of Literature

The vertical jump has been assessed in a number of studies, involving contrasting methodologies, and with respect to a range of variables. The literature was therefore organized in terms of the uses and types of vertical jump performance, the methods of analysis, anatomy, physiology and biomechanics of the movement, and finally the timing and sequencing of the countermovement vertical jump. This organizational approach allows understanding of the current methods of measuring vertical jump height, and the importance of identifying specific relationships and differences between takeoff and maximum velocities in predicting vertical COM displacement during the countermovement vertical jump.

The countermovement jump

The countermovement vertical jump (CMVJ) is composed of various phases. As the name suggests, the countermovement vertical jump is initiated with a countermovement, where eccentric stretching of the musculature precedes concentric force production. The phases of the jump can be defined in terms of the velocity of the COM, which is either positive or negative in value depending on the direction of movement (Hudson, 1986). The countermovement is defined as negative, when the COM is moving downwards, resulting in negative velocity of the COM. This velocity reaches zero during the transition between eccentric and concentric contraction, and then begins to move upwards, or positively, as the force production phase begins (Hudson, 1986). Although muscular activity and force production occur during the eccentric, or countermovement, when muscle tissues are stretched, force production is defined as positive work where tendons rapidly shorten and muscle tissue contracts, eventually causing the COM to rise (Wilson & Flanagan, 2008).



Backswing Force Production Critical Instant

Figure 1: Countermovement jump photo sequence (Feltner, Fraschetti & Crisp, 1999)

Figure 1 illustrates the jump phases used to qualitatively analyze the countermovement jump. The phases are described as preliminary movements, backswing, force production, critical instant and follow through (Alexander & Way, 2009). The preliminary movements involve the participant setting the feet and readying for the jump. This is followed by the backswing phase, where the COM is lowered, and muscles are stretched prior to being contracted (McGinnis, 2005). Next, force production begins by muscles contracting concentrically, leading to a critical instant, which involves takeoff from the ground ((McGinnis, 2005). Finally, the participant is in follow through during flight including the point of maximum vertical displacement (Alexander & Way, 2009; McGinnis, 2005).

The countermovement jump action is carried out through a quick flexion of the knees, hips and dorsiflexion of the ankle, as well as hyperextension at the shoulder, with arms extended at the elbow. While performing a countermovement vertical jump, the COM of the participant's body drops prior to moving the COM upwards, as opposed to the squat jump where participants begin the movement with the knees and hips already flexed, and the ankle dorsiflexed (Harman, Rosenstein, Frykman & Rosenstein, 1990). The force production opposes the countermovement, involving extension of the knees and hips, plantar flexion at the ankle, and flexion at the shoulder (Feltner, Fraschetti & Crisp, 1999). Cheng (2008) identifies that often the elbow joint can be assumed motionless as the joint is found to move only within 7 degrees while the participant is in contact with ground. As a result, he suggests that contributions from this joint may be ignored, instead focusing on torque at the shoulder joint (Cheng, 2008). Both the squat jump, starting from a flexed position, or the CMVJ, starting at standing position, can be carried out with the participant using, or not using, the arms to assist in force production. In general, the countermovement and the use of the arms both result in increases in vertical jump height, and when used in combination, can additively combine to improve jump height (Feltner, Fraschetti & Crisp, 1999). The countermovement jump with arm swing is of interest in this study, for the tendency of the movement to be found in sport settings.

Vertical jump assessment

The use of the vertical jump, as a method of assessing and predicting movement performance, lower limb muscle power, and athletic potential is common throughout the literature (Aragon-Vargas, 2000; Markovic & Jaric, 2007; Moir, 2008). The variable of importance from this test is generally considered vertical jump height. Although a great deal of importance is placed on the actual number obtained through tests of vertical jump height, performance during the test is largely dependent on the type of test used, and the technique used during the jump (Aragon-Vargas, 2000). The vertical jump can be assessed through a number of different methods or techniques, the most enduring method, however, is the standing countermovement vertical jump (CMVJ; Vanezis & Lees, 2009). The CMVJ is used due to its simplicity in terms of performance, but is also similar to the movements found naturally in sport environments (Vanezis & Lees, 2009).

The benefits of assessing vertical jump performance lies in the ability to understand, train and coach jumping skill. Identifying variables that influence success in vertical jump height allows modification in training techniques that focus on specific aspects of the movement (Cheng, 2008). The ultimate goal is therefore to create a framework of variables influencing vertical jump height, and subsequent means of altering jump technique, or training to optimize performance (Bobbert & Van Soest, 1994). Studies generally aim to use predictors of vertical jump that can be altered (Davis, Bosley, Gronell, Keeney, Rossetti, Mancinelli & Petronis, 2006). Both trainable and un-trainable variables are, however, responsible for determining vertical jump height. Variables that cannot be altered through training include age or gender, while factors such as strength, coordination, or technique (measures of neuromuscular functioning), muscle power, and muscle fibre type can, in some cases, be altered through training (Davis, Bosley, Gronell, Keeney, Rossetti, Mancinelli & Petronis, 2006; Vanezis & Lees, 2009).

Measurement of vertical jump

Vertical jump performance varies in terms of the technique used, but the methods of analyzing the jump, also have implications on the ability to examine causal relationships between given variables and vertical jump height. The CMVJ, in this study is examined using the jump and reach height field test, measured from the Vertec apparatus, as well as through laboratory tests, including 3D video analysis, 3D force platform analysis, and through combination of these methods.

Jump and reach test

Defining vertical jump height is important prior to selecting a method of measuring jump height. Vertical jump height can be examined in terms of jump and reach height or can be defined with respect to the vertical displacement of the COM (Moir, 2008). Though the vertical displacement of the COM, measured using 3D video analysis, provides a closer estimation of jump height, the most commonly used method to estimate jump height is the Sargent’s test, or the jump and reach test (1924; cited in Aragon-Vargas, 2000). During the jump and reach test the participant first conducts a stand a reach test, with arms extended above the head, touching the highest vertical point with the dominant hand (Harman, Rosenstein, Frykman & Rosenstein, 1990). The participant then jumps maximally and records the highest point of contact on either a wall, or jump system, such as a Vertec apparatus (Channell & Barfield, 2008; Harman, Rosenstein, Frykman & Rosenstein, 1990). The jump and reach test offers benefits in that it supplies the participant with a physical goal to reach. This external focus of the test is suggested to result in superior performance and learning (Wulf & Lewthwaite, 2009). The method of touching a wall at the maximum point of contact has been reported to have a reliability of 0.93, as reported by Johnson and Nelson (1974; in Aragon-Vargas, 2000). This method has been criticized, however, for its restrictive nature in terms of having to jump directly beside a wall, as opposed to straight up in the air, which may impede jump height (Harman, Rosenstein, Frykman & Rosenstein, 1990). The participant is required to reach toward the wall, while at the vertical peak of the jump, reaching away from their body, therefore losing height from the jump and reach. As a result, Vertec jump systems have been developed as a tool to measure jump and reach, while still allowing the participant to simply jump straight up in the air, touching vanes at the highest point of contact. Furthermore, this method has shown reliability amongst athletes including NCAA Division I men's volleyball players and male and female elite weightlifters at the Olympic training center (Channell & Barfield, 2008).

Other methods of calculating vertical jump height include the use of uniform acceleration equations of motion to provide a theoretical calculation of the vertical displacement of the COM during flight. Two methods, calculating theoretical jump height, are commonly used when estimating vertical jump height gathered from a force platform, or jump mat, measuring flight time of the participant (Aragon-Vargas, 2000; Dowling & Vamos, 1993; Moir, 2008). As was previously discussed, vertical jump height can be calculated using the equation 1. Conversely, one may calculate a theoretical vertical jump height from the participant's flight time using equation 2.

Though these other methodologies exist to determine vertical jump height, jump and reach simply provides the most commonly used test due to its ease of use and minimal equipment required. The validity of the test, however, has been questioned in terms of reported discrepancies between jump and reach and COM displacement data (Moir, 2008).

Kinematic data

In contrast to the jump and reach test's simplicity, and reliance on the highest point of contact with the fingers, kinematic analysis allows determination of the COM, as estimated through marked joint vertices and their movement through space, over time (Aragon-Vargas, 2000). Kinematic analysis specifically involves video recording movements and digitization of the video sample. Digitization is carried out using computer software, creating a spatial model of the segments being examined (Vanezis & Lees, 2009). Joint vertices are identified creating a digitized model of the entire body, separating the model into body segments, which can then be analyzed with computer software to measure segment displacements, velocities and acceleration throughout the video clip (Vanezis & Lees, 2009). Due to the level of depth at which this method of inquiry is carried out, and the reliance on sound mechanical concepts, determination of jump height from kinematic analysis of the COM is considered the gold standard in vertical jump height assessment (Aragón-Vargas, 2000).

Digitization and subsequent kinematic analysis is dependent on the initial placement of reflective markers, which serve to provide landmarks that represent joint vertices during digitization (Vanezis & Lees, 2009). The placement of these reflective markers is therefore highly important in terms of both validity and reliability. Accurately placing reflective markers at joint markers is generally carried out with the identification of bony landmarks, representing joints (Vanezis & Lees, 2009). Bony landmarks, identifying joints of interest include the tip of the acromion process at the shoulder joint, the lateral epicondyle of the humerus at the elbow joint, the styloid process of the ulna at the wrist joint, the greater trochanter of the femur at the hip joint, the lateral epicondyle of the femur at the knee joint, and the lateral malleolus of the fibula at the ankle joint (Vanezis & Lees, 2009). The top of the head is also identified, as is the length of the foot, as measured from the calcaneal tuberosity to the tip of the distal phalynx of the 1st metatarsal bone (Vanezis & Lees, 2009). From all of the above bony landmarks 17 vertices can be labeled. In creating a digitized model, the ears can also be included to identify rotation of the head, ultimately creating a model of 19 vertices, representing the human body. Applying this 19-point anthropometric model to a participant allows calculation of the total body COM from data identifying the COM of each segment. The placement of reflective markers determines the validity of the created digitized model. Placement of the reflective markers from trial to trial, and from participant to participant, further determines reliability, with the possibility of movement of the markers on the skin causing a potential source of reliability loss (Vanezis & Lees, 2009). Although the issue of reliability, in terms of marker placement, can be made, in practice the method of digitizing human movement through the use of reflective markers has shown evidence of both validity and reliability (Aragón-Vargas, 2000).

Though a great deal of importance is placed on locating bony landmarks and attaching reflective markers, ultimately one must digitize the points, creating a digital model of the actual human participant (Vanezis & Lees, 2009). The process of digitizing body landmarks can be carried out by either manual or automatic methods, where the reflective markers are either identified in each frame of video manually, or are identified through recognition by computer software (Yeadon, Trewartha & Knight, 2004). Each of these methods has limitations and drawbacks. For instance, manual digitization, as might be expected, can be extremely time consuming as each frame of the video must be digitized individually (Yeadon, Trewartha & Knight, 2004). Automatic digitization is generally far less time consuming, though the ability of the computer to recognize reflective markers is imperfect, and the location of markers can be missed (Yeadon, Trewartha & Knight, 2004). Combing automatic and manual digitizing therefore allows errors to be picked out and frames with unidentified markers to be manually identified (Yeadon, Trewartha & Knight, 2004).

Finally, the sampling frequency also has implications on the ability to draw conclusions from the data. For faster movements, higher sampling rates are required, offering more images of information in a given amount of time (McGinnis, 2005). Video footage is generally 60Hz, or 60 frames per second, though faster movements, as in the case of the countermovement jump, should have suitably higher sampling rate (McGinnis, 2005). The available method of digitization often determines sampling frequency as a higher frequency returns a greater number of images to be digitized, therefore increasing the time requirements for manual digitization. Also, worth consideration is whether analysis will be carried out in 2 or 3 dimensions. Two or 3D digitization is possible, where two-dimensional analysis only acquires data from one camera, 3D analysis uses a minimum of two cameras (Robertson, Caldwell, Hamill, Kamen & Whittlesey, 2004). As may be understood using the analogy of sampling frequency, however, the more cameras acquiring data, the more information that must be digitized. With respect to the countermovement vertical jump, two-dimensional digitization can often be used, as the movement is generally considered to occur symmetrically, when comparing movements on the right and left sides of the body, on each side of the sagittal plane (McGinnis, 2005). The most valid measurement of COM displacement during the vertical jump is, however, 3D video analysis (Aragón-Vargas, 2000).

Though kinematic exploration through digitization provides a much more in depth examination of segment velocities, and the calculation and representation of the COM through the use of digitized video, necessary equipment is costly and difficult to use (Aragon-Vargas, 2000). As a result, the use of kinetic data, obtained from a force platform provides an alternative that allows the calculation of COM velocity through integration of ground reaction forces (Aragon-Vargas, 2000). Due to the nature of this exploration, focusing on the distinction between COM velocity from peak positive value to takeoff, and the requirement of high sampling frequency to capture the rapid movement, force platform data provides invaluable information.

Kinetic data

Unlike jump and reach tests, kinetic analysis of vertical jump performance only reveals measures of ground reaction forces, when the participant is in contact with the ground. The pattern of force application during the countermovement jump appears in Figure 2, illustrating a negative peak indicating the countermovement, followed by positive peaks, the first representing flexion of the arms during force production, and finally extension of the hip and knee joints at the second positive peak (Dowling & Vamos, 1993; Feltner, Fraschetti & Crisp, 1999). The flat horizontal line beyond 1.3 seconds demonstrates the loss of contact with the ground, or takeoff.

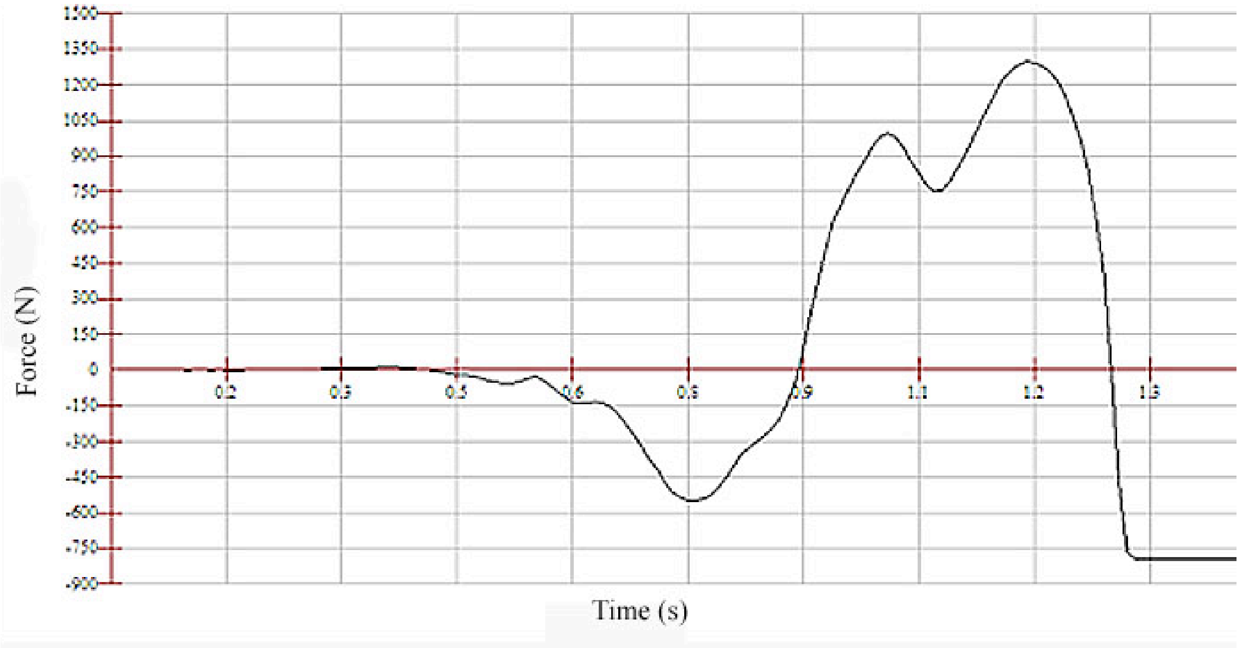


Figure 2: Force vs. time curve during countermovement vertical jump

This method of inquiry offers analysis that can be precisely calibrated, offering excellent reliability and small measurement error, as well as sampling rates unmatched by video footage (Aragon-Vargas, 2000). Furthermore, this method of measuring vertical jump characteristics utilizes assumptions that are generally accepted. These assumptions include the representation of the COM measured via ground reaction forces, calculation of COM velocity and displacement through integration of ground reaction forces, and the use of the gravitational constant in these calculations (Aragon-Vargas, 2000; Dowling & Vamos, 1993; Moir, 2008; Young and Freedman, 2003). Measurement of ground reaction forces, through integration and application of equations of uniform acceleration to calculate jump height, also allows calculation of COM velocity, power and impulse values (Moir, 2008). As the name suggests, the force platform measures force in three dimensions, and traces the application of the ground reaction forces onto the platform across time. The raw data from the force platform therefore comes in the form of forces at each available time that the data is acquired, depending on the sampling frequency.

From this raw force data, velocity in the direction of interest can be calculated through integration (Moir, 2008). Integrating force over a given time interval, and dividing by the mass on the force platform returns the velocity of the COM. This can be understood through equation 6 (Young & Freedman, 1995).

$$v = \frac{1}{m}\int_{t_o}^{t_f} F \cdot dt \tag{6}$$

where:

v: is velocity of the COM in the direction under consideration

m: is the mass on the force platform

t_f: is the final time over the interval being examined

t_o: is the initial time over the interval being examined

$F \cdot dt$: is force as a function of time

Furthermore, impulse can be calculated through the use of equation 7 (Young & Freedman, 1995).

$$I = F\Delta t \tag{7}$$

where:

I; is impulse

F: is Net Force in a given direction under consideration

Δt: is change in time

For the calculation of instantaneous power in a given direction (x, y or z), or net force, this can be regarded as the rate at which force does work on the given mass (Young & Freedman, 1995). Mathematically this can be understood with equation 8.

$$P(t) = F(t) \cdot v(t) \tag{8}$$

where:

$P(t)$: is instantaneous power

$F(t)$: is instantaneous net force the given direction

$v\ (t)$: is instantaneous velocity in the given direction

t: is the time at which measurements are taken

The sampling frequency of force platform analysis allows a sensitive measure of movement characteristics and temporal information regarding the body's COM. As the CMVJ is a ballistic movement, occurring very rapidly over time, it is beneficial to collect temporal information at high sampling frequency. It has been reported that sampling frequencies as low as 300Hz can cause approximately 2% underestimation of jump height, while sampling frequencies over 1000Hz almost entirely remove this source of error (Moir, 2008). The calculation of jump height is generally encouraged to be determined through use of the takeoff velocity of the COM, though other methods, including time in the air from takeoff to landing can also be used (Moir, 2008). Synchronization of kinematic analysis through video digitization with kinetic force platform information is also possible, though examining force platform data separate from digitized video allows later comparisons to be made, if synchronization is not possible (Aragon-Vargas, 2000; Moir, 2008). A downside to this method, however, is the difference in available sampling rate between video analysis and force platform data. Video analysis, for example, offers less information because it has lower sampling rates than a force plate, especially during rapid movements like the vertical jump. In the case of a force plate, the sampling frequency of the force platform needs to be reduced to match the video footage, resulting in the same loss of information. As a result, Moir (2008) proposed the integration of COM velocity, measured from force platform data, as a means of calculating COM displacement. Computationally, this can be understood from equation 9 (Young & Freedman, 1995).

$$d = \int_{t_o}^{t_f} v \cdot dt \tag{9}$$

where:

d: is COM displacement in a given direction

t_f: is the final time over the interval being examined

t_o: is the initial time over the interval being examined

$v \cdot dt$: is velocity as a function of time in the direction under consideration

The use of this equation in computing vertical COM displacement at standing versus takeoff allows measurements to be acquired at the sampling frequency of the force platform, and therefore does not require synchronization of video and force platform data (Moir, 2008). In fact, the force plate method does not require the use of video footage at all; as a result, this method was further explored in this analysis by comparing acquired force plate values to those obtained through measurement of vertical COM displacement from 3D video analysis.

Overall, it is worth noting that variability from measurements, or estimates, of jump height can be the result of the sensitivity of the instrument, or as a result of small measurement error (Aragon-Vargas, 2000). Variability can be examined in terms of both reliability and error (Aragon-Vargas, 2000). The goal in determining jump height in any setting is to rely on data with high reliability and small measurement error. Kinetic data, obtained from a force platform offers high sampling frequency that can be used to minimize measurement error, the result of interpolating information between sampled data. Examination of the CMVJ is possible by the various methods identified above, exploring the possibility of more accurately determining jump height from force platform data alone may reduce the sources of measurement error. Comparing methods of jump height calculation from 3D force platform data, and jump height measured from COM displacement during 3D kinematic analysis allows the assessment of such techniques.

Factors that impact vertical jump performance

Vertical jump height is determined by a number of different factors, which can be examined through various methods of analysis. Depending on the method of analysis, differing factors will be highlighted in terms of their significance relative to vertical jump height. Significant correlations between muscular strength and rate of force production, an indication of muscular power, have been identified as contributing to vertical jump height (Peterson, Alvar & Rhea, 2006; Sheppard, Cronin, Gabbett, McGuigan, Etxebarria & Newton, 2008). Confounding variables have also been identified, which have implications on the significantly contributing variables. Some of these include age, sex, body composition, physical activity level and skill (Markovic & Jaric, 2007). Jump height, however, is ultimately determined by the vertical velocity of the COM at takeoff, which is in turn influenced by factors including biomechanics and physiology (Oddsson, 1987). Hay and Reid outline a deterministic model of variables influencing vertical jump height (1988; in Feltner, Fraschetti & Crisp, 1999). Figure 3, presents this deterministic model, suggesting that jump height is a function of takeoff height and flight height, each of which are functions of other variables. Takeoff height is seen to be composed of biomechanical variables physique and takeoff position, while flight height is determined by variables including takeoff velocity, mass, and ground reaction forces, which are produced as a result of segment contributions (Feltner, Fraschetti & Crisp, 1999). Variables including the forces produced by each segment are the result of biomechanics as well as the physiology of constituent muscles.

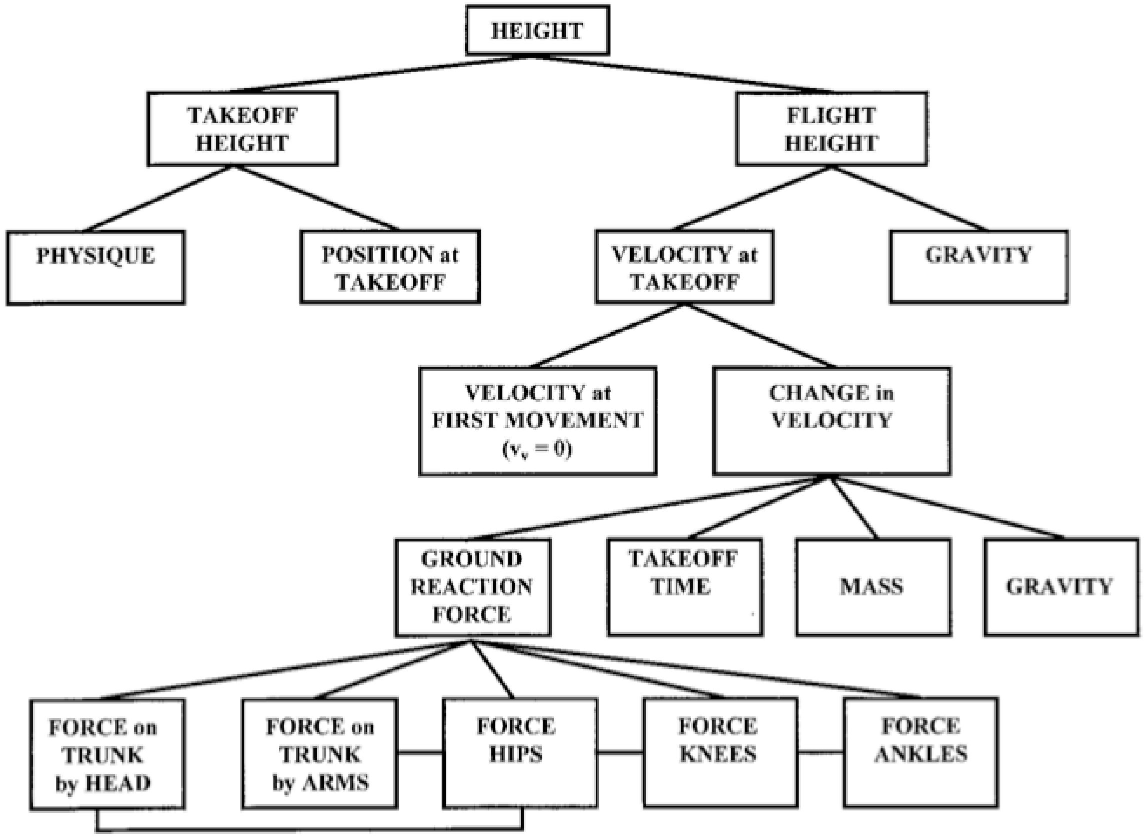


Figure 3: Deterministic model of vertical jump (Hay and Reid, 1988; in Feltner, Fraschetti, & Crisp, 1999)

Strength

Referring to Figure 3, force production at each joint is the result of muscular strength in the associated muscles. Numerous studies have been performed assessing muscular strength in relation to vertical jump height. Channel and Barfield (2008) suggest that low strength, the result of poor muscular development impedes athletic performance, including vertical jump, and provides a key source of trainable improvement for less-trained individuals. Similarly, muscular strength of the lower limb joints, reflected in measured joint torques, is described as the main determinant of vertical jump performance (Cheng, 2008; Vanezis & Lees, 2009).

Interestingly, muscular strength alone may not serve as the best predictor, as it is suggested that the rate of force production may actually be the more appropriate variable than pure strength (Peterson, Alvar & Rhea, 2006). Specifically, higher jumps are suggested to be faster, with all stages temporally closer to takeoff (Harman, Rosenstein, Frykman & Rosenstein, 1990). Characteristics influencing jump height are therefore dependent on muscle force production as well as shortening velocity. Furthermore, body mass adjusted muscular strength is also a better predictor of vertical jump performance than absolute strength, suggesting that training should likely be carried out with the intent of increasing strength at high velocity, if the aim is to improve vertical jump (Dowling & Vamos, 1993; Peterson, Alvar & Rhea, 2006).

Training gains, observed in studies on ballistic resistance training were specifically attributed to neural factors, the result of improved motor unit recruitment and inhibition of protective antagonist muscle action (Channell & Barfield, 2008). Overall, it is the combination of strength and speed, expressed in terms of power that may more significantly influence vertical jump height (Channell & Barfield, 2008). Force production during the CMVJ is generally regarded as consisting of two separate entities, maximal force and the rate of force production (Peterson, Alvar & Rhea, 2006). The relationship between force and time therefore deserves more attention.

Speed

If the goal in training is to improve the rate of force production, it is important to identify the relationship between force and velocity, in terms of muscular output. The force-velocity relationship dictates interactions between muscular contraction velocity and the force of contraction (Peterson, Alvar & Rhea, 2006). Specifically, muscles contract concentrically, during force production, such that speed is inversely proportional to the load, as is apparent on the concentric side of the curve, revealing a hyperbolic shape, shown in Figure 4 (Peterson, Alvar & Rhea, 2006). The eccentric side of the curve demonstrates the inverse hyperbolic shape, where high muscular force is produced at high velocity, though the muscle is increasing in length. Here energy is stored in the muscle elastically, though forces responsible for moving the COM upwards have not yet been produced.

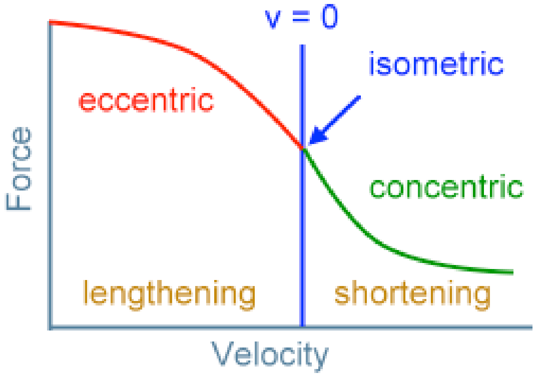


Figure 4: Force-velocity curve of skeletal muscle (Bloomfield, Ackland, & Elliot, 1994)

The product of force and velocity is defined as power, measured in Watts, which in terms of muscular output is dependent on both biological and mechanical factors (Markovic & Jaric, 2007). These factors include muscle size, fibre type and layout, as well as muscle length and speed of contraction, where specifically the speed-strength relationship of the leg extensors is identified as important in vertical jumping (Markovic & Jaric, 2007; Young, Wilson & Byrne, 1999).

Regarding each of these factors, large muscle size can generally be associated with greater muscular strength, though it is suggested that slower movements are more strongly influenced by maximum strength, therefore larger muscle size is not always an indication of greater muscular power (Young, Wilson & Byrne, 1999). Speed of muscular contraction, a better indicator of muscular power, is largely dependent on muscle fibre type, as well as the load on the muscles (Peterson, Alvar & Rhea, 2006). In terms of fibre type, classifications are divided in terms of fast and slow twitch muscle fibres, though hybrid fibres, combing to some intermediate rate of contraction, are also possible (Andersen, Andersen, Magnusson, Suetta, Madsen, Christensn et al., 2005). As is apparent from Figure 4, a greater load on the muscles, including the participant's own bodyweight, will reduce the speed at which the muscles can contract, however, stronger and faster, or more powerful, muscles allow heavier loads to be moved at higher velocities (Peterson, Alvar & Rhea, 2006). As a result, power is a good determinant of jump height when adjusted for body mass, though actual muscle power cannot be directly measured in complex human movements, rather this is left to measurement through ground reaction forces (Markovic & Jaric, 2007).

Fibre type, dictates the speed of contraction, but fibre alignment or layout has implications on the speed of force development as well. Muscle types can be described by the angles at which they act, or the fibre orientation relative to the tendon and the rest of the muscle, in addition to their contractile speed (Boesch & Kreis, 2001). The angle of orientation is termed the pennation angle, allowing muscles to be termed in relation to these angles (Boesch & Kreis, 2001). Classification of muscle fibre arrangements fall into the headings, longitudinal, fusiform, radiate, unipennate, bipennate or circular (Boesch & Kreis, 2001; Plowman & Smith, 2008). Muscle fibres that run parallel, or nearly parallel, to the muscle can be termed longitudinal or fusiform, fibres oriented on one or both sides of the tendon are termed unipennate or bipennate, respectively, and circular fibres, as the name suggests, form a circle (Boesch & Kreis, 2001; Plowman & Smith, 2008).

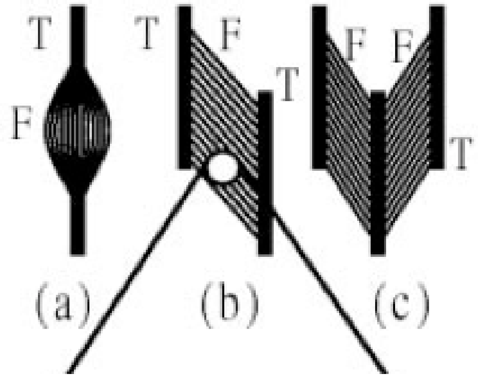


Figure 5: Common muscle fibre arrangements

Figure 5, demonstrates 3 examples of fibre arrangements (a) illustrating the arrangement of a fusiform muscle, (b) demonstrating a unipennate muscle, and (c) revealing a bipennate muscle, where T denotes tendon, and F denotes muscle fibre (Boesch & Kreis, 2001). Plowman (2008) suggests that muscle fibre arrangements such as longitudinal or fusiform muscles allow for greater muscle shortening due to their unidirectionality and greater length, though shorter muscles with angles of pennation shorten little, but are capable of creating more force. Furthermore, parallel muscle fibres can be more useful for high velocity contractions, while muscles with fibres at given pennation angles maximize cross-sectional area, creating greater force (Plowman & Smith, 2008). Overall, the relationship between force and velocity is essential in determining vertical jump height; therefore examination of ground reaction forces, and their effect on COM velocity is of importance.

Coordination

The importance of strength and speed has been established in the literature, however the ability to control each in terms of activation is also important (Bobbert & Van Soest, 1994; Domire & Challis, 2007). The sequencing of muscle activation has been suggested to be of importance, and it is proposed that the investigation of muscle strength and technique is worthwhile in differentiating between good and poor performers of the vertical jump (Vanezis &

Lees, 2009). Studies involving electromyography (EMG), shedding light into the recruitment and firing rate of motor units, suggest that increased muscle activity reflects increased force output. It is, however, possible that EMG could reflect increased synchronization of motor units, which may not necessarily indicate increased muscle force (Andersen, Andersen, Magnusson, Suetta, Madsen, Christensn et al., 2005). Hudson (1986) proposed that coordination is the result of optimal sequential production of individualized forces, and that timing and sequencing of segmental movement is the basis of coordination. Looking at this definition in terms of muscular control, it can be understood that activation occurs as a result of signals from the central nervous system (CNS) through electrical impulses, and that the generation of joint torque is the result of muscle forces that are caused by neural excitations (Spagele, Kistner & Gollhofer, 1999).

With respect to the specific technique used in the CMVJ, the countermovement causes the force producing muscles to both stretch while contracting, eccentrically, and then contract and shorten, concentrically. This stretching can be examined at the level of muscle fibres. Wilson and Flanagan (2008) propose that spindle fibres, imbedded in and parallel to muscle fibres, are innervated by specialized afferent neurons. During rapid stretching, as seen in the CMVJ, deformation of these spindle fibres stimulates reflexes, thought to involve structures in the spinal cord and brain, which may cause coordinated reflexive contraction of the muscle (Wilson & Flanagan, 2008). Stored energy, in the form of elastic energy is often attributed to increases in joint torques during the CMVJ, and it has been reported that no differences are apparent in EMG activity during vertical jumping versus isometric contractions (Wilson & Flanagan, 2008). This suggests that increases in torque during the countermovement jump are not the result of reflex activity (Wilson & Flanagan, 2008). As a result it is possible that competitive inhibition of some motor units could result in certain intersegment sequences emerging. The outcome of segment velocities and sequencing include the velocity of the COM.

Overall, there is evidence suggesting that intersegment coordination can influence vertical jump performance, and this area of performance deserves attention (Vanezis & Lees, 2009). Knowing that jump technique and intersegment coordination and timing offer avenues of research, it is useful to address means of optimizing vertical jump performance from these variables, and possible methods of training improvements. Dowling and Vamos (1993) suggest that even if a training program was known to affect peak force or power, other interactions and determinants must also be examined before the true potential for improvements in jumping performance can be made. Sequencing and timing provides one such opportunity of exploration, specifically the examination of changes in the velocity of the COM from maximum to takeoff during the countermovement vertical jump may provide a means of examining coordination in future studies.

Kinetic chain

Improvements in jump height, the result of proposed storage of elastic energy during rapid muscle stretches, followed by concentric contraction, also occurs through assistance in force generation from a transfer of momentum by individual segments. The transfer of energy through the body as a result of sequential timing is termed the kinetic chain (Cheng, 2008; Dowling & Vamos, 1993; Vanezis & Lees, 2009). The CMVJ provides an interesting examination of the transfer of energy through the body during jump phases; the legs are associated with the greatest contribution to force production, while the arms have been proposed to assist in force generation by two means. Firstly, arm swing following the countermovement has been proposed to increase ground reaction impulse through increasing the load on the legs, increasing a stretch in the leg muscles. Secondly, improvement in force generation is suggested to come from a transfer of momentum to the rest of the body near takeoff (Dowling & Vamos, 1993; Cheng, 2008). The build up of energy is suggested to come from the shoulders and elbows, which allows extra work to be done at the hip, also increasing ground reaction impulse (Dowling & Vamos, 1993; Cheng, 2008; Lees, Vanrenterghem, & De Clercq, 2004). Luhtanen and Komi (1978) specifically report segment contributions of 56% for knee extension, 22% for the plantar flexion, 10% for arm swing and 2% for head swing, in reaching takeoff velocity for maximum jump. In terms of transferring momentum to the rest of the body, it is suggested that arm swing increases both the height and velocity of the COM at takeoff (Lees, Vanrenterghem, & De Clercq, 2004). Although contributions of the arms are proposed to increase vertical jump height by two mechanisms, in reality neither theory can exclusively explain the improved performance, instead improvements are the likely result of these mechanisms acting together (Lees, Vanrenterghem, & De Clercq, 2004).

Although "transmission of force" has been suggested, other authors deem this theory too simplistic, instead it is thought that upward acceleration of the arms actually allows the trunk to raise, leaving more time for extension of the legs (Payne, 1968; Dapena, 1993; in Davis, Bosley, Gronell, Keeney, Rossetti, Mancinelli & Petronis, 2006). The product of force and time, representing impulse, suggests that the more time over which a force is applied allows for greater impulse, which will produce greater jump height, as long as the movement is carried out rapidly enough to use the elastic energy stored during countermovement (Davis, Bosley, Gronell, Keeney, Rossetti, Mancinelli & Petronis, 2006). Velocity of the centre of mass is dependent on impulse, which causes upward acceleration. Segmental accelerations produce torques on the corresponding joints that dictate jumping technique (Oddsson, 1987). As a result, the temporal coordination patterns between segment movements determine impulse, COM velocity, and in turn jump height (Oddsson, 1987). Research by Cheng (2008) indicates the sequence of timed movements as occurring at the shoulder, the knee, the hip and finally the ankle joint, illustrating a downward sequence of joint activation. This sequencing of joints furthers previous research proposing that movement initiates in proximal segments, while distal segments initiate movement when adjacent proximal segments reach peak velocity (Hudson, 1986).

Overall, the proposed sequencing is suggested to positively impact vertical jump height. The inclusion of the arms during the CMVJ suggests that increased force, impulse and segment velocities allow increased COM velocity at takeoff, which directly determines jump height. Specific use of rapid stretching of muscles during the countermovement portion of the jump is suggested to provide a means of increasing jump height. The possible transfer of energy and segmental velocity is therefore projected as having benefits to vertical jump technique.

Anthropometric characteristics

Body size, or anthropometric characteristics of the performer offers a source of variability among participants that serve to explain vertical jump proficiency. In research by Riggs & Sheppard (2009) anthropometric factors including somatotype and body composition were shown to influence ground reaction forces and vertical jump height amongst male and female beach volleyball athletes. Specifically, rapid movements are shown to be dependent on body size. Normalized body size, correcting power production for participant weight, in particular, offers a better means of predicting vertical jump proficiency (Markovic & Jaric, 2007). After normalization for body size, muscle power and jump height are shown to closely relate, suggesting that leg power alone may not accurately shed light into the ability to produce a skilled jump. Overall it is suggested that jumping is most sensitive to increases in strength to weight ratios of the participant, though studies have also linked greater segment or limb length with increased vertical jump height (Bobbert & Van Soest, 1994; Davis, Bosley, Gronell, Keeney, Rossetti, Mancinelli & Petronis, 2006). Similarly, power output has been positively correlated with lower extremity muscle mass (Riggs & Sheppard, 2009). It can be noted, however, that gender differences may produce separate sets of predictors, probably the result of anthropometric differences, including shorter limb length and lower limb muscle mass in female vs. male participants (Davis, Bosley, Gronell, Keeney, Rossetti, Mancinelli & Petronis, 2006). For these reasons, only females were examined in this study, as gender appears to pose as a confounding variable in terms of vertical jump height proficiency.

Eccentric muscular contraction

The specific definition of rapid muscle stretches, during simultaneous muscle activation is termed eccentric contraction (Dowling & Vamos, 1993). The function of eccentric contractions in the CMVJ is to allow negative work prior to positive work, completed through concentric contraction (Dowling & Vamos, 1993). Due to the fact that eccentric contraction allows stretching of the muscle, concentric contraction in the CMVJ occurs while the muscle is already under tension (Harman, Rosenstein, Frykman & Rosenstein, 1990). It is suggested that this already present tension supplies more available energy to be used in force generation (Harman, Rosenstein, Frykman & Rosenstein, 1990). Specific examination of the transition from eccentric to concentric movement during the CMVJ is worth consideration (Wilson & Flanagan, 2008).

Stretch-shortening cycle

The use of negative work, prior to positive work, as a result of rapid muscle stretching is referred to as the stretch-shortening cycle (Dowling & Vamos, 1993; Ettema, 2001; Harman, Rosenstein, Frykman & Rosenstein, 1990; Henchoz, Malatesta, Gremion & Belli, 2006; Sheppard, Cronin, Gabbett, McGuigan, Etxebarria & Newton, 2008; Vanezis & Lees, 2009; Wilson & Flanagan, 2008; Zameziati, Morin, Deiuri, Telonio & Belli, 2006). The stretch-shortening cycle (SSC) is specifically the result of eccentric muscle stretching, which is suggested to store elastic energy for use during concentric muscle contraction (Harman, Rosenstein, Frykman & Rosenstein, 1990). The SSC has been widely investigated from a number of approaches, but in each case being able to efficiently use the SSC during athletic performance has been identified as critical to the execution and success of maximal jumps, found in a number of sports (Riggs & Sheppard, 2009). Unfortunately for athletes, the SSC involves high force, causing high tendon tension; therefore the associated muscles are required to be strong and well coordinated in terms of neuromuscular activity (Vanezis & Lees, 2009). Stretch-shortening contractions rely on the storage of elastic energy, and its subsequent release in rapid succession (Ettema, 2001). Performance enhancement through the use of the SSC is often attributed to the recoil of elastic energy following eccentric stretching of the muscle, though performance gains are dependent on the amount of time spent in isometric contraction between stretching and shortening of the muscle (Zameziati, Morin, Deiuri, Telonio & Belli, 2006).

During eccentric stretching of the muscles, in the countermovement phase of the CMVJ, a significant amount of energy can be stored in the stretched muscle, which can be at least partly recovered during concentric contraction (Zameziati, Morin, Deiuri, Telonio & Belli, 2006). The recovery of this energy is related to the time between eccentric and concentric phases of the movement, defined as coupling time (Zameziati, Morin, Deiuri, Telonio & Belli, 2006). The sum of coupling time and the duration of stretching and shortening is more easily measured, however, referred to as contact time, and these times are shown to be significantly positively correlated

(Zameziati, Morin, Deiuri, Telonio & Belli, 2006). Coupling time is described physiologically as the time required for modification of actin-myosin cross-bridges (Zameziati, Morin, Deiuri, Telonio & Belli, 2006). Confirmation of this theory is proposed in that cross bridge formation has been suggested to last 340ms during isometric contraction, while coupling times have been estimated from contact time as requiring 300ms (Zameziati, Morin, Deiuri, Telonio & Belli, 2006). Wilson and Flanagan (2008) confirm that the reduction of coupling time optimizes the use of the SSC, creating more powerful muscular contractions. Furthermore, Henchoz, Malatesta, Gremion & Belli (2006) suggest that elastic energy that is not used in rebounding during concentric contraction is turned into heat if the muscle is allowed to relax.

Ettema (2001) suggests the structure of the elastic component of muscle separates the muscle in terms of the contractile element, or muscle fibres, and the series elastic element, or tendon. A parallel elastic element is also suggested to create passive stretch in unstimulated muscle, consisting of the muscle membranes, including the epymisium, perimysium and endomysium and the sarcolema (Martins, Pato, & Pires, 2006).

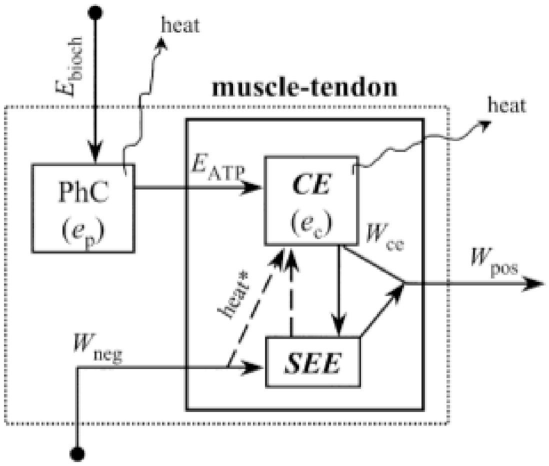


Figure 6: Skeletal muscle-tendon structure model (Ettema, 2001)

Figure 6 demonstrates how metabolic energy ($E_{biochem}$), in the form of ATP controls the contractile element (*CE*), which is converted into mechanical energy (Ettema, 2001). Negative work (W_{neg}), however, in the form of the stretching of the muscle, is stored and reused by the series elastic element (*SEE*; Ettema, 2001). Together, the contractile element and the series elastic element, or muscle fibres and tendon respectively, create positive work (W_{pos}), associated with jumping (Ettema, 2001). This structuring of the muscle fibres attempts to explain the ability of the muscle to stretch as a result of negative energy during the countermovement, allowing the contractile element to relax in an isometric state, followed by the modification of cross bridges and the shortening of the muscle due to contraction by the contractile element (Ettema, 2001). The process of muscular contraction following stretching is also separated in terms of the efficiency of the muscle. Ettema (2001) refers to muscle efficiency as being expressed in terms of biochemical and mechanical efficiency. As a result, the SSC may be more reflective of the mechanical efficiency of the muscle, rather than simply the biochemical efficiency, which is responsible for active muscle work production (Ettema, 2001).

Muscle stiffness is one particular aspect of mechanical efficiency that can be understood in terms of the SSC. Muscle stiffness is a function of the change in force by the change in length (Wilson & Flanagan, 2008). A stiff muscle performs better at purely concentric contractions, as the series elastic element is not able to store energy as effectively as a more compliant muscle, due to decreased extensibility (Ettema, 2001). Biochemical and mechanical conversions of energy, however, are not perfectly linked in series or parallel, therefore it is possible for muscle efficiency to exceed biochemical or mechanical efficiency without reflecting these proposed components (Ettema, 2001). Rather these proposed descriptions serve to partially explain the controversial role of elastic energy in the SSC. It has, however, been described by Henchoz, Malatesta, Gremion & Belli (2006) that overall, stored elastic energy during negative work in the series and parallel elastic elements improve the mechanical efficiency of positive work. Overall, it is proposed that force is directly proportional to the length of the series elastic and contractile elements, as well as contraction velocity, which in turn affect COM velocity at takeoff, and jump height (Bobbert & Van Soest, 1994).

Muscle fibre type

Reflective of elastic and contractile properties of muscle is fibre type, which is linked to vertical jump height (Andersen, Andersen, Magnusson, Suetta, Madsen, Christensn et al., 2005; Harman, Rosenstein, Frykman & Rosenstein, 1990; Wilson & Flanagan, 2008). Overall, individuals with predominantly fast twitch fibres are better able to recover stored elastic energy than slow twitch fibres, and are able to produce force more quickly and at greater magnitude (Andersen, Andersen, Magnusson, Suetta, Madsen, Christensn et al., 2005; Harman, Rosenstein, Frykman & Rosenstein, 1990). Fast and slow twitch fibres, as their names suggest, are distinguished by the rate at which they contract (Plowman & Smith, 2008). The differences in contraction rate, however, are the outcome of several other properties associated with the fibres. The contractile, or twitch, properties are influenced by the type and size of nerves that innervate them, with muscle fibres also being differentiated by metabolism (Plowman & Smith, 2008). In general, skeletal muscles are innervated by alpha (α) motor neurons, with fast twitch fibres being innervated by α_1 motor neurons and slow twitch fibres being innervated by α_2 motor neurons (Plowman & Smith, 2008). Alpha motor neurons differ in size and conduction velocity, which serve to explain their influence on the rate of muscle fibre contraction. Small motor neurons, or α_2 motor neurons, have slow conduction velocities and are recruited at lower thresholds, which in terms of muscular demands would be described by low force output (Plowman & Smith, 2008). Conversely, large motor neurons, or α_1 motor neurons, have fast conduction velocities and are recruited at higher thresholds, or high force output, as in the case of the vertical jump (Plowman & Smith, 2008). In fast twitch fibres, muscle excitation and cross-bridging rates are shown to be quicker, therefore allowing the production of force more quickly (Andersen, Andersen, Magnusson, Suetta, Madsen, Christensn et al., 2005). As a result, fast twitch muscle fibres have been significantly correlated to vertical jump performance (Vanezis & Lees, 2009).

With respect to fibre metabolism, slow and fast twitch fibres can be further differentiated. Fast twitch fibres can be subdivided into categories. Unlike twitch speed and innervation, metabolism can be represented as a continuum, where properties can merge and blend (Plowman & Smith, 2008). The two metabolic processes at opposing ends of the continuum are glycolysis and oxidative phosphorylation (Plowman & Smith, 2008). Glycolysis is more representative of fast twitch fibres, while oxidative phosphorylation is more representative of slow twitch fibres (Plowman & Smith, 2008). Glycolysis is an energy pathway that catabolyzes glucose or glycogen, producing pyruvate when oxygen is present, and lactate when oxygen is not present (Plowman & Smith, 2008). Conversely, oxidative phosphorylation uses the electron transport chain to synthesize ATP, from ADP (adenosine diphosphate) and P_i (phosphate; Plowman & Smith, 2008).

From the continuum of metabolism, muscle fibres have been characterized as being type I (slow twitch), as well as type IIX fast twitch, also referred to as type IIB, and type IIA fast twitch fibres (Andersen, Andersen, Magnusson, Suetta, Madsen, Christensn et al., 2005; Plowman & Smith, 2008). Type IIX fibres are reported to contract twice as fast as type IIA, and 9 to 10 times faster than type I muscle fibres, property that is beneficial in rapid movements like the vertical jump. In terms of the metabolism, type I fibres are referred to as slow oxidative fibres, type IIA fibres are termed fast oxidative glycolytic, and type IIX fibres are termed fast glycolytic (Plowman & Smith, 2008). It can therefore be understood that hybrid fibres have correspondingly intermediate contraction rates to type I and type IIX fibres, revealing metabolic processes combined from each (Andersen, Andersen, Magnusson, Suetta, Madsen, Christensn et al., 2005; Plowman & Smith, 2008). The importance of muscle fibre type on athletic performance, and specifically the vertical jump, is that force and velocity characteristics are strongly positively correlated with muscle power and vertical jump height. As a result, it would seem that fast twitch muscle fibre is more effective at producing greater COM velocity and vertical jump height.

Specifically regarding the CMVJ, differences in technique have been proposed to relate to fibre type. Wilson & Flanagan (2008), suggest that individuals with predominantly slow twitch muscle fibres compensate for slower rate of force production, or power production, by making better use of the countermovement. Relationships between muscle stiffness and fibre type have also been suggested, in that individuals with greater musculotendinous stiffness produce force at greater rate, a characteristic of fast twitch muscle fibre (Wilson & Flanagan, 2008). Furthermore, it is proposed that time delay between electrical activity in the muscle and mechanical response is a predictor of muscle fibre type (Wilson & Flanagan, 2008). In terms of the vertical jump, reduced musculotendinous stiffness has been associated with reduced muscle activation, decreased force production and reduced jump height (Wilson & Flanagan, 2008). That being said, there is, however a likely ideal range of stiffness in the lower extremities that maximize performance and minimize risk of injury (Wilson & Flanagan, 2008).

Countermovement jump sequencing and timing

Vertical jump height during the CMVJ is shown to be dependent on a number of different variables. Variables of interest during force production include peak and mean force, peak and mean power, takeoff COM velocity, and impulse (Dowling & Vamos, 1993; Riggs & Sheppard, 2009). Further research can therefore be conducted to examine the relationships between such variables and jump height (Peterson, Alvar & Rhea, 2006). Although examining correlations between variables does not infer cause and effect, it does offer the ability to interpret relationships between these factors (Peterson, Alvar & Rhea, 2006). It has been suggested that the pattern of force application is more important than absolute strength among performers of the CMVJ, therefore it has been proposed that it is beneficial to examine strength and power measures separately (Dowling & Vamos, 1993; Peterson, Alvar & Rhea, 2006). Overall, it is suggested that proficiency in vertical jumping is determined by differences in strength, speed and coordination between individuals (Dowling & Vamos, 1993).

Countermovement

Examination of the countermovement in terms of timing and sequencing allows relationships between negative work and jump height to be made. The countermovement, regarding vertical jump height is known to cause improvements in jump performance, though the mechanisms have evolved as research has been conducted (Dowling & Vamos, 1993). Storage of elastic energy, the use of stretch shortening contractions, as well as increased force generation time, have all been identified as positive outcomes of the countermovement (Dowling & Vamos, 1993).

Examining the depth of the countermovement, and the resultant effects on jump height, suggests that increased COM drop depth during countermovement can increase force production time, which can increase impulse (Domire & Challis, 2007). Although research by Domire and Challis (2007) was conducted through computer simulation, the suggestion was made that greater jump height as a result of increased squat depth could be found if technique training at deeper squat was performed. The authors suggest that improved jump height through deeper countermovement squat could be the result of learned coordination, though, as was previously discussed, muscle fibre type may also play a role in this (Domire & Challis, 2007). Slow twitch fibres may benefit more from increased countermovement time through increases in impulse (Domire & Challis, 2007; Wilson & Flanagan, 2008).

Overall, though the mechanism behind improvements in jump height from the use of countermovement may be the result of multiple factors working together, the outcome is greater jump height. Furthermore, the countermovement vertical jump is a naturally occurring sport movement, justifying further examination of this movement in attempting to examine vertical jump performance.

Force production

Following the countermovement, force production raises the COM until the moment of takeoff. The ultimate goal in the force production phase, which separates good performers from poor performers in the vertical jump, is the ability to produce greater muscle forces at a faster rate (Vanezis & Lees, 2009). Force platform data sheds light into force time curves, allowing identification of temporal and kinetic variables identified from force, and power vs. time curves (Dowling & Vamos, 1993).

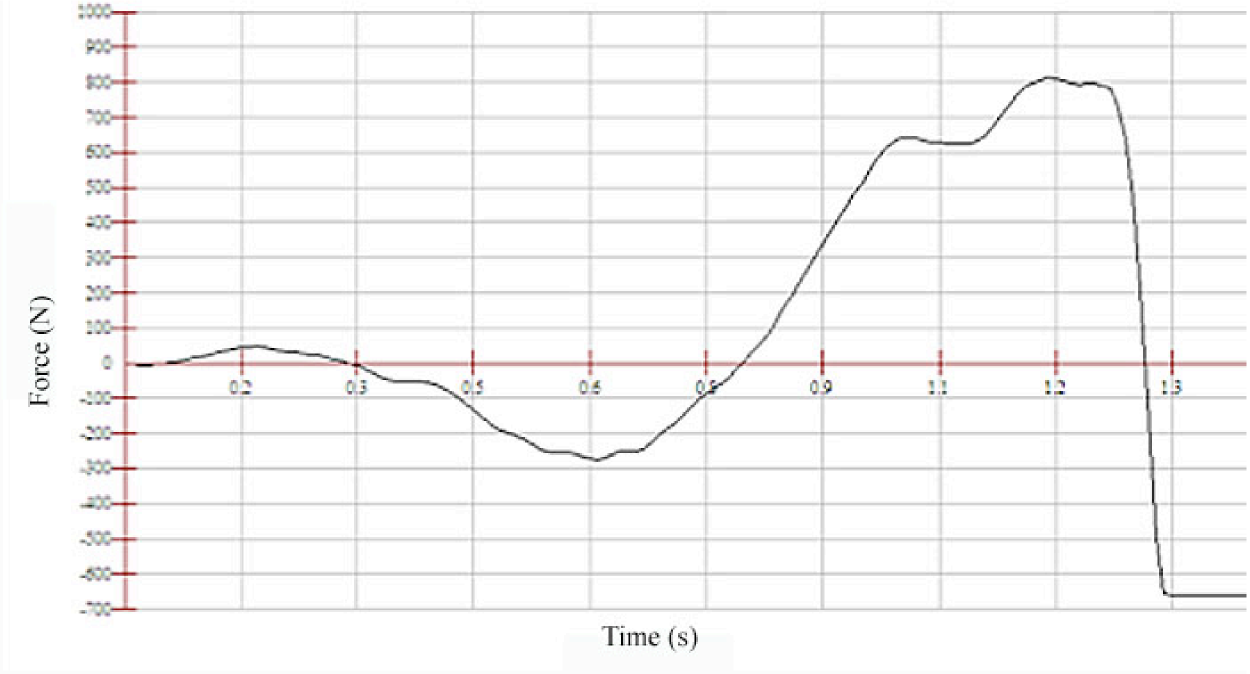


Figure 7: Ground reaction force vs. time during countermovement vertical jump

A measure of net force vs. time for a participant carrying out a countermovement vertical jump, as shown in Figure 7, illustrates important information that can easily be identified mathematically, or from simple examination of the curve. When examining Figure 7 it should be noted that zero denotes that no ground reaction forces are present, aside from gravity acting on the mass of participant. As a result, zero represents the reading on the force platform when participant’s body mass is stationary. Peak positive force can be identified as the maximum positive peak on the plot located at approximately 1.2 seconds. Furthermore, the point of takeoff can be identified simply as the negative region of the curve beyond approximately 1.3s, illustrated as a flat horizontal line, the negative value of the participant’s mass. Integration of this force vs. time curve allows calculation of velocity, which can also be plotted as a function of time.

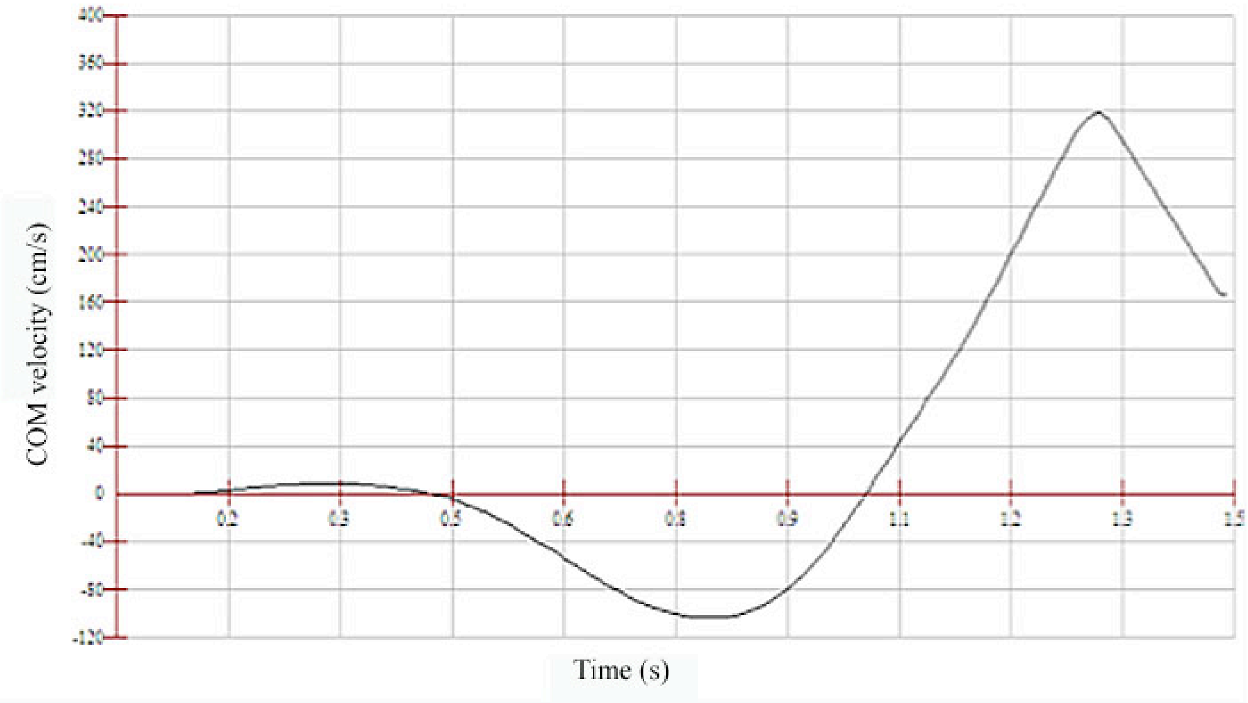


Figure 8: COM velocity vs. time during countermovement vertical jump

The COM velocity vs. time curve, shown in Figure 8, allows visual identification of peak positive COM velocity, and takeoff COM velocity. Figure 8 illustrates a slight positive increase in COM velocity from 0 to 0.2s, during preliminary movements of the participant, followed by the countermovement, where the COM is accelerated downwards until approximately 0.8s, where force production begins. Finally, maximum COM velocity is observed as the positive peak on the graph, and takeoff velocity can be calculated mathematically from the point of takeoff on the force vs. time curve.

Using temporal information from the pattern of force application, variables including peak power, peak force, and peak impulse, can be selected that are most suitable for optimizing performance (Dowling & Vamos, 1993). Specifically, selected parameters from force-time curves have been shown to offer high correlation coefficients through multiple regression, which can be used to accurately predict vertical jump height during countermovement jumps (Oddsson, 1987). Specifically, force-time parameters may be selectively identified and used to develop highly specific training programs through examination of weaknesses in examined variables relating to vertical jump height (Oddsson, 1987). Generally, training has been suggested to use the stretch-shortening cycle, which aims to improve the rate of force development rather than simply the amount of force (Dowling & Vamos, 1993)

Power

Although power is a function of force, it includes the distance over which force is applied in a given amount of time (Markovic & Jaric, 2007). Peak power, as a result, has been shown to be a good single predictor of jump performance, and conversely the jump test is effective in estimating peak power output (Dowling & Vamos, 1993; Harman, Rosenstein, Frykman & Rosenstein, 1990; Riggs & Sheppard, 2009). It has, however, been suggested that jumping performance is based on the muscle's ability to develop impulse rather than power, being the product of force and the duration of force application, rather than force and velocity (Markovic & Jaric, 2007). In any case, the pattern of force application, the magnitude of force produced, and the time over which the force is produced is shown to influence jump height through its effects on velocity of the COM. One should also note that power or impulse should be expressed relative to the participant's mass for true understanding of the ability to maximize vertical jump height (Riggs & Sheppard, 2009).

Examining the pattern of force and power application across time, sheds light into the activation of musculature. It is suggested that power originates in proximal joints, but decreases as power increases in distal joints (Voigt, Simonsen, Alkjaer, Boisen-Moller & Klausen, 1999). This can be understood in the series of activation from the hip to the knee and finally to the ankle (Voigt, Simonsen, Alkjaer, Boisen-Moller & Klausen, 1999). Dowling and Vamos (1993), recommend that future studies examine why peak power correlates so positively with vertical jump height. It has been proposed that examining changes in velocity, specifically from maximum to takeoff, may shed light into the relationship between jump height and power.

Velocity

Takeoff velocity of the centre of mass is one of the fundamental objectives of the vertical jump, as the vertical height attained by the COM is a function of vertical velocity at takeoff and takeoff position (Dowling & Vamos, 1993; Hay & Reid, 1988; in Feltner, Fraschetti & Crisp, 1999; Hudson, 1986). Furthermore, movements that require high final velocity should aim to have a force pattern that reaches maximum late in the movement (Dowling & Vamos, 1993). Velocity of the COM is a function of concentric force generation by the associated muscles with the movement; therefore, high concentric velocities are necessary to maintain high movement speeds (Peterson, Alvar & Rhea, 2006).

Takeoff vs. maximum velocity

Overall, it has been proposed that the positioning of the COM prior to takeoff is of less importance than takeoff velocity of the COM (Moir, 2008). Interestingly, high movement speeds achieved during force production do not necessarily correspond exactly with takeoff velocity of the COM. Through research it has been shown that peak positive COM velocity does not occur at takeoff, but consistently before takeoff (Harman, Rosenstein, Frykman & Rosenstein, 1990). Graphically, this can be understood when superimposing a curve of velocity of COM versus time, over a curve of ground reaction force versus time, illustrated in Figure 9. This approach identifies the difference between the maximum velocity of the COM and takeoff, showing the time between these events as well as the decrease in velocity of the COM.

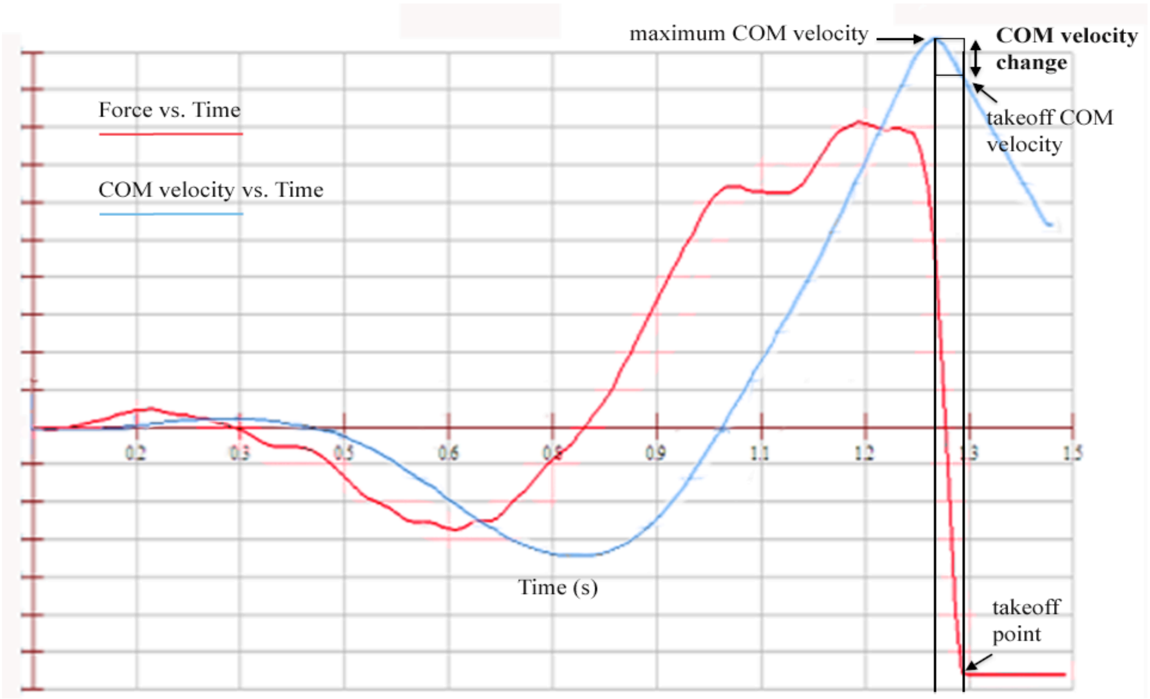


Figure 9: Graphical representation of takeoff and maximum COM velocity differences

The change from maximum velocity of the COM to takeoff is proposed to occur when the large muscles around the hip and thigh have already fully contracted, leaving only the plantar flexors to continue generating vertical ground reaction force (Harman, Rosenstein, Frykman & Rosenstein, 1990). The difference between maximum velocity of the COM relative to takeoff velocity can be examined in terms of the maximum velocity and net impulses of the segments associated with force production (Luhtanen & Komi, 1978). On average, Luhtanen & Komi (1978) reported that takeoff velocity of the COM was only 76% to 84% of the theoretical maximum, calculated by the velocity of the contributing segments. The authors propose that losses in velocity are the result of time differences in maximum velocity versus takeoff, and that training may allow reductions in this time (Luhtanen & Komi, 1978).

Specific differences between maximum COM velocity and takeoff velocity have been reported; suggesting that peak velocity consistently occurs 0.03s before takeoff (Harman, Rosenstein, Frykman & Rosenstein, 1990). The consistency of this time however could be a product of the acquisition frequency and the method of examination used. In the case of research by Harman, Rosenstein, Frykman & Rosenstein (1990), examination was carried out using a force platform at a sampling frequency of 500Hz. Increasing the acquisition rate, however, correspondingly increases the ability to distinguish between more closely located temporal phenomena (Moir, 2008). Because higher jumps are faster, with all stages temporally closer to takeoff, it is useful to examine the CMVJ with high sampling frequency (Harman, Rosenstein, Frykman & Rosenstein, 1990). Sampling frequencies as low as 300Hz can cause approximately 2% underestimation of jump height, using the calculation of theoretical jump height from takeoff velocity, therefore improving the methodology to remove this source of error should be the goal (Moir, 2008). Sampling frequencies over 1000Hz almost entirely remove this source of error. It becomes apparent that choosing an sampling frequency of at least 1000Hz allows a method of analyzing changes in COM velocity from maximum to takeoff with more precision (Moir, 2008).

From Figure 3, the deterministic model of vertical jump, it is apparent that jump height is dependent on both takeoff height and flight height (Hay and Reid, 1988; in Feltner, Fraschetti, & Crisp, 1999. Calculation of flight height from takeoff velocity alone is carried out using equation 1. Equation 1, however, does not include any information regarding takeoff height. Aragón-Vargas (2000) suggested that jump height could be corrected for takeoff height using equation 3. Subtracting standing height from takeoff height simply adds the position of the participant’s COM at takeoff to the calculated value of jump height using takeoff COM velocity. This method of jump height calculation shows evidence of content validity, though measurement error associated with the required variables has implications on the reliability, accuracy, and subsequent concurrent validity with COM displacement from 3D video (Aragón-Vargas, 2000).

According to Moir (2008), correction of takeoff COM velocity can be conducted by integration, computing vertical COM displacement at takeoff. Moir (2008), however, assessed the concurrent validity of vertical jump height measurement using corrected takeoff COM velocity as the criterion, with comparisons to the time in air method and the use of takeoff COM velocity alone. Force platform analysis was carried out in males and females (N=50 for each group) though no comparisons were made to COM displacement from video (Moir, 2008). Though the researcher identified that the accuracy of vertical jump height calculation was poor when combining video and force platform data, the established gold standard remains 3D video analysis (Aragon-Vargas, 2000; Moir, 2008). While comparisons to vertical COM displacement from 3D video analysis have been made in research, force platform analysis should be further explored as means of assessing vertical jump height with greater sampling frequency, and containing less measurement error.

As a result, it was proposed that examining the differences between maximum and takeoff COM velocities, at a sampling frequency of at least 1000Hz, would reveal the ability to more accurately measure each of these velocities. Subsequently, differences between calculated values of jump height, using either maximum or takeoff COM velocity, were compared to the gold standard (3D video analysis) in vertical jump height determination.

Research goals

The overall goals of this study were outlined prior to identifying the purpose and research questions. The aims of the research sought to:

1. Examine relationships and differences among the explored methods of jump height determination.

2. Create a method of predicting vertical COM displacement that relies solely on force platform data, at greater sampling frequency than video analysis, and without the assumptions associated with accurate and reliable marker placement (Wilson at al., 1999).
3. Demonstrate evidence of validity in each method of jump height determination relative to vertical COM displacement from 3D video.

Research questions

1. What are the relationships and differences between vertical jump heights measured amongst the field test (Vertec) and the laboratory methods (3D video and force platform analysis) under consideration? More specifically, what are the relationships and differences between the measurements of vertical jump height from the Vertec, 3D force platform analysis, using takeoff versus maximum COM velocities, 3D video analysis, and the methods of correcting takeoff velocity with takeoff position, proposed by Aragon-Vargas (2000) and Moir (2008)?
2. To what extent can jump height from 3D video analysis be predicted through linear regression, using maximum COM velocity measured from 3D force platform analysis?
3. To what extent does each method of vertical jump height determination demonstrate evidence of validity relative to vertical COM displacement from 3D video analysis?

CHAPTER 3

Methodology

Participants

Following approval from the Lakehead University Research Ethics Board, 13 female varsity university volleyball players were recruited for the study, providing a sample size that allowed statistical power and appropriate generalizations to be made from the data (Diekoff, 1992). Descriptive statistics for the sample (n=13) are summarized in Table 1, illustrating participant characteristics including age, height and mass.

Table 1: Participant descriptive statistics for age, height and mass

Variable	**Average**	**Maximum**	**Minimum**	**Standard Deviation**
Age (Years)	19.3	22	18	1.32
Height (m)	1.71	1.83	1.60	0.06
Mass (kg)	69.93	80.80	57.15	7.91

A sample size of 13 female participants allowed calculation of the maximum error of the estimate in measurements drawn from the data. Maximum error of the estimate was computed using equation 10 (Khazanie, 1996; Sincich, 1985).

$$E = z_{\alpha/2}\left(\frac{\alpha}{\sqrt{n}}\right) \tag{10}$$

where:

E: is the maximum error of the estimate

$z_{\alpha/2}$: is the z score at a given confidence interval

σ: is the known standard deviation of the population

n: is the sample size

In the calculation, the 95 percent confidence interval was used, therefore setting $z_{\alpha/2} = z_{0.025/2} = 1.96$ (Khazanie, 1996; Sincich, 1985). A standard deviation of 4.0cm from normative data for female participants aged 15-29 years, and a sample size of 13 female participants returned a maximum error of the estimate of 2.17cm (refer to Appendix A for calculation). From the formula for determining the maximum error of the estimate it should be apparent that the maximum error of the estimate (E) increases as sample size decreases (Khazanie, 1996; Sincich, 1985).

Recruitment occurred through convenience sampling of the Lakehead University Women's Volleyball Team. Participants included only female varsity university athletes, employing experienced jumpers with appropriate familiarity with the movement. During initial recruitment of potential participants, potential risks and benefits of the study were explained. Informed consent was obtained prior to participation. Participants were surveyed for age, and completed a PAR-Q, identifying criteria for exclusion from physical activity, including pre-existing medical conditions, or predisposing factors to injury, including muscle strains or ligament sprains.

Procedure

Following the scheduling of testing time with the participants and the availability of the required equipment and lab setting, participants were asked to arrive at the multipurpose lab, SB1028, located in the CJ Sanders Fieldhouse at Lakehead University, on the testing day ready to complete maximal vertical jumps. Participants were informed of the requirements to be rested, properly nourished and hydrated on the day of testing, to avoid injury.

Prior to the arrival of participants, the two-camera, 3D video analysis system, the force platform and the Vertec were set up, such that calibration and measurement could occur efficiently. Basler A602f-2 cameras were spaced 6.5 metres from the force platform at an angle of 120 degrees relative to each other. Cameras were specifically set up such that camera 1 was setup at 90 degrees to the performer, when standing on the force platform facing forward (See Figure 10 for visual description of instrumentation setup). Camera 2 was therefore 120 degrees from camera 1, or 30 degrees from directly in front of the participant. Each camera was set at a height of 1.10m, from ground to the base of the camera lens. Lights were also set up at the same height (1.10m) directly beside each camera to enhance the reflected light from the joint markers; overhead lighting in the room was turned off such that all light was from the 2 lighting sources, removing the likelihood of background objects being identified as body segments during automatic digitization.

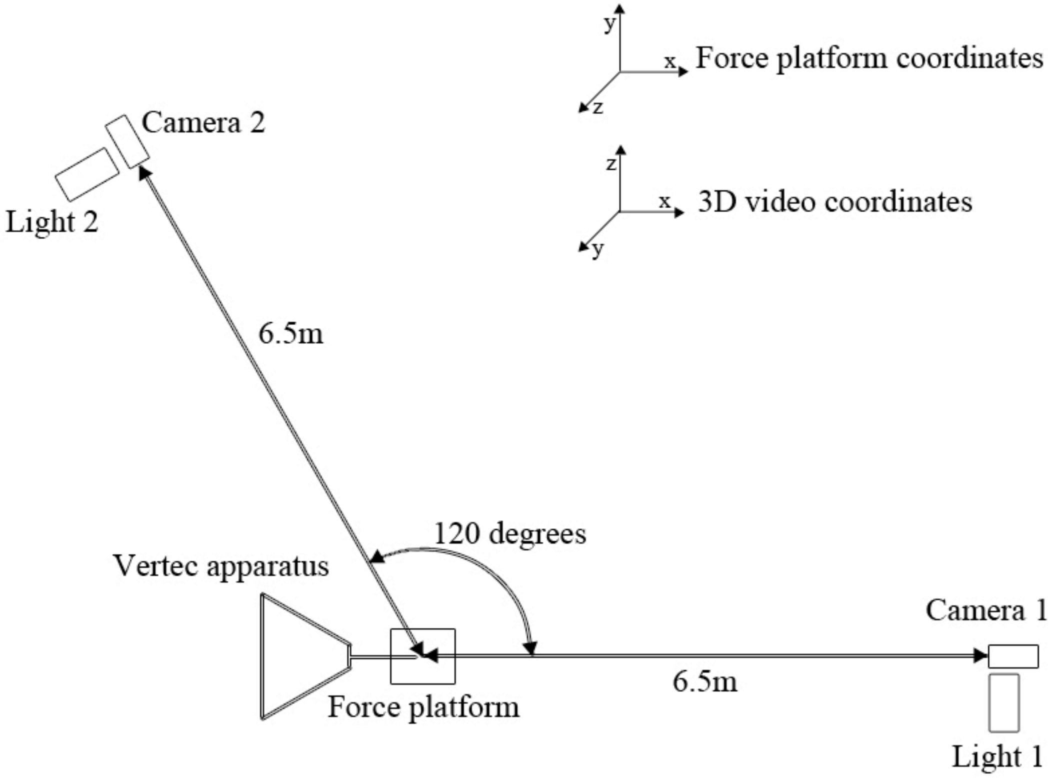


Figure 10: Instrumentation setup

A calibration tree was used, defining the x, y, z-axes, and their associated planes of motion in the Vicon Motus computer software (Yeadon, Trewartha, & Knight, 2004). The Vicon

Motus calibration tree was placed such that the centre of the calibration tree was directly above the centre of the force platform. The calibration tree allowed spatial calibration volume of $7.07m^3$, reaching a maximum height of 2.00m above the ground, as shown in Figure 11.

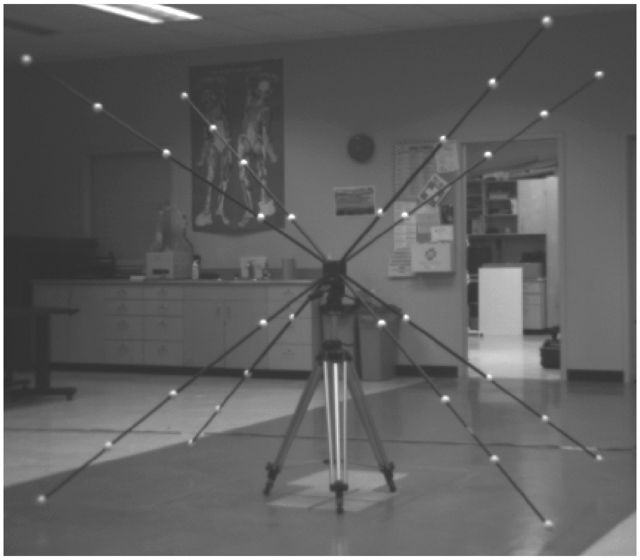


Figure 11: Vicon calibration tree

Upon arrival, participants completed a standard warm up, consisting of cardiovascular progression, raising the body temperature of the participant and increasing blood flow to the muscles. The participants each performed a standard team warm up, incorporating dynamic stretches, though static stretching was discouraged, due to proposed detrimental effects on tasks requiring maximal force and power production (Wilson & Flanagan, 2008).

The specific warm-up that participants completed generally consisted of light walking or jogging for approximately 5 minutes, or until the participant began to perspire, followed by calisthenics where the joints were moved through their full range of motion at slow speed. Participants then progressed into more dynamic stretches, readying the associated muscles of the countermovement vertical jump for performance. Examples of dynamic stretches included rotational arm swings, or arm circles at fast speed, as well as leg swings. Finally, squatting movements, without jump, moved the participant through the full range of motion for the hip, knee and ankle joints.

Following warm up, reflective markers were placed on each participant through identification of bony landmarks, representing the left and right shoulder, elbow, hip, knee, and ankle joints. Identification of bony landmarks included the tip of the acromion process at the shoulder joint, the lateral epicondyle of the humerus at the elbow, the styloid process of the ulna at the wrist joint, the greater trochanter of the femur at the hip joint, the lateral epicondyle of the femur at the knee joint, and the lateral malleolus of the fibula at the ankle joint. Markers were also placed on the left and right ear, as well as on the top of the head, or at the peak of the head along the sagittal suture. The identified joint markers were used to form the 19-point spatial model, outlined in Figure 12.

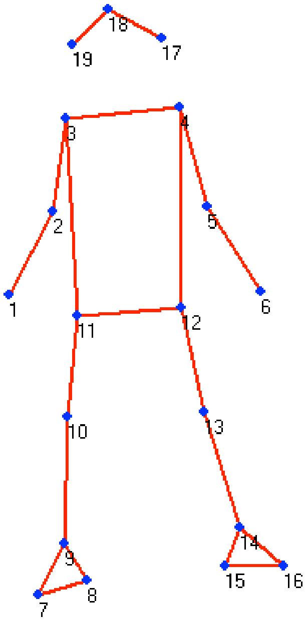


Figure 12: Vicon Motus 19-point spatial model

The Vertec was then aligned over the force platform such that the participant could jump directly up and contact the highest possible vane. The Vertec was positioned such that the base of the apparatus was clear of the participant, and in no way hindered the jump. At this point, a stand and reach value was taken for the participant, through the use of a tape measure attached at the top of the Vertec, inline with the vanes of the apparatus. The participant reached upward, through flexion at the shoulder and full extension at the elbow joint with the dominant hand, or the same hand that would be used during the jump and reach. The vertical height of the third metacarpal, or middle finger was taken at the value for the stand and reach.

The force platform was then calibrated to zero and the participant's weight was measured. The participant was then given jump instructions, indicating that the participant was required to remain standing upright and motionless on the force platform. Specifically, any movements associated with the countermovement, or backswing, prior to data acquisition required that the trial be repeated. Following measurement of participant mass, a 3, 2, 1 count was given, prior to countermovement vertical jump performance. Data acquisition was initiated for both the force platform and 3D video equipment at the 2-count, such that any anticipatory movements, or early onset of the countermovement was recorded. Acquisition duration for the force platform was set at 2 seconds, while acquisition duration of the 3D video data was set at 5 seconds, due to the necessity to capture peak jump height for video analysis.

Jump testing was then carried out. Three-dimensional force platform data, 3D video data, and Vertec jump and reach values were acquired simultaneously for each trial. Each participant completed a single trial, followed by subsequent trials in the event that part of the movement was not captured by either the force platform, or video system. Trials were repeated to a maximum of three, ensuring that all required movements occurred in the data acquisition window. Analysis was then carried out using force platform data and AMTI software, as well as through digitized video data from the two-camera 3D video analysis system and Vicon Motus Version 8.0 software.

Instrumentation

Three-dimensional video analysis

Vertical jump height was assessed using kinematic data, obtained through video digitization using reflective markers to identify joints and segments of interest, identified in Figure 12. The reflective markers were attached to participant clothing or skin with temporary adhesive, which were then recognized by computer software during digitization. Data acquisition was carried out using two Basler A602f-2 cameras, combining video footage to produce a 3D 19-point digitized spatial model of the performer. Data acquisition was carried out at a sampling frequency of 100Hz, or 100 frames per second, a frame rate that was sufficiently high to analyze the high-speed movement, but still allows identification of the reflective markers (Wilson et al., 1999). The 2 lights sources employed 300W bulbs, providing adequate light to identify reflective joint markers (Wilson et al., 1999). Video calibration defined axes, planes and real world distances in three-dimensions, which were then used for calculations during digitization. The Vicon Motus calibration tree used has 4 intersecting axes, consisting of 8 rods, with a total of 32 markers (4 on each rod).

Jumps trials were video recorded and converted to digital video files that were then analyzed using Vicon Motus Version 8.0 software. Computations of segment and total body COM relied on the mathematical model used by the Vicon Motus software. The mathematical model identifies body segments, the proximal and distal points that make up the segment and the values (percent distance on the body segment, and percent of total body mass) used to compute the location of the COM. This data is presented in Table 2.

Table 2: Vicon Motus centre of mass computation data

Segment	Proximal Point	Distal Point	% Distance from proximal point	% Body Mass
Right Forearm	Right Elbow	Right Wrist	41.8	2.3
Left Forearm	Left Elbow	Left Wrist	41.8	2.3
Right Upper Arm	Right Shoulder	Right Elbow	49.1	2.6
Left Upper Arm	Left Shoulder	Left Elbow	49.1	2.6
Right Thigh	Right Hip	Right Knee	40.0	10.3
Left Thigh	Left Hip	Left Knee	40.0	10.3
Right Shank	Right Knee	Right Ankle	41.8	4.3
Left Shank	Left Knee	Left Ankle	41.8	4.3
Right Foot	Right Ankle	Right Toe	44.9	1.5
Left Foot	Left Ankle	Left Toe	44.9	1.5

Note. Revised from Clauser, McConnville, & Young, 1969; in Hinrichs, 1990

Data conditioning was performed using Vicon Motus Version 8.0 software. Data smoothing was carried out via cubic (3rd order) spline, allowing interpolation between acquired data points, or digital video frames (Robertson et al., 2004). Data filtering employed a fourth order low-pass Butterworth filter, where optimal cutoff frequencies were determined from 3D raw coordinates (Robertson et al., 2004). Resultant cutoff frequencies ranged from 3-4Hz for each trial. Vertical centre of mass displacements were then computed from 3D transformed coordinates, the result of data smoothing.

Three-dimensional force platform analysis

The force platform provided kinetic and temporal information related to ground reaction forces and COM movement characteristics. Through integration of ground reaction forces kinematic information regarding the COM was also computed. A 46cm x 46cm force platform was used for assessing ground reaction forces, in three-dimensions, using the associated Advanced Mechanical Technology Inc (AMTI) NetForce software for calculations of COM velocity. Calculations of power, impulse, and the timing of maximum and minimum values were also determined, as is outlined in equations 7 and 8 using the associated BioAnalysis software.

Calibration and zeroing of the force platform provides strong reliability and validity for these measurements (Moir, 2008).

Vertec

The Vertec apparatus consisted of vanes, indicating increments of jump height to an accuracy of 1.6cm. The highest contacted vane during the jump and reach test, was then used in calculating jump height; jump height was calculated as stand and reach height subtracted from jump and reach height. Placement of the Vertec apparatus directly above the participant ensured that peak jump and reach height was measured. This eliminated the need for the participant to reach away from the body, or away from the vertical axis, along which the vertical jump should take place to maximize vertical jump height. This is in contrast to the Sargent's test, outlined in the review of literature, where the participant contacts a wall, which is displaced horizontally from the vertical jump axis (Aragon-Vargas, 2000).

Measurement accuracy and significant digits

Measurement accuracy and precision, relating to expression of significant digits should be addressed prior to data analysis (Robertson et al., 2004). Measurements were expressed throughout the results of this study to the highest number of significant digits, dependent on the degree of accuracy of the associated measurement technique. For a complete description of the accuracy and expression of significant digits for each measurement method in this study refer to Appendix E.

Data analysis

The discussion of statistical analysis techniques have been categorized in terms of the research questions that each addresses. Data analysis was therefore separated into the assessment of differences, relationships, and prediction of 3D video vertical COM displacement amongst the examined methods.

Measurement method relationships

The nature of the relationships between the laboratory methods was carried out using bivariate Pearson product-moment correlations. These included the measured jump height values from the Vertec, the use of maximum versus takeoff COM velocity from force platform analysis, vertical COM displacement from 3D video analysis, and the takeoff COM velocity correction methods proposed by Aragon-Vargas (2000) and Moir (2008). In addition to relationships between the measured values of vertical jump height, variables related to timing of the COM from maximum to takeoff velocity, and the difference between maximum and takeoff velocities were also explored through Pearson-product moment correlations.

The Pearson product-moment correlation produces a value ranging from -1 to 1 (Diekoff, 1992; Khazanie, 1996; Sincich, 1985). The Pearson product-moment correlation, r, and the statistical significance of the relationship shed light into the nature of the relationship, being either positive or negative, as well as the likelihood that a sample drawn from a population where no correlation exists would yield a correlation (Khazanie, 1996). Furthermore, r^2 provides a linear measure of the relationship strength (Diekoff, 1992). Values range from 0 to 1, where 0 indicates a complete lack of any linear relationship, while 1 indicates a perfect linear relationship (Diekoff, 1992).

Reliability was assessed using intraclass correlations for digitization of a single jump trial, from video footage, twice. Reliability of manual digitization, automatic digitization and a combined manual and automatic methods were each assessed. In each case, intraclass correlation method ICC(3,1), as outlined by Shrout and Fleiss (1979), was used. The selected ICC(3,1) is a two-way mixed model, where each selected variable was assessed by a single digitizing method (Shrout & Fleiss, 1979). In this model the selected methods of digitization were the only available and are therefore the only methods of interest. For the results of the 3D video reliability assessment refer to Appendix F.

Prediction of three-dimensional video vertical centre of mass displacement

Analysis of the prediction of vertical COM displacement from 3D video involved the use of linear regression. Maximum COM velocity was first used in predicting COM displacement from 3D video analysis. Next, concurrent validity was assessed through linear regression. In evaluating concurrent validity of the measurement methods, each measurement method was used as the predictor, with vertical COM displacement from 3D video as the criterion. The predictors in this case involved, jump height values from the Vertec, the use of maximum versus takeoff COM velocity from force platform analysis, and the takeoff COM velocity correction methods proposed by Aragon-Vargas (2000) and Moir (2008).

Linear regression, allowed assessment of correlation coefficients and coefficients of determination, R and R^2 values respectively. Furthermore F change values, from regression analysis, and significance values indicated whether R was significantly different than zero (Diekoff, 1992). The standard error of the estimate revealed the error contained within the predictive regression equation, in the units of the dependent variable, metres. Regression equations, both standardized and un-standardized, including constants were created with t-values and p-values indicating the significance of each predictor in the equation (Diekoff, 1992). Finally, an ANOVA shed light into the differences between the regression and residual variables, indicating the predictive strength of an equation using only the predictor (Diekoff, 1992).

Statistical significance, for each predictor included, was determined through *F*-values and *p*-values (Diekoff, 1992).

Measurement method differences

Analysis of the differences between the explored measures of vertical jump height was carried out using an ANOVA for repeated measures. The use of an ANOVA for repeated measures explored the differences between each measurement method. The repeated measures ANOVA allowed exploration of multiple comparisons in locating the source of the statistically significant differences between each measure of vertical jump height amongst the participants.

The ANOVA initially assessed differences between the selected methods of determining vertical jump height. These included the use of the Vertec, the use of maximum versus takeoff COM velocity from force platform analysis, vertical COM displacement from 3D video analysis, and the takeoff COM velocity correction methods proposed by Aragon-Vargas (2000) and Moir (2008). Examining the structure of the ANOVA for repeated measures, the independent variable was the method of vertical jump height determination. The dependent variable in this case was the measured value of vertical jump height. During the ANOVA procedure, the equality of variances was first examined through Levene's Test (Diekoff, 1992).

For the Levene's test, statistical significance indicates a violation in the assumption of homogeneity of variance, which is required in the use of parametric statistics (Diekoff, 1992). Statistical significance was determined from the probability level $p \leq 0.05$. The *F*-value indicates the degree to which the variances differ, while the significance value indicates the probability that this difference occurred due to chance (Diekoff, 1992). In the case of this analysis, no statistically significant differences were found in the Levene's test, indicating that the assumption of homogeneity of variance was met (Diekoff, 1992).

For tests of between-subjects effects, again *F* values and significance values were used to indicate statistically significant differences between the measured jump height values, using each respective method (Diekoff, 1992). During the repeated measures ANOVA, means for each method of jump height determination were specifically calculated; therefore the mean jump height for each method was calculated for the sample (Diekoff, 1992). The difference between these means and statistical significance was determined.

Overall, the outlined statistical procedures enabled evaluation of the differences between the laboratory and field methods of vertical jump height determination. The relationships between laboratory and field tests were evaluated in relation to the gold standard. Additionally, calculation of vertical jump height from linear regression, using vertical COM displacement from 3D video analysis as the criterion, allowed assessment of concurrent validity regarding each other jump height measurement method. The overall goal was therefore to establish a means of computing vertical jump height from 3D force platform analysis alone, which would show evidence of validity in relation to 3D video analysis.

CHAPTER 4

Results

Participants included 13 female intercollegiate volleyball players, obtained by convenience sampling of the Lakehead University Varsity Women's Volleyball Team. Signed consent forms, including Physical Activity Readiness Questionnaires, were obtained from 13 participants, following initial recruitment of 17 available team members. Participants were obtained with permission from the head coach of the varsity team such that testing occurred following the standard warm up carried out by members of the team, but prior to the commencement of a regularly scheduled practice. Once participants were obtained for testing no participants were lost due to drop out from the study.

The seven total methods of vertical jump height determination under consideration are summarized in Table 3. For clarity, abbreviations used for each variable and the methods of determining the corresponding jump height measurements are described in Appendix C. Data was once again categorized in terms of the research questions that are addressed under each heading. The results are therefore separated into assessment of relationships, prediction, and differences.

Descriptive statistics for vertical jump heights are summarized in Table 3, revealing vertical jump height means for each method. Standard deviations associated with each method are also presented allowing assessment of the variability in measurements associated with each method. Raw jump height values from each respective method of jump height measurement are summarized in Appendix D. Frequency distributions relative to the normal curve are summarized in Appendix H for each vertical jump height measurement method.

Table 3: Vertical Jump height method descriptive statistics

Measurement Method	Mean (m)	Standard Deviation (m)
VJHvid	0.47	0.05
VJHvertec	0.48	0.06
$VJHv_{toff}$	0.304	0.050
$VJHv_{max}$	0.347	0.051
VJHAV	0.47	0.06
VJHMoir	0.467	0.067
$VJHv_{max}R$	0.468	0.047

Note.
VJHvid is vertical COM displacement from 3D video
VJHvertec is jump height from the Vertec
$VJHv_{toff}$ is jump height from takeoff COM velocity
$VJHv_{max}$ is jump height from maximum COM velocity
VJHAV is jump height for corrected takeoff velocity from Aragon-Vargas
VJHMoir is jump height for corrected takeoff velocity from Moir
$VJHv_{max}R$ is jump height from the regression using $VJHv_{max}$

Measurement method relationships

Bivariate Pearson correlations were computed between each method of vertical jump height determination and the criterion, or gold standard, VJHvid. Table 4, presents the strength of the relationships between each method and VJHvid, as well as corresponding levels of significance. Appendix I illustrates the relationships between the methods of jump height determination relative to 3D video via scatterplots. The Pearson *r* represents the Pearson product-moment correlation coefficient, which provides a measure of the correlation, or linear dependence of one variable on another (Diekoff, 1992). The Pearson correlation ranges in value from -1 to +1, indicating the strength and direction of the relationship, 1 representing a perfect linear correlation, and the sign indicating the nature of the change in one variable as the other increases (Diekoff, 1992). A positive correlation dictates that as one variable increases in value the other also increases, while a negative correlation indicates that as one variable increases the other decreases.

The level of statistical significance represents the probability that the obtained correlation could have occurred due to chance, ranging in value from 0 to 1 (Diekoff, 1992). In each case a significance level of *p*<0.05 was used in determining statistical significance, representing the 95% confidence level that the obtained relationship did not occur due to chance (Diekoff, 1992).

Table 4: Bivariate Pearson correlations between jump height measurement methods and VJHvid

Correlated variables		**Pearson r**	**significance**
VJHvid	VJHvertec	**0.476	.100
VJHvid	$VJHv_{toff}$	***0.879	.000
VJHvid	$VJHv_{max}$	***0.907	.000
VJHvid	VJHAV	***0.758	.002
VJHvid	VJHMoir	***0.771	.002
VJHvid	$VJHv_{max}R$	***0.907	.000

Note. *low **moderate ***strong correlation
VJHvid is vertical COM displacement from 3D video
VJHvertec is jump height from the Vertec
$VJHv_{toff}$ is jump height from takeoff COM velocity
$VJHv_{max}$ is jump height from maximum COM velocity
VJHAV is jump height for corrected takeoff velocity from Aragon-Vargas
VJHMoir is jump height for corrected takeoff velocity from Moir
$VJHv_{max}R$ is jump height from the regression using $VJHv_{max}$

Statistically significant correlations were observed between VJHvid and $VJHv_{toff}$, VJH_{max} and $VJHv_{max}R$ at *p*=0.000, while VJHAV and VJHMoir revealed correlations with VJHvid at *p*=0.002 level. Conversely, VJHvertec ddi not reveal a statistically significant correlation with VJHvid, being 0.476 at *p*=0.100, above the 95% confidence level, *p*<0.05.

Further bivariate Pearson correlations, identified as significant at p<0.05 are examined in Table 5, revealing the strength of the relationship and the level of significance between the given variables under consideration in the analysis. Variables included the 7 methods of vertical jump height determination, as well as variables including temporal differences between the occurrence of maximum COM velocity and takeoff COM velocity, and the difference between the absolute values of these velocities.

Similar to Table 4, the Pearson *r*-values in Table 5 represent Pearson product-moment correlation coefficients, providing a measure of the correlation, or linear dependence of one variable on another, ranging from -1 to +1 (Diekoff, 1992). Again, the level of statistical significance represents the probability that the obtained correlation occurred due to chance, ranging in value from 0 to 1 (Diekoff, 1992). The $p<0.05$ level was used in determining statistical significance, representing the 95% confidence level (Diekoff, 1992).

Table 5: Statistically significant bivariate Pearson correlations

Correlated variables		**Pearson r**	**Significance**
$VJHv_{toff}$	$VJHv_{max}$	0.990	.000
$VJHv_{toff}$	VJHAV	0.800	.001
$VJHv_{toff}$	VJHMoir	0.839	.000
$VJHv_{max}$	VJHAV	0.838	.000
$VJHv_{max}$	VJHMoir	0.855	.000
$VJHv_{max}$	$VJHv_{max}R$	1.000	.000
ttoff-tmax	vmax-vtoff	0.971	.000
$VJHv_{toff}$	ttoff-tmax	-0.597	.031

Note. Significant at p<0.05
VJHvid is vertical COM displacement from 3D video
VJHvertec is jump height from the Vertec
$VJHv_{toff}$ is jump height from takeoff COM velocity
$VJHv_{max}$ is jump height from maximum COM velocity
VJHAV is jump height for corrected takeoff velocity from Aragon-Vargas
VJHMoir is jump height for corrected takeoff velocity from Moir
$VJHv_{max}R$ is jump height from the regression using $VJHv_{max}$
ttoff-tmax is the difference between time of maximum velocity and time of takeoff velocity
vmax-vtoff is the difference between maximum velocity and takeoff velocity

Prediction of three-dimensional video vertical centre of mass displacement

Linear Regression Analysis was carried out as a means of predicting vertical jump height as measured from 3D video analysis (VJHvid) with the 6 other methods of vertical jump height determination. Values of R, R^2, MSE (mean square error) and Error (the square root of MSE) are presented in Table 6.

Table 6: Regression analysis

Model	***R***	***R^2***	***MSE* (m)**	**Error**
VJHvid = 0.440*VJHvertec + 0.259	0.476	0.226	0.05	0.22
VJHvid = 0.907*VJHv$_{toff}$ + 0.193	0.879	0.772	0.026	0.161
VJHvid = 0.929*VJHv$_{max}$ +0.146	0.907	0.822	0.023	0.151
VJHvid = 0.709*VJHAV + 0.132	0.758	0.574	0.04	0.188
VJHvid = 0.601*VJHMoir + 0.188	0.771	0.595	0.035	0.186
VJHvid = VJHv$_{max}$R + 1.06E-5	0.907	0.822	0.023	0.151

Note.
VJHvid is vertical COM displacement from 3D video
VJHvertec is jump height from the Vertec
VJHv$_{toff}$ is jump height from takeoff COM velocity
VJHv$_{max}$ is jump height from maximum COM velocity
VJHAV is jump height for corrected takeoff velocity from Aragon-Vargas
VJHMoir is jump height for corrected takeoff velocity from Moir
VJHv$_{max}$R is jump height from the regression using VJHv$_{max}$

R represents the strength of the correlation between the predictor and the criterion (VJHvid), while R^2 represents the proportion of the variance in VJHvid explained by the given method of vertical jump height measurement (Diekoff, 1992). Mean square error (*MSE*), in Table 6, represents the Standard Error of the Estimate, or the average absolute error associated with prediction of jump height using the provided regression equations, in the units of the dependent, or criterion, variable (Diekoff, 1992). Mean square error (*MSE*) is therefore defined as the square root of the residual variance (Diekoff, 1992). Furthermore, error in Table 6 represents the prediction error, which is simply the square root of *MSE*, or the Standard Error of the Estimate (Diekoff, 1992). The Mean Square Error is therefore more easily interpreted in the units of the dependent variable, here being metres, representing vertical jump height.

The use of VJHv$_{max}$ accounted for the greatest proportion of the variance in VJHvid as seen in Table 6. Specifically, VJHv$_{max}$ accounted for 82.2% of the variance in VJHvid with a *MSE* of 0.023m, indicating that 82.2% of the variability in measurements of vertical jump height using 3D video was explained through measurements of vertical jump height computed using maximum COM velocity from a force plate. The value for *MSE* indicates that in measuring vertical jump height, using maximum COM velocity, the acquired measurements were within

0.023m of what is considered to be the actual jump height. $VJHv_{toff}$ accounted for the next highest proportion of the variance in VJHvid, 77.2% with a *MSE* of 0.026m. VJHAV and VJHMoir accounted for 57.4% and 59.5% of the variance in VJHvid respectively, with respective values of *MSE* 0.04m and 0.035m. Finally, VJHvertec accounted for the lowest proportion of the variance in VJHvid, with the highest *MSE* (22.6% and 0.05m respectively).

Measurement method differences

Following assessment of the ability to predict vertical jump height, differences between the associated methods of jump height measurement were examined. An ANOVA for repeated measures shed light into the differences in the means associated with each method. Table 7 reveals the results of a test of homogeneity of variance.

Table 7: Test of homogeneity of variances

Levene Statistic	**Degrees of freedom 1**	**Degrees of freedom 2**	**Significance**
0.362	6	84	0.901

The Levene statistic, in Table 7, illustrates *F*(6,84)=0.362, *p*=0.901. The results of this test suggest between group variances were not statistically significantly different, and therefore met the assumptions of parametric statistics, assuming homogeneity of variances amongst compared groups.

From the results of the test of homogeneity of variances, computed through Levene's statistic, an ANOVA for repeated measures was computed, and is summarized in Table 8.

Table 8: Repeated measures analysis of variance summary

Source	**Sum of Squares**	**Degrees of freedom**	**Mean Square**	**F**	**sig.**
Intercept	16.773	1	16.773	1073.421	.000
Error	0.188	12	0.016		

Table 8, shows that the 7 methods of vertical jump height determination revealed statistically significant differences among their means, as is demonstrated from the *F*(1,12)=1073.421, *p*=0.000.

Further exploration into the location of the statistically significant differences was explored through pairwise comparisons. The results of the pairwise comparisons for the repeated measures ANOVA are summarized in Table 9.

Table 9: Repeated measures analysis of variance pairwise comparisons summary

Compared jump tests		**Mean Difference (m)**	**Std. Error (m)**	**sig.**
VJHv$_{toff}$	VJHvertec	-0.17	0.015	.000
VJHv$_{toff}$	VJHvid	-0.17	0.007	.000
VJHv$_{toff}$	VJHv$_{max}$	-0.043	0.002	.000
VJHv$_{toff}$	VJHv$_{max}$R	-0.165	0.010	.000
VJHv$_{toff}$	VJHAV	-0.17	0.009	.000
VJHv$_{toff}$	VJHMoir	-0.163	0.002	.000
VJHv$_{max}$	VJHvertec	-0.13	0.016	.000
VJHv$_{max}$	VJHvid	-0.12	0.006	.000
VJHv$_{max}$	VJHv$_{max}$R	-0.121	0.010	.000
VJHv$_{max}$	VJHAV	0.12	0.009	.000
VJHv$_{max}$	VJHMoir	-0.120	0.001	.000

Note.
VJHvid is vertical COM displacement from 3D video
VJHvertec is jump height from the Vertec
VJHv$_{toff}$ is jump height from takeoff COM velocity
VJHv$_{max}$ is jump height from maximum COM velocity
VJHAV is jump height for corrected takeoff velocity from Aragon-Vargas
VJHMoir is jump height for corrected takeoff velocity from Moir
VJHv$_{max}$R is jump height from the regression using VJHv$_{max}$

Table 9 shows that statistically significant differences were observed between each method of vertical jump height determination in comparison to vertical jump heights measured using takeoff COM velocity, and maximum COM velocity. Each were significant at *p*=0.000. Table 9 specifically shows that VJHv$_{toff}$ was statistically significantly different than each other method of vertical jump height determination, as was VJHv$_{max}$. Importantly, the pairwise comparisons identified a statistically significant difference between VJHv$_{toff}$ and VJHv$_{max}$. The statistically significant relationship between $VJHv_{toff}$ and $VJHv_{max}$ was identified as having a mean difference of -0.043m, p=0.000, suggesting that $VJHv_{toff}$ underestimates $VJHv_{max}$. Conversely, no other statistically significant differences were observed between any of the other methods of vertical jump height determination.

CHAPTER 5

Discussion

Relationships between measurements of vertical jump height

Five laboratory methods measuring vertical jump height were examined in this study, with comparison of three of these methods to the gold standard, or criterion method of measuring vertical jump height, 3D video analysis (VJHvid). Three of the selected laboratory methods of vertical jump height determination involved 3D force platform analysis alone, while the others involved the sole use of 3D video analysis, or the combination of 3D video and 3D force platform analyses. Computing vertical jump height using equation 4 has been covered in the review of literature, but is the basis of determining the vertical COM displacement from takeoff velocity alone.

Relationships between laboratory measures of vertical centre of mass displacement

From Table 3, it is apparent that the means for $VJHv_{toff}$ and $VJHv_{max}$ differ from the means of VJHvid, VJHAV and VJHMoir. Furthermore, examining Table 4 reveals the nature of the relationship that $VJHv_{max}$, $VJHv_{toff}$, VJHAV and VJHMoir have with VJHvid. First, examining the correlation between VJHvid and VJHAV, the strength of the relationship was identified as r=0.758, p=0.002. This is in contrast to the strength of the relationship between 3D video vertical COM displacement and the Aragon-Vargas (2000) method of correcting takeoff velocity presented by Aragon-Vargas (2000), R=0.952. The strength of this relationship was lower, however, than the use of either takeoff COM velocity or maximum COM velocity in the results presented in both this study and the study by Aragon-Vargas (2000). The strength of the relationship between 3D video vertical COM displacement and takeoff COM velocity in this study was r=0.879, p=0.000, while Aragon-Vargas (2000) reported R=0.961. The use of maximum COM velocity was exclusive to this study and was found to have a correlation of *r*=0.907, *p*=0.000, with 3D video vertical COM displacement.

The correlation between VJHvid and VJHMoir in this study was identified as *r*=0.771, *p*=0.002; also lower than the use of either takeoff or maximum COM velocity alone. The results presented by Moir (2008), however, did not use 3D video during the measurement of vertical jump height, therefore comparisons cannot be made between the strength of the relationship between this technique and 3D video jump height. Like the use of maximum COM velocity, comparison of VJHMoir to VJHvid was established in this study. Importantly, VJHMoir demonstrated a stronger correlation with VJHvid than the combined use of video and force platform data expressed through VJHAV.

Overall, it is evident that maximum COM velocity showed the strongest positive relationship with VJHvid, suggesting that this measure was more indicative of actual jump height, measured from 3D video analysis. The strength of the relationship between VJHvid and $VJHv_{max}$, however, suggests that this relationship is worth stronger consideration in measuring vertical jump performance.

Relationship between vertical centre of mass displacement and Vertec jump height

The Vertec apparatus is a well-established field method of measuring vertical jump height, computing the difference between stand and reach, versus jump and reach values (Channell & Barfield, 2008; Harman, Rosenstein, Frykman & Rosenstein, 1990). Comparisons of the established field test were made, however, to the examined laboratory tests. Vertical jump heights, measured from the Vertec (VJHvertec), are summarized with the other methods of jump height determination in Table 3. The mean for VJHvertec (0.47m) was notably equal to the mean jump heights recorded for VJHvid (0.47m) and VJHAV (0.47m), and similar to the mean of

VJHMoir (0.468m). When examining bivariate Pearson correlations, however, summarized in Table 4, the relationship between jump height measured from the Vertec and VJHvid, the criterion, appeared to be weaker. This trend is in agreement with results presented by Leard et al., (2007), where a correlation of r=0.906 was found between jump height from the Vertec and 3D video vertical COM displacement, while a correlation of r=0.967 was found between jump height from the Vertec and force platform analysis. Leard et al. (2007) used the time in air, force platform, method of vertical jump height measurement.

The correlation between VJHvertec and VJHvid from this study is presented in Table 4, r=0.476, p=0.100. Not only was this relationship far weaker than the other correlation coefficients summarized in Table 4, but also, this relationship was not statistically significant (p>0.05). Conversely, the strongest correlation between force plate jump heights and 3D video jump height was observed between VJHv$_{max}$ and VJHvid, r=0.907, p=0.000. Examining the results from this study, in conjunction with the results presented by Leard et al. (2007), it seems that Vertec jump height was less representative of vertical COM displacement than jump height calculated via force platform analysis.

Differences between measurements of vertical jump height

Further examining Table 3, the discrepancy between the means for the use of COM velocity alone, maximum or takeoff, appears to severely underestimate jump heights from 3D video footage, the Aragon-Vargas (2000) method, the Moir (2008) method, and measurements from the Vertec. This is in agreement with the results presented by both Aragon-Vargas (2000) and Moir (2008). Aragon-Vargas (2000) reported mean jump heights of 0.520m for 3D video, 0.361m for the use of takeoff COM velocity, and 0.505m for corrected takeoff velocity. Meanwhile, Moir (2008) reported mean jump heights for males of 0.368m for the use of takeoff

COM velocity and 0.467m for corrected takeoff velocity, and mean jump heights for females of 0.207m for the use of takeoff COM velocity and 0.307m for corrected takeoff velocity. It is therefore apparent that in each case the use of COM velocity alone underestimates measures of jump height from 3D video or using corrected COM velocity. The differences between measures of vertical jump height should therefore be more carefully explored.

Differences between laboratory test measurements of vertical centre of mass displacement

Takeoff COM velocity and maximum COM velocity each demonstrated strong linear relationships with jump heights measured from 3D video analysis. The nature of the differences between takeoff and maximum COM velocities, in measuring vertical jump height, was therefore worth consideration. Although the use of maximum COM velocity was not explored in previous literature, data presented by Aragon-Vargas (2000) and Moir (2008) allow comparisons to be made with the results from this study. Takeoff COM velocity alone revealed a stronger correlation with 3D video vertical COM displacement. Aragon-Vargas (2000) reported that the use of takeoff COM velocity alone revealed a correlation of R=0.961 with video vertical COM displacement, while the use of corrected takeoff COM velocity revealed a correlation of R=0.952. Examination of the differences between methods of vertical jump height measurement was therefore carried out through an analysis of variance (ANOVA) for repeated measures.

The results from the repeated measures ANOVA in this study are summarized in Table 8, suggesting that statistically significant differences were present between the means of the methods considered. As a result, pairwise comparisons were used to determine the source of the differences (Diekoff, 1992). Addressing the Aragon-Vargas (2000) method of measuring vertical jump height, despite the lower positive correlation with VJHvid, statistically significant differences between the means of VJHvid and VJHAV were not found in pairwise comparisons.

The pairwise comparisons are summarized in Table 9. This method, however, utilizes 3D video analysis in its calculation of the difference between standing and takeoff position. As a result, it was questioned why one would use the force platform at all in this analysis. The gold standard has been previously considered to be 3D video analysis (Aragon-Vargas, 2000). Measuring the difference, however, between standing and takeoff position from video analysis, it seems impractical to discard the simple calculation of vertical COM displacement from the acquired video footage, which is required for the correction of jump height using takeoff COM velocity. For these reasons, it seems worthwhile to use data acquired from 3D force platform analysis alone, as a possible means of determining vertical jump height.

Moir (2008) subsequently proposed the calculation of COM takeoff height from only force platform data. Despite the fact that this method showed evidence of content and construct validity, measuring variables that are accepted to influence vertical jump height, as outlined in the deterministic model, actual computation of vertical COM displacement was subject to error as a result of the BioAnalysis software. Similar to the Aragon-Vargas (2000) method, statistically significant differences between the means of VJHvid and VJHMoir were not found in pairwise comparisons. Overall, the reliance on fundamentally sound reasoning in using the takeoff velocity correction method, the result of content and construct validity, resulted in values of vertical jump height that were not statistically significantly different from VJHvid. When considering, however, the strength of the positive linear relationship between $VJHv_{max}$ and VJHvid, this avenue of exploration seems valuable.

Table 9, identifies differences between the means of VJHvid and $VJHv_{toff}$, mean difference of -0.17m, p=0.000, as well as between VJHvid and $VJHv_{max}$, mean difference of

-0.12m, $p=0.000$. Furthermore, statistically significant differences were found between the means of $\mathrm{VJHv}_{\mathrm{toff}}$ and $\mathrm{VJHv}_{\mathrm{max}}$, -0.043m, $p=0.000$, suggesting that vertical jump height measurements between these methods were significantly different when using takeoff COM velocity versus maximum COM velocity. Combing the stronger positive relationship between VJHvid and $\mathrm{VJHv}_{\mathrm{max}}$, with the statistically significant difference between $\mathrm{VJHv}_{\mathrm{toff}}$ versus $\mathrm{VJHv}_{\mathrm{max}}$ suggested that maximum COM velocity was likely more suitable in predicting VJHvid, and its use is statistically significantly different than using takeoff COM velocity.

Differences between vertical centre of mass displacement and Vertec vertical jump height

Statistical differences between the laboratory methods of vertical jump height determination were compared to vertical jump heights measured using the Vertec apparatus. Examining the results from the pairwise comparisons in the repeated measures ANOVA procedure, presented in Table 9, it is clear that VJHvertec is statistically significantly different than $\mathrm{VJHv}_{\mathrm{toff}}$ and $\mathrm{VJHv}_{\mathrm{max}}$ ($p<0.05$). Overall, the results from this study contrast results presented by Leard et al. (2007), with respect to the differences between Vertec jump height and 3D video vertical COM displacement. Leard et al. (2007) compared jump heights measured via the Vertec, 3D video analysis, and force plate data using a one-way ANOVA. Statistically significant differences were reported amongst the three measurement methods $F(2,235)=5.51$, $p<0.05$ (Leard et al., 2007) and post hoc analysis revealed that jump height measured via the Vertec was statistically significantly different than 3D video vertical COM displacement, mean difference of -0.042m, $p=0.005$, while jump height using the time in air method from force plate data was not statistically different, 0.0051m, $p=0.972$.

The results from this study revealed a statistically significant difference between VJHvertec and $\mathrm{VJHv}_{\mathrm{toff}}$, mean difference of -0.17m, $p=0.000$. Similarly, statistically significant differences between VJHvertec and VJHv$_{max}$ were evident from the mean difference, -0.13m, p=0.000. Statistically significant differences were not, however, found between VJHvid and VJHvertec from the pairwise comparisons. Overall, despite the low correlation between jump heights from the Vertec and 3D video, the measured values are similar in absolute value, and these values were not statistically significantly different from each other. This finding in some ways enforces the use of the Vertec as a field test that is capable of delivering values of jump height that do not statistically significantly differ from the gold standard, 3D video analysis. Unfortunately, the moderate correlation with VJHvid suggests that caution should be used when making inferences about vertical COM displacement.

Prediction of vertical centre of mass displacement through regression

Bivariate correlations between jump heights, calculated using maximum versus takeoff COM velocity, and vertical COM displacement measured via 3D video analysis, revealed that maximum COM velocity has a stronger linear relationship. These correlations suggest that the predictive strength of either maximum or takeoff COM velocity should be considered with respect to vertical COM displacement from 3D video. This approach furthered the research of Aragon-Vargas (2000), focusing on the use of 3D video analysis as the criterion variable, or gold standard, with each other measurement method serving as the predictor. In contrast to Aragon-Vargas (2000), however, this study also examined the Moir (2008) method of correcting takeoff velocity with takeoff position, employing force platform data alone.

Aragon-Vargas (2000) reported that the use of takeoff COM velocity alone resulted in a correlation coefficient of R=0.961 and a coefficient of determination of R^2=0.906, while the present study returned values of R=0.879 and R^2=0.772. These values are noticeably in contrast between studies, however, in each case takeoff velocity alone provided better prediction of 3D video vertical COM displacement than the correction of takeoff velocity with takeoff position.

Examining Table 3, displaying the mean values for jump height, calculated through the various methods under consideration, VJHvid, mean of 0.47m, was noticeably underestimated using either v_{toff} or v_{max} alone, having means of 0.304m and 0.347m respectively. Linear regression allowed VJHv_{toff} and VJHv_{max} to be corrected, allowing each to better predict vertical COM displacement, measured via 3D video. Table 6, summarizes linear regression analysis, revealing predictive vertical jump height equations from VJHv_{max} and VJHv_{toff} as the predictors separately. In each case, VJHvid was used as the criterion variable.

Predicting vertical centre of mass displacement using maximum versus takeoff velocity

Further examination of Table 6, shows R and R^2 values, shedding light into the predictive ability of either variable. Again, R gives an indication of the strength of the correlation between the predictor and the criterion (VJHvid), notably corresponding to the r-values presented in Table 4. Conversely, R^2 represents the proportion of the variance in VJHvid explained by each predictor. Examining the R^2 values in Table 6 it is clear that VJHv_{max} accounted for 90.7% (R^2=0.907) of the variance in VJHvid, while VJHv_{toff} accounted for 87.9% (R^2=0.879). From the results presented by Aragon-Vargas (2000) it was observed that takeoff velocity alone accounted for a greater proportion of the variance in 3D video vertical COM displacement than the method of correcting takeoff velocity. From the R^2 values presented in this study it is clear that the use of maximum COM velocity, in computing vertical jump height, provided better prediction of 3D video vertical COM displacement than takeoff COM velocity or correction of takeoff velocity. As a result, the findings from this study served to confirm the results presented by Aragon-

Vargas (2000), but also revealed a method of jump height determination offering greater prediction of vertical COM displacement.

In this analysis, vertical jump height calculated using v_{max}, corrected using linear regression was denoted as $VJHv_{max}R$ (Vertical Jump Height using v_{max} from Regression analysis). Again, examining Table 3 it is clear that $VJHv_{max}R$ (mean 0.468m) produced vertical jump height values in better agreement to VJHvid (mean 0.47m), and with greater accuracy, expressed through a greater number of significant digits. The greater accuracy was the result of the reliance on force plate data, sampled at higher frequencies than video data. Increased accuracy and decreased measurement error associated with measurements taken from force plate data provided agreement with the Aragon-Vargas (2000) and Moir (2008) results. Examination of the bivariate Pearson correlations in Table 4, and the results of the linear regression analysis in Table 6, it is clear that that the Pearson correlation coefficient r, R and R^2 values, were the same as those produced from $VJHv_{max}$ alone. The identical values are due to the fact that each method of jump height determination relied on the same variable, v_{max}, and therefore produced identical correlations and proportions of variance explaining VJHvid. The regression model using maximum COM velocity to predict vertical COM displacement from 3D video simply corrected for the underestimation of jump height using v_{max} alone.

Predicting vertical centre of mass displacement through correction of takeoff velocity

In addition to the comparison between the use of either maximum or takeoff COM velocities, in predicting VJHvid, comparison was also made to the Aragon-Vargas (2000) and Moir (2008) methods of vertical jump height determination. Again, examining Table 6, VJHAV provided a predictive regression equation, with VJHvid as the criterion variable. The Aragon-Vargas (2000) method of correcting takeoff velocity was presented as R=0.961 and R^2=0.924 by

Aragon-Vargas, while the results from this study, presented in Table 6, resulted in R=0.758 and R^2=0.574. The R^2 value again suggests that 57.4% of the variance in VJHvid was accounted for in the predictive equation using VJHAV. Conversely, Table 6 reveals that the Moir (2008) method resulted in R=0.771 and R^2=0.595 in the present study, suggesting that 59.5% of the variance in VJHvid was accounted for by the VJHMoir predictive equation. This indicates that the Moir (2008) method offered better prediction of 3D video vertical COM displacement than the Aragon-Vargas (2000) method, though each method actually accounted for less of the variance in the criterion than takeoff COM velocity alone. As a result, the use of VJHv_{max} appeared to be a better predictor of VJHvid than VJHv_{toff}, VJHAV, or VJHMoir.

Overall, $v_{max,}$ appeared to offer the best prediction of COM vertical displacement from 3D video analysis (VJHvid) of the explored methods. Use of v_{max} accounted for more of the variance in VJHvid, and had the strongest correlation with VJHvid, in comparison to v_{toff}, the Aragon-Vargas (2000) and the Moir (2008) methods of correcting v_{toff} with takeoff height. Maximum COM velocity therefore demonstrated the strongest evidence of concurrent validity with 3D video analysis, of the examined laboratory methods.

Prediction of vertical centre of mass displacement using the Vertec

Similar to assessment of the predictive strength of vertical jump height measured via alternative laboratory tests to 3D video, the predictive strength of established field test, the Vertec apparatus (VJHvertec), was examined. Examining the correlation between VJHvertec and VJHvid (r = 0.476, p=0.100), it is clear that the established field test lacked a strong relationship with the gold standard in laboratory tests. Although, Leard et al. (2007) reported a stronger correlation between Vertec jump height and 3D video vertical COM displacement, r=0.906, ultimately, the correlation with jump height computed via force plate data was higher, r=0.967.

This, in conjunction with the statistically significant difference reported between Vertec jump height and 3D video vertical COM displacement suggests that force plate data allowed better prediction of vertical COM displacement (Leard et al., 2007). The results from this study therefore expanded on these findings, instead exploring the predictive ability of each vertical jump height measurement method through linear regression.

In this study, despite a lack of statistically significant differences between VJHvertec and VJHvid during pairwise comparisons following the repeated measures ANOVA, the ability of VJHvertec to predict VJHvid was examined. The predictive ability of VJHvertec was assessed using regression analysis. Table 6 reveals a predictive equation for VJHvid, using VJHvertec as the predictor. Examining the associated R and R^2 values, 0.476 and 0.226 respectively, suggests that a low proportion (22.6%) of the variance in VJHvid was accounted for using VJHvertec as the predictor. The predictive strength of the Vertec apparatus was therefore shown to be quite low with respect to estimation of vertical COM displacement. Overall, measurements from the Vertec provide a good indication of jump and reach height, though centre of mass displacement should not be confused with Vertec jump height.

Validity

This study focused on evaluating the criterion-related validity, specifically concurrent validity, of each examined method of jump height determination, using VJHvid as the criterion, or gold standard. Criterion-related validity compares measurements from an accepted standard, or criterion, that gives an accurate representation of a variable (Sim & Arnell, 1993). Concurrent validity is purported to compare the measurement of a given variable by both the criterion method and an alternative method at approximately the same time, in an attempt to show convergence between these methods (Sim & Arnell, 1993). Assessment of concurrent validity therefore incorporates measures of the ability of a predictor to explain the variance in the criterion variable, as well as to produce values with little error (Aragon-Vargas, 2000). Linear regression analysis supplies a means of assessing concurrent validity; therefore the results summarized in Table 6 were reviewed with greater scrutiny. Examining Table 6, concurrent validity was indicated through R^2 values, and through measures of mean square error, or the average absolute error associated with prediction of jump height measured in metres. A method of measurement that explained a high degree of variance in the criterion variable (R^2 close to 1) and demonstrated low mean square error (*MSE*) as therefore identified as showing evidence of concurrent validity.

Validity in computing vertical centre of mass displacement from maximum velocity

It was demonstrated that the use of v_{max}, in calculating vertical COM displacement accounted for the most variance in VJHvid, when compared to the other methods, having the highest R^2 value, accounting for 82.2% of the variance in VJHvid. Furthermore, when examining Table 6, it is apparent that VJHv_{max} and VJHv_{max}R demonstrated the lowest values for mean square error (*MSE*), each being 0.023m. The use of maximum centre of mass velocity therefore demonstrated the strongest evidence of validity from the available methods of jump height determination. In contrast, VJHvertec demonstrated the highest *MSE* (0.05m), VJHAV revealed a *MSE* of 0.04m, VJHMoir showed a *MSE* of 0.035m, and VJHv_{toff} demonstrated a mean square error of 0.026m.

Overall, VJHv_{max} and VJHv_{max}R showed the strongest evidence of validity of the examined methods of vertical jump height measurement. Though VJHAV showed evidence of validity, correcting takeoff velocity for takeoff position, accounted for less variance in VJHvid, and showed greater mean square error than v_{toff} alone. These results are in agreement with those presented by Aragon-Vargas (2000), who similarly revealed that methods of vertical jump height measurement from force platform data alone presented higher R^2 values than the method of correcting vertical jump height using takeoff position from video footage. The results from the Aragon-Vargas (2000) study resulted in the proposed Moir (2008) method, relying solely on force platform data. Unfortunately, the results presented by Moir (2008) use the takeoff velocity correction method, from force platform data alone, as the criterion; therefore no comparisons were made to vertical COM displacement from video analysis. Consequently, comparisons between concurrent validity presented by Moir (2008) were limited with the present study, which used 3D video analysis as the criterion. It should be noted that the Aragon-Vargas (2000) study presented values for R^2 higher than those in the present study. Similarly, mean square error values (*MSE*) presented by both Aragon-Vargas (2000) and Moir (2008) were lower than those presented in this study.

Measurement error associated with vertical jump height determination methods

From the Aragon-Vargas (2000) study, the proportion of the variance in vertical COM displacement, from 3D video analysis, accounted for by takeoff COM velocity, from 3D force platform analysis, was 92.4% (R^2=0.924). Examining the results presented by Aragon-Vargas (2000), a *MSE* of 3.76E-04m (0.376mm) was revealed, using takeoff COM velocity as the predictor, while Moir (2008) presented a *MSE* of 3.13E-04 (0.313mm). A possible explanation for the discrepancies between *MSE* values from Aragon-Vargas (2000) and Moir (2008), in comparison to values for *MSE* in the present study, is the expression of measurements to the number of significant digits of the available measurement technique. Measurements in the present study were assessed on the ability to meaningfully express measurements based on the accuracy of the device. Though in many cases, following mathematical computations, values were often expressed by computer software to a greater number of significant digits than the measurement method is actually capable of accurately measuring. As a result, values of *MSE* and Error may reflect greater accuracy than actual measurements from the equipment that was used. For this reason, great care was taken in presenting results in this study, expressed in terms of the measurement capability of the methods explored, rather than values returned after computations by the associated computer software.

Overall, the *MSE* values do, however, shed light into the error associated with measurements taken from the given device. Therefore, within the results from this study, comparisons were made in terms of selecting measurement techniques that contain the lowest measurement error. Sampling frequency was specifically identified as having implications on measurement accuracy and the subsequent expression of significant digits, the result of measurement error. Differences between the sampling frequencies associated with video analysis and force platform analysis resulted in contrasting *MSE* values, summarized in Table 6. Notably force platform analysis measurement techniques have lower *MSE* values, the result of greater sampling frequency and greater measurement accuracy. Sampling frequency for 3D video analysis has been identified as 100Hz while sampling frequency for 3D force platform analysis has been identified as 1000Hz. Increased sampling frequency allows increased accuracy, through decreased measurement error. Increased error during the correction of takeoff velocity using takeoff position, measured from video analysis, can be explained regarding the ability to accurately identify the instant of takeoff, from the 100Hz sampled video footage. Digitization error is also worth consideration when using video analysis, which has been addressed in terms of video resolution, and was further addressed through examination of reliability in Appendices F and G.

Vertical jump height measurement limitations

Vertical jump heights calculated using the equation of uniform acceleration differed from the Aragon-Vargas (2000) and the Moir (2008) methods of vertical jump height determination. The Aragon-Vargas (2000) and Moir (2008) methods use takeoff COM velocity in the equation of uniform acceleration, but accounts for the change in body position from standing to takeoff, which is not accounted for in using takeoff COM velocity alone. This method offers a valuable correction to the use of takeoff COM velocity. In practice, however, the Aragon-Vargas (2000) method relies on two contrasting techniques for COM measurement. Furthermore, the computation of takeoff COM height outlined by Moir (2008), was limited by the software used to compute takeoff height in this study.

Regarding the combined use of video and force platform data, one of the more noticeable differences in terms of video versus force platform methods is the sampling frequency at which each acquires data. In this study, a sampling frequency of 100Hz was used for video footage, while a sampling frequency of 1000Hz was used for force plate data. The ability to reliably determine the precise point of takeoff from the ground, when using video footage, was therefore questioned, as video footage was not synchronized with force plate data, where the point of takeoff is far more easily located. As a result, the ability to accurately and reliably identify the difference between standing and takeoff position raised questions about the validity of this method of correction in practice. Conversely, calculation of takeoff COM height, outlined by Moir (2008), was carried out through integration of vertical COM velocity.

Prior to calculation of vertical COM displacement using the Moir (2008) method, integration of vertical ground reaction forces was calculated. This process required force data to be normalized relative to participant mass, followed by the use of participant mass again in the integration process, as outlined in equation 6. In computing COM velocity, it is clear that participant mass measured from the force platform, must be converted to mass (m) which is then used to divide the integral of the ground reaction forces, with respect to time. The reliance on participant mass proved to be important mathematically, therefore consistent use of the proper participant mass was required at each step. Unfortunately, a limitation in the BioAnalysis software, used in this analysis, made computation of COM displacement less reliable. The BioAnalysis software computed the vertical COM velocity integral, though the raw values were not accessible to the user. Manual integration using other capable software, in this case Microsoft Excel, was possible, though the same participant mass, expressed to the same number of significant digits is important in computing COM velocity in agreement with the BioAnalysis software.

The limitation of the Bioanalysis software became further evident in that the mass used in normalization of vertical ground reaction forces and in computation of participant mass, was also inaccessible to the user. Though participant mass can be examined from the force-time curves for each participant, presented as the negative of participant mass, once the participant has left the force platform, it was unclear whether this was the value used by the software during calculations. This posesda potential source of error in calculations of vertical COM displacement from force platform data alone, in the method proposed by Moir (2008). Although the correction of takeoff velocity using takeoff COM height showed evidence of content and construct validity, as outlined by the deterministic model for vertical jump height, concurrent validity with vertical COM displacement from 3D video analysis was less evident (Sim & Arnell, 1993; Hay and Reid, 1988; in Feltner, Fraschetti, & Crisp, 1999).

Further exploration of vertical jump height measurement methods

In addition to the bivariate correlations explored between VJHvid and each other method of vertical jump height determination, other statistically significant correlations were discovered. These correlations were explored with respect to their meaning. Table 5, summarizes statistically significant bivariate correlations between the various methods of vertical jump height determination, and other factors related to properties of COM velocity.

Table 5 reveals several correlations that were somewhat predictable, but are worth discussion. The temporal sequencing of takeoff versus maximum COM velocity occurs very rapidly, which dictates that these values are similar in nature. As was observed in the similarity between vertical jump heights calculated using maximum and takeoff COM velocities, these values revealed a strong positive linear relationship. $VJHv_{toff}$ and $VJHv_{max}$ showed a Pearson r of 0.990 at p=0.000. Despite this strong relationship, it has been shown that jump heights calculated using these values were statistically significantly different. Furthermore, the ability of v_{max} to predict vertical COM displacement from 3D video was better. Examining relationships with v_{max} revealed that $VJHv_{max}R$ showed a perfect linear correlation (r=1.000) with $VJHv_{max}$. This predictable relationship is due to the fact that $VJHv_{max}R$ simply differs from $VJHv_{max}$ by linear constants. Each data point, therefore, remained in the same position relative to the others, but was simply inflated by the regression constants. As a result, $VJHv_{max}R$ and $VJHv_{max}$ shared the same relationships with each other variable.

Examining the relationship between $VJHv_{toff}$ and VJHAV, a correlation of r=0.800, at p=0.001, showed that despite the correction of v_{toff} using takeoff position, a strong linear relationship was still present. Despite the correction, however, v_{toff} alone accounted for more of the variance in VJHvid and showed less error, therefore showing evidence of better concurrent validity than VJHAV. VJHv$_{max}$ shared a relationship with VJHAV, expressed through and *r* of 0.838 at *p*=0.000. The Aragon-Vargas (2000) method of correcting v$_{toff}$ therefore had a stronger relationship with the strongest predictor of VJHvid. The decreased correlation between VJHAV and VJHv$_{toff}$ was likely the product of digitization error and the ability to locate the point of takeoff.

Relationships between VJHMoir, VJHv$_{toff}$ and VJHv$_{max}$ are presented in Table 5, indicating that, similar to VJHAV, a stronger positive linear relationship was observed with VJHv$_{max}$. VJHMoir revealed a strong positive correlation of *r*=0.839 at *p*=0.000 with VJHv$_{toff}$, and a positive correlation of *r*=0.855 at *p*=0.000 with VJHv$_{max}$. Overall, comparing the linear relationships between VJHv$_{toff}$ and VJHv$_{max}$ with VJHAV and VJHMoir, suggested that correcting takeoff COM velocity with takeoff position, simply improved the strength of the relationship between either of the correction methods, and jump height from maximum COM velocity.

Timing and sequencing

Final exploration of the temporal sequencing of v$_{toff}$ and v$_{max}$ revealed two statistically significant relationships worth note. Examining the difference between the temporal occurrence of v$_{max}$ and v$_{toff}$, expressed as t$_{toff}$-t$_{max}$, the difference between v$_{max}$ and v$_{toff}$ revealed a Pearson *r* of 0.971 at *p*=0.000. This strong positive relationship suggested that as the time between v$_{max}$ and v$_{toff}$ increases, so too does the difference between v$_{max}$ and v$_{toff.}$. Simply put, participants who reduce the amount of time between v$_{max}$ and v$_{toff}$ will have values of v$_{toff}$ more similar to v$_{max}$, or will be able to leave the ground with greater velocity. Conceptually, this may be important, as participants who demonstrate faster movement time, will produce faster takeoff velocity.

Although it has been shown that v_{max} was the better predictor of vertical COM displacement from 3D video analysis, it can be understood that the goal is to leave the ground with the greatest velocity. Having v_{toff} more similar in value to v_{max} accomplishes this goal, as was expressed in this relationship. These findings further the suggestions of Vanezis and Lees (2009), proposing that differences between good and poor performers should be investigated with respect to temporal sequencing, though in the context of muscle activation. Force plate analysis presents ground reaction forces, which serve to measure the outcome of muscle activation: force production. Hudson (1986), however, suggested that coordination results from optimal sequencing of force production, which may be inferred from COM velocity, integrated using ground reaction forces.

In contrast to the strength of the relationship between timing and velocity differences, a statistically significant ($p<0.05$) strong negative relationship of -0.597, at $p=0.031$, was found between $VJHv_{toff}$ and the difference between takeoff time and maximum COM velocity time. Though the strength of this relationship was relatively weak compared to the other previously mentioned correlations, it does deserve some attention and explanation. The practical significance of a negative relationship between the time difference from maximum to takeoff COM velocity, and $VJHv_{toff}$ suggests that as the movement time decreases, takeoff velocity increases. This relationship is similar to the previously explained relationship between COM velocity timing and the difference between maximum and takeoff COM velocities, but directly showed that as takeoff velocity increases, the time between v_{max} and v_{toff} decreases. Overall, the temporal relationships that were identified through bivariate correlations suggest that decreasing the time between maximum and takeoff COM velocities will result in greater takeoff velocity, which will in turn result in greater jump height. These relationships are in agreement with previous research by Harman, Rosenstein, Frykman and Rosenstein (1990) indicating that higher jumps were faster, with all stages occurring temporally closer to takeoff. Further examination of these relationships therefore offers avenues for future exploration, investigating differences between takeoff and maximum COM velocities, and the temporal sequencing of these velocities in relation to subsequent vertical jump height.

Future considerations for centre of mass velocity

Previously, peak power has been identified as a strong predictor of vertical jump height (Dowling and Vamos, 1993). Power can be expressed mathematically through equation 8. Notably, power includes force, which is expressed relative to participant's mass. Examining temporal relationships with respect to COM velocity alone, however, is not measured with respect to participant mass; participant mass is divided out of COM velocity during integration, as is apparent in equation 6. Examination of the differences between maximum and takeoff COM velocity therefore allows assessment of movement characteristics, independent of mass. Consequently, it is proposed that changes in COM velocity, from maximum to takeoff, may represent characteristics of muscle contraction rate, indicative of muscle fibre type, rather than muscle force. This topic may be explored in future research in this area.

CHAPTER 6

Summary and Conclusions

In conclusion, this study evaluated the concurrent validity of vertical jump height measured using maximum COM velocity, in relation to established methods of measuring vertical jump height, when compared to 3D video vertical COM displacement. Examination of the relationships and differences among the examined methods of vertical jump height, and the subsequent ability of each to predict 3D video vertical COM displacement, was identified and discussed in the analysis of this study. Overall, vertical jump height was assessed in 13 female varsity volleyball players, ranging in age from 18 to 22 years, during the countermovement vertical jump. Analysis of elite female jumpers ensured that participants were familiar with the countermovement jump, and were capable of completing vertical jumps with minimal risk of injury. The external validity, or generalizability, of the results from this study however, is limited to female varsity volleyball players aged 18-22 years, performing a countermovement vertical jump.

Summarizing the outcomes of this research can be more easily addressed through re-examination of the research questions and purposes of this study. The goals of this research sought to:

1. Examine relationships and differences between the explored methods of jump height determination.
2. Create a method of predicting vertical COM displacement that relies solely on force platform data, at greater sampling frequency than video analysis, and without the assumptions associated with accurate and reliable marker placement (Wilson at al., 1999).

3. Demonstrate evidence of concurrent validity for each method of jump height determination relative to vertical COM displacement from 3D video.

As a result, research questions were formulated that addressed each of these goals, with specific reference to the methods of measuring vertical jump height established in the literature. The first research question therefore aimed at exploring relationships and differences between each vertical jump height measurement method. The first research question was: *What are the relationships and differences between vertical jump heights measured amongst the field test (Vertec) and the laboratory methods (3D video and force platform analysis) under consideration? More specifically, what are the relationships and differences between the measurements of vertical jump height from the Vertec, 3D force platform analysis, using takeoff versus maximum COM velocity, 3D video analysis, and the methods of correcting takeoff velocity with takeoff position, proposed by Aragon-Vargas (2000) and Moir (2008)?*

In each case, vertical COM displacement from standing to peak flight height, measured from 3D video analysis, was used as the criterion. Conclusions from the data suggest that maximum COM velocity, from 3D force platform analysis, was most highly correlated with vertical COM displacement, measured from 3D video analysis (r=0.907, p=0.000). Jump height measurements calculated using maximum COM velocity alone, however, were statistically significantly different from vertical COM displacement measured from 3D video (mean difference 0.12m, p=0.000).

The Vertec apparatus showed the lowest correlation with 3D video jump height (r=0.476, p=0.476), though from pairwise comparisons, the acquired measurements did not statistically significantly (p<0.05) differ from 3D video jump height. The ability of the Vertec, however, to predict 3D video jump height was the poorest of the explored jump height measurement methods. The proportion of the variance in the 3D video jump height explained by the Vertec was 22.6% (R^2=0.226), with a mean square error of 0.05m.

Beyond examining the relationships and differences between each vertical jump height measurement method, the research sought to better predict vertical COM displacement, measured via 3D video, using maximum COM velocity, measured via force platform data alone. The second research question was: *To what extent can jump height from 3D video analysis be predicted through linear regression, using maximum COM velocity measured from 3D force platform analysis?*

The results from this study revealed that linear regression analysis allowed prediction of vertical COM displacement, from 3D video, using maximum COM velocity as the predictor. Computing jump height from maximum COM velocity allowed the creation of the following linear regression equation:

$$\mathrm{VJHvid} = 0.929 * \mathrm{VJHv}_{\mathrm{max}} + 0.146$$

Maximum COM velocity accounted for the most variance in 3D video jump height (R^2=0.907) and the lowest mean square error (*MSE*=0.026m) of the selected methods of jump height determination.

Finally, this research sought to establish measures of concurrent validity between each of the explored measurement methods and vertical COM displacement from 3D video analysis. The third research question was: *To what extent does each method of vertical jump height determination demonstrate evidence of validity relative to vertical COM displacement from 3D video analysis?*

This question was addressed through linear regression, summarized in Table 6. The proportion of the variance in the criterion that was accounted for by predictor was expressed, along with mean square error (*MSE*) of the measurement technique. In each case, vertical COM displacement from 3D video was used as the criterion, and each respective measurement method was used as the predictor. Overall, jump height from maximum COM velocity accounted for the greatest proportion of the variance in vertical COM displacement from 3D video, with the lowest *MSE* (82.2%, *MSE*=0.023m) followed respectively by takeoff COM velocity (77.2%, *MSE*=0.026m), the Moir (2008) method (59.5%, *MSE*=0.035m), the Aragon-Vargas (2000) method (57.4%, *MSE*=0.04m), and the Vertec (22.6%, *MSE*=0.05m).

Overall, this study identifies a previously unexplored means of measuring and predicting vertical jump height, measured from 3D force platform analysis. The results suggest that maximum COM velocity offererd stronger correlation with vertical COM displacement, measured by the gold standard in vertical jump height measurement, 3D video analysis. Maximum COM velocity explained a greater proportion of the variance in 3D video analysis and contained less measurement error than any of the jump height determination methods that were examined. Importantly, measurement of vertical jump height using 3D force platform data alone actually showed lower mean square error than either the Aragon-Vargas (2000) method, or the Moir (2008) method, correcting takeoff velocity with takeoff position. The Aragon-Vargas (2000) method measures takeoff position from 3D video analysis, therefore this method demonstrates that video analysis actually added a source of error to the measurement. Conversely, the method proposed by Moir, though relying on mathematically correct concepts offers room for computational errors, which in the case of this study was the result of software limitations.

Finally, analysis of the reliability of digitization during movements outside the calibrated area offers further insight into possible errors relating to video acquisition and digitization.

Future explorations should also focus on measurements of COM timing, and the influence of these factors on vertical jump height. The significance of the findings from this study will allow future investigations of vertical COM displacement to be explored with greater ease and decreased measurement error. This provides benefits for researchers and sport organizations, allowing measurement of athletic performance via force platform analysis alone.

In summary, the important findings from this study, within the identified limitations include:

1. A statistically significant positive correlation existed between maximum COM velocity and vertical COM displacement measured from 3D video.
2. The correlation between jump height measured using maximum COM velocity and vertical COM displacement from 3D video was stronger than between takeoff COM velocity and jump height from 3D video.
3. Linear regression, using maximum COM velocity as the predictor, allows a method of predicting jump height from 3D video that showed the highest evidence of validity of the examined methods.
4. Despite the use of 3D video analysis as the gold standard, digitization from video analysis presented a source of error that exceeds the error in force platform data alone. This source of error included digitization error, also being a product of software data resolution.

Recommendations for future research include:

1. The statistical findings from this study, in terms of statistically significant correlations between maximum, versus takeoff, COM velocity and vertical jump height, from 3D video analysis, should be replicated and further examined.

2. The use of maximum COM velocity in computing vertical jump height during the countermovement vertical jump should be examined in other populations.
3. Temporal relationships between maximum and takeoff COM velocities with respect to vertical jump height should be explored as a possible means of explaining vertical jump proficiency, and characteristics of muscle fibre type.
4. Reliability with respect to sampling frequency and high-speed movements should also be further examined, and compared to digitization of segments outside the calibrated volume.
5. Computation of corrected takeoff COM velocity using takeoff position from force platform data, outlined by Moir (2008), should be carried out in an attempt to bypass the software limitations presented in this study.
6. The use of the Vertec, in inferring vertical COM displacement should likely be avoided. Vertec analysis should be isolated to measurement of jump and reach height.

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APPENDICES

Appendix A

Sample size calculation

For a normally distributed population and known standard deviation, equation 10 can be used to compute the maximum error of the estimate, *E* (Khazanie, 1996; Sincich, 1985).

For a 95 percent confidence interval:

$$\alpha = 0.05$$

$$z_{\alpha/2} = z_{0.025/2} = 1.96$$

(Khazanie, 1996; Sincich, 1985).

Using the empirical rule, stating that approximately 95.4% of observations will fall in the interval:

$$(\bar{x}-2s,\ \bar{x}+2s)$$

Whereas, approximately 99.7% of all observations will fall in the interval:

$$(\bar{x}-3s,\ \bar{x}+3s)$$

(Khazanie, 1996; Sincich, 1985)

Furthermore, Chebyshev's Rule also states that for a data set, irrespective of frequency distribution, whether symmetric or skewed, at least 89% of the observations will fall within 3 standard deviations of the mean:

$$(\bar{x}-3s,\ \bar{x}+3s)$$

(Khazanie, 1996)

As a result, it will be assumed that almost all data within:

$$\mu \pm 3\sigma$$

Therefore, the range in the population can be understood as approximately:

$$6\sigma$$

(Khazanie, 1996; Sincich, 1985)

Using normative data outlined in Appendix B, the data should fall between approximately 20cm and 44cm for female participants aged 15-29. A range of 24cm will therefore be used.

Using the assumption that the range will include 6σ, the following calculation can be carried out:

$$\text{Range} = 6\sigma = 24\text{cm}$$

$$\sigma = 24\text{cm}/6$$

$$\sigma = 4.0\text{cm}$$

Therefore the equation 10 can be expressed as:

$$E = 1.96\left(\frac{4.0cm}{\sqrt{n}}\right)$$

As *E* represents the maximum error of the estimate, one can be 95% confident that the estimate $\bar{x}$ will not differ from the true mean μ by more than E (Khazanie, 1996; Sincich, 1985). As a result, *E* can be calculated for any given sample size, such that jump height is predicted within ± *E* cm (Khazanie, 1996; Sincich, 1985).

If a sample size of 13 participants is obtained:

$$E = 1.96\left(\frac{4.0cm}{\sqrt{13}}\right)$$

Therefore,

$$E = 1.96\left(\frac{4.0cm}{\sqrt{13}}\right) = 2.17cm$$

This can be understood conceptually as acquiring a sample of 13 participants will allow one to be 95% confident that $\bar{x}$ will not differ from the true mean, μ, by more than 2.17cm (Khazanie, 1996; Sincich, 1985).

Appendix B

Jump height normative data

Age	Needs Improving	Fair	Good	Very Good	Excellent
15-19	< 27	28-31	32-35	36-39	> 40
20-29	< 24	25-28	29-33	34-37	>38

Note. Vertical Jump Height (cm) for Females (CSEP, 2003)

Appendix C

Methods of vertical jump height measurement and corresponding abbreviations

Vertical jump height measurement abbreviation	Vertical jump height measurement method description
VJHvid Vertical jump height video	Vertical jump height from vertical displacement of the COM, measured via 3D video analysis
VJHvertec Vertical jump height Vertec	Vertical jump height from difference between jump and reach and stand and reach values, measured via Vertec apparatus
VJHv_{toff} Vertical jump height takeoff COM velocity	Vertical jump height from vertical displacement of the COM, measured via 3D force platform analysis, calculated from equation of uniform acceleration ($h=v^2/2g$) using takeoff COM velocity
VJHv_{max} Vertical jump height maximum COM velocity	Vertical jump height from vertical displacement of the COM, measured via 3D force platform analysis, calculated from equation of uniform acceleration ($h=v^2/2g$) using maximum COM velocity
VJHAV Vertical jump height (Aragon-Vargas, 2000)	Vertical jump height from combination of COM takeoff velocity, measured via 3D force platform analysis, and COM takeoff position, measured via combination of 3D video analysis, as proposed by Aragon-Vargas (2000)
VJHMoir Vertical jump height (Moir, 2008)	Vertical jump height from combination of COM takeoff velocity and COM takeoff position, each measured via 3D force platform, as proposed by Moir (2008)
VJHv_{max}R Vertical jump height maximum COM velocity regression equation	Vertical jump height from vertical displacement of the COM, measured via 3D force platform analysis, calculated from regression equation using equation of uniform acceleration ($h=v^2/2g$) with maximum COM velocity

Appendix D

Raw jump heights for each jump height measurement method

Participant	VJHvid (m)	VJHvertec (m)	$VJHv_{toff}$ (m)	$VJHv_{max}$ (m)	VJHAV (m)	VJHMoir (m)	$VJHv_{max}R$ (m)
1	.44	.42	.2839	.3260	.45	.4685	.4489
2	.41	.41	.2177	.2625	.42	.3463	.3899
3	.49	.39	.3128	.3649	.51	.4353	.4850
4	.50	.46	.3854	.4177	.52	.5482	.5340
5	.54	.52	.3795	.4343	.56	.5794	.5495
6	.51	.50	.3190	.3637	.53	.4653	.4838
7	.40	.41	.2441	.2897	.40	.3905	.4151
8	.51	.48	.3081	.3620	.49	.5601	.4823
9	.40	.46	.2655	.3030	.45	.4359	.4275
10	.41	.53	.2770	.3156	.43	.4604	.4392
11	.45	.53	.2801	.3221	.47	.4170	.4452
12	.53	.56	.3642	.4027	.54	.4852	.5201
13	.50	.53	.3113	.3473	.39	.4799	.4686

Appendix E

Measurement accuracy and significant digits

In general, accuracy describes the discrepancy between a measured value and the true value (Windolf, Gotzen & Morlock, 2008). Conversely, precision relates to the repeatability of measurements taken under identical circumstances (Windolf, Gotzen & Morlock, 2008). With respect to the accuracy of 3D video analysis, interpreting accuracy and precision is largely dependent on the available software screen resolution. The Vicon Motus software data resolution is reported to be 656 x 492 pixels (www.vicon.com). As a result, the field of view must be taken into account in calculating the smallest measured value that can be detected as a change in location. The field of view for video acquisition in this study was approximately 5.00m x 3.75m, resulting in an area of $18.75m^2$. From the real world field of view, the distance in metres corresponding to the movement from one pixel to the next was calculated. Here, 1 pixel was found to equal 0.0076m, or 0.76cm from the following Vicon Motus resolution calculation.

Vicon Motus software screen resolution: 656 x 492 pixels

Camera (real-world) field of view: 5.00m x 3.75m = 18.75m^2

5.00m/656pixels = 3.75m/492pixels = 0.76cm/pixel

Three-dimensional video analysis measurements of displacement were therefore rounded to the nearest whole centimetre, as the accuracy of this measurement technique was limited by the available field of view and data resolution (Wilson, Smith, Gibson, Choe, Gaba, & Voels, 1999).

The accuracy of the 3D force platform analysis, expressing ground reaction forces, was measured to the nearest 0.001N. This allowed subsequent COM velocities to be measured to the nearest 0.001ms^{-1}. This conclusion was reached from the conversion of Newtons to SI units, being kgms^{-2} (Young, Wilson & Byrne, 1999). It is therefore evident that measurements taken to the nearest 0.001N represent values to the nearest 0.001kgms^{-2}, and when integrated with respect to time, dividing by mass (measured in kilograms), results in measurements to the nearest 0.001ms^{-1}, or the nearest 0.1cms^{-1}. Furthermore, following this same line of reasoning, displacement measurements can accurately be expressed to the nearest 0.001m, or 0.1cm.

Finally, for the Vertec apparatus, the spacing and width of the vanes limited the accuracy of measurements. Vane spacing was measured to be approximately 1.6cm, though the tape measure, used to measure stand and reach values was accurate to the nearest millimeter. As a result, measurements from the Vertec apparatus were also rounded to the nearest whole centimeter.

Appendix F

Three-dimensional video reliability results

Reliability was examined with respect to 3D video analysis. Intraclass correlations were used to shed light on the ability of the researcher to reliably identify joint markers during manual digitization and the ability of the Vicon Motus software to reliably identify joint markers through automatic digitization. The combined effects of manual and automatic digitization procedures, in additively combining to computationally locate the centre of mass of each participant, were also assessed in terms of reliability. Table 10 summarizes these procedures.

Table 10: Peak flight height intraclass correlations

Variable	**Digitization Method**	**Model**	**Intraclass Correlation**	**Sig.**
Right Hip	Auto	ICC(3.1)	.927	.000
Left Heel	Manual	ICC(3.1)	.912	.000
Centre of Mass	Auto and Manual	ICC(3.1)	.886	.000

Table 10 shows a summary of intraclass correlations (ICC) for each digitization method and the selected variable that was considered over 23 digitized frames at the peak of flight height. In each case the intraclass method that was used was ICC(3,1), as outlined by Shrout and Fleiss (1979). The selected ICC(3,1) is a two-way mixed model, where each selected variable is assessed by a single digitizing method, either the researcher or the Vicon Motus Software, or through a combined method. In this model the selected methods of digitization are the only available, automatic or manual, and are therefore the only methods of interest. Furthermore, reliability was calculated for single measures, where the spatial location of the joint marker was identified in each frame, but was then resolved to only the vertical component, being the only component of movement under consideration in the analysis. As a result, the vertical location of each marker considered in the intraclass correlation was compared to the location of the same marker, at the same time in the video sequence. Resultant intraclass correlations are reported in

Table 10. Notably automatic digitization of the right hip, 0.927 *p*=0.000, was higher than that of the left heel, 0.912 *p*=0.000, which was manually digitized. The combined influence of manual and automatic digitization methods was reported in the ICC of the COM, 0.866 *p*=0.000, consisting of 19 marker locations, each digitized in combined automatic and manual methods, depending on the visibility of the marker in the video footage.

The intraclass correlations presented in Table 10 reflect more representative values of reliability over the important frames of interest, at the height of peak flight. Conversely, intraclass correlations were computed over 12 frames used in determining participant standing height and combined in the intraclass correlation analysis of the subsequent 23 jump height frames. As a result, a total of 35 digitized frames were tested for intraclass correlation, shedding light into the overall reliability of the digitizing procedure. Table 11 summarizes intraclass correlations in two identical trials of a single participant for three variables.

Table 11: Combined standing and peak flight height intraclass correlations

Variable	**Digitization Method**	**Model**	**Intraclass Correlation**	**Sig.**
Right Hip	Auto	ICC(3.1)	.999	.000
Left Heel	Manual	ICC(3.1)	.999	.000
Centre of Mass	Auto and Manual	ICC(3.1)	.999	.000

The results summarized in Table 11 simply serve to demonstrate the difference between reliability in digitizing frames over total body movement versus standing, and subsequent measures of peak flight height versus standing height.

Appendix G

Types of reliability in measurement of vertical jump height

Three-dimensional video digitization was explored in this study through test-retest reliability, digitizing the same trial twice. Comparing the results of the present study to those put forth by Aragon-Vargas (2000), reliability for vertical COM displacement from 3D video analysis was reported through test-retest reliability on 5 trials by each participant. As a result, the reliability presented by Aragon-Vargas (2000) represents the reliability of the measurement technique, rather than the reliability of the digitization process, which is presented in this study. In any case, the results presented by Aragon-Vargas (2000) for test-retest reliability, across the 5 completed trials for each participant, are expressed through a reliability correlation coefficient (R). The reliability coefficient (R) was presented as 0.994, for 3D video analysis at a sampling frequency of 60Hz (Aragon-Vargas, 2000). The coefficient of determination was also presented, R^2=0.987, representing the proportion of the explained variance, in relation to total variance, in vertical COM displacement from video analysis (Aragon-Vargas, 2000; Diekoff, 1992). This test-retest reliability, in measuring vertical COM displacement, is therefore interpreted to be high, demonstrating that 3D video analysis showed strong evidence of reliability.

Test-retest reliability, in terms of digitization, was not assessed by Aragon-Vargas (2000), the expressed reliability does, however, give an indication of the test-retest reliability in measuring vertical COM displacement across trials. This information is useful in interpreting the reliability of vertical COM displacement measurements used in this study, though the sampling frequency for video footage is 100Hz in the present study, rather than 60Hz, offering greater accuracy. Greater accuracy, however, can in some cases deflate reliability. This may be due to the measurement and expression of more sensitively, or accurately, measured decimal places. In the case of this exploration of reliability, automatic and manual digitization procedures were carried out on selected markers over 12 video frames at standing height and over 23 frames during peak flight. Digitization was carried out in both camera views to obtain vertical components of marker locations from 3D analysis. The digitization procedures can therefore be examined separately in terms of automatic and manual methods, as well as in terms of measurements taken at peak flight alone, and when including standing.

Automatic digitization reliability

Automatic digitization was carried out on the right hip marker, which was visible in both camera angles over the entire course of the required 12 frames at standing and 23 frames at peak flight. Intraclass correlation (3,1) was used in each assessment of the test-retest reliability of identical trials. Test-retest reliability was assessed at only peak flight, as well as during standing and at peak due to the fact that digitization during standing yields very high reliability correlations, ICC=0.999, *p*=0.000, as is apparent in Table 11, of Appendix F. This is the result of markers remaining relatively motionless during standing. The high intraclass correlation coefficients presented in Table 11, of Appendix F, when including frames at standing height, are similarly high to those presented by Aragon-Vargas (2000). It is unclear, however, in the methodology and the expression of reliability values by Aragon-Vargas (2000), whether the researcher included all digitized frames or used automatic or manual digitization methods.

Table 10, in Appendix F, summarizes intraclass correlations used in assessing the test-retest reliability of each digitization process over the 23 video frames at peak flight height. Table 10, in Appendix F, shows that automatic digitization of the right hip over the vertical component at peak flight height resulted in an ICC of 0.927, at *p*=0.000. This suggests that from digitizing the same trial twice, values for right hip vertical locations were in 92.7% agreement across the 23 trials considered. The fact that the values are not in perfect agreement is likely the result the ability of the software to reliably locate the centre of the joint marker from trial to trial. Though imperfect, this intraclass correlation coefficient at peak flight is relatively high, but this does present a limitation of the automatic digitization process. The decreased intraclass correlation coefficient value for automatic digitization in this study is noticeably less than the reliability coefficient presented by Aragon-Vargas (2000). This may indicate that the inclusion of digitized frames at standing height, remaining relatively motionless, may inflate the reliability coefficient presented by Aragon-Vargas (2000).

Manual digitization reliability

Manual digitization in this study was carried out on the left heel marker, which could not be digitized through automatic procedures in the Vicon Motus software. In contrast to automatic digitization, manual digitization produced an ICC of 0.912, at p=0.000. The intraclass correlation values for manual versus automatic digitization reveal that automatic digitization demonstrates slightly stronger reliability than manual digitization, though both methods show limitations when taking measurements during flight. Similar to automatic digitization, intraclass correlation coefficients for manual digitization were inflated when including frames at standing height. Manual digitization when including standing frames resulted in ICC=0.999, p=0.000. It is therefore apparent that the inclusion of frames where the participant remains relatively motionless inflates the reliability measures. Once again, it is unclear in the methodology presented by Aragon-Vargas (2000) which digitization method and across which frames the data was analyzed.

The reliability of digitizing the entire 19-point model was also assessed in this study, computing the total body vertical 3D COM displacement. Reliability of vertical COM location is indicative of combined manual and automatic digitization procedures over all 19-marker locations. Evaluating the total body COM when including standing frames resulted in ICC=0.999, *p*=0.000, and ICC of 0.886, *p*=0.000, during flight. Examining the intraclass correlation coefficient during flight, it is clear that the digitization error associated with 19 moving joint markers in 2 camera views, using both manual and automatic methods, results in decreased reliability. The contrasting results reported in Tables 10 and 11, however, were purposefully shown to demonstrate the phase dependent nature of reliability with respect to digitization and the ability of the software to acquire measurements outside the calibrated volume. It is therefore suggested that reliability may be artificially inflated when examining video frames where joint markers remain relatively motionless. As a result, it is proposed that the results presented by Aragon-Vargas (2000) likely included video frames from standing through peak flight, bringing the reliability coefficient closer to the values presented in Table 11, of Appendix F, for the present study.

Influences of joint markers on reliability

Reliability, expressed through intraclass correlations, appears to be lower for rapidly moving markers than for stationary markers. Further analyzing the contrasting intraclass correlations, including or not including the 12 frames at standing, it should be understood that the calibrated volume using the Vicon Motus calibration tree allows measurements within this volume to a vertical height of 2.00 metres. Measurements outside this volume, though possible, may be less reliably measured, which may attribute to lower intraclass correlations for measurements at peak flight height, the result of decreased measurement accuracy.

The issue of measurements taken outside the calibrated volume was explored by Windolf, Gotzen & Morlock (2008), suggesting that measurement accuracy was influenced by digitization of movements outside the calibrated volume. It is suggested that loss of measurement accuracy outside the calibrated volume is the result of spatial distortion, though the authors did not indicate that precision was influenced by measurements taken outside the calibrated volume (Windolf, Gotzen & Morlock, 2008). Overall, it is important to recognize that the reliability of digitization during 3D video analysis is capable of producing high ICC values, though these values depend on the method of digitization, the frame rate of data acquisition, the speed at which the segment markers are moving, the visibility of the marker in the available camera views, and the location of the markers relative to the calibrated volume.

Force platform analysis reliability

Aragon-Vargas (2000) also tested the reliability of force platform analysis, using takeoff COM velocity and corrected takeoff COM velocity, across 5 trials by each participant. Test-retest reliability using takeoff COM velocity alone, in computing jump height, was expressed through the reliability correlation coefficient, R=0.986, and the coefficient of determination, R^2=0.972 (Aragon-Vargas, 2000). Similarly, reliability of the correction method for takeoff velocity, using takeoff position, was also assessed, where R=0.970 and R^2=0.942 (Aragon-Vargas, 2000). From these analyses, it is apparent that both takeoff and corrected takeoff COM velocity show strong reliability, though takeoff COM velocity alone shows stronger test-retest reliability. As in the case of test-retest reliability for vertical COM displacement from 3D video analysis, test-retest reliability for force platform analyses were not established in this study due to the performance of a single trial by each participant. For this reason, the reliabilities presented by Aragon-Vargas (2000) are useful, in making inferences about the test-retest reliability of the methods used in this study. It should be noted, however, that as with video footage, a higher sampling frequency was used for force platform analysis in this study, 1000Hz versus 300Hz, allowing greater measurement accuracy.

Appendix H

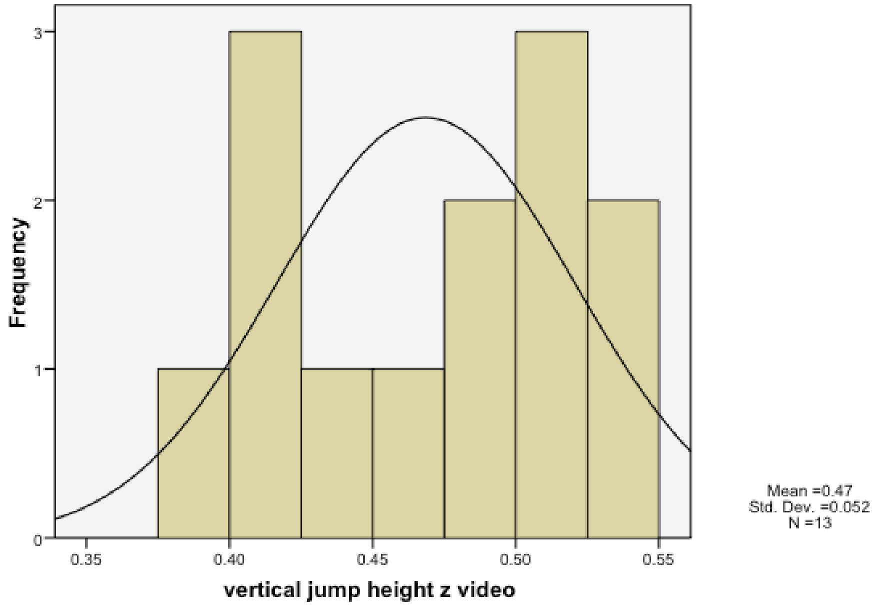

Figure 13: 3D video jump height frequency distribution relative to normal distribution

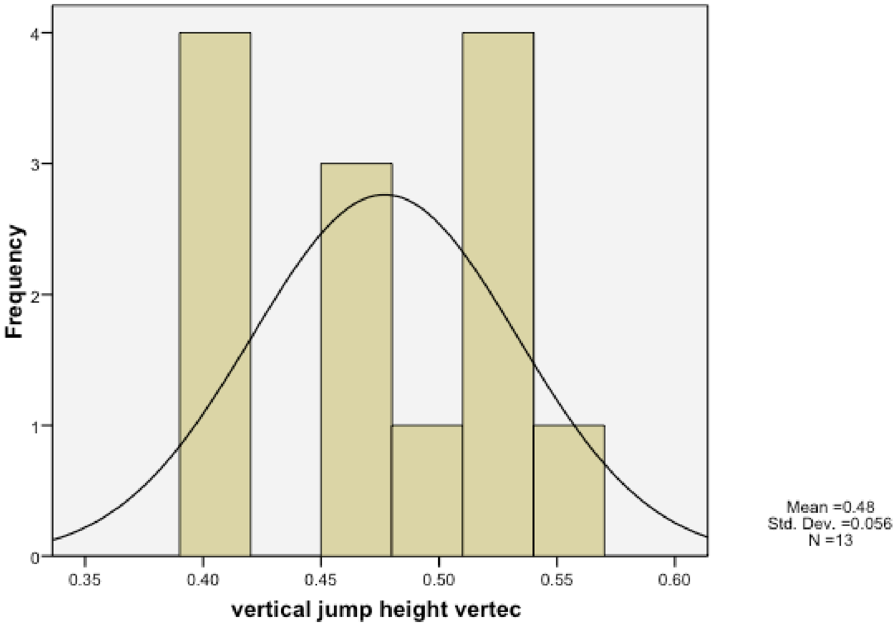

Figure 14: Vertec jump height frequency distribution relative to normal distribution

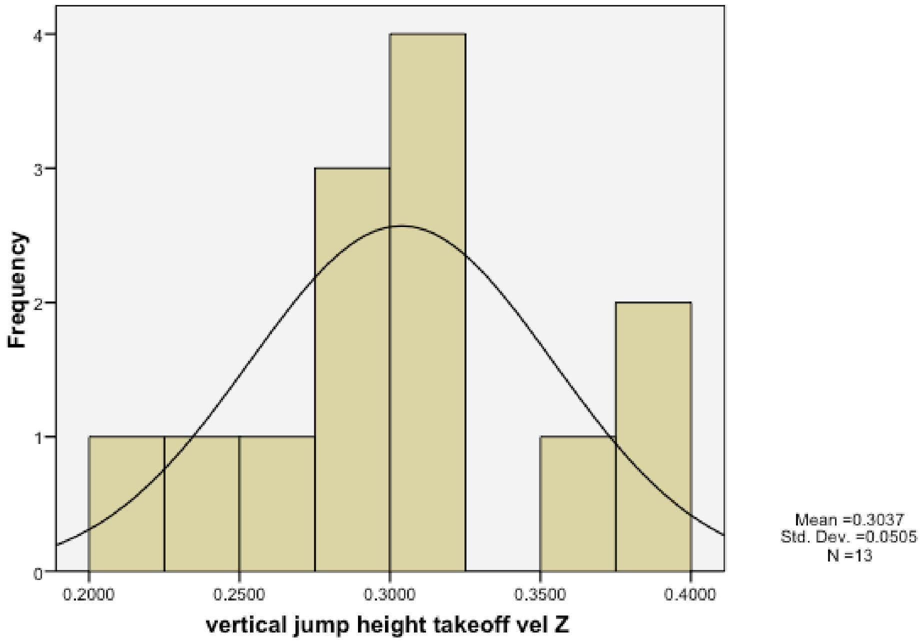

Figure 15: Takeoff centre of mass velocity jump height frequency distribution relative to normal distribution

Figure 16: Maximum centre of mass velocity jump height frequency distribution relative to normal distribution

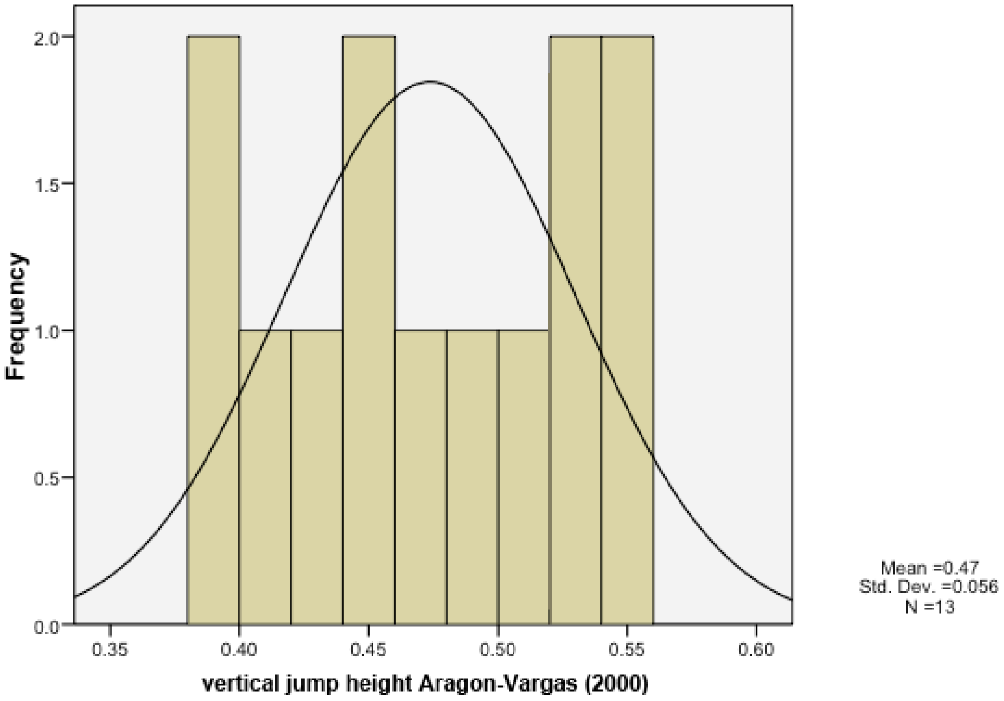

Figure 17: Aragon-Vargas (2000) jump height frequency distribution relative to normal distribution

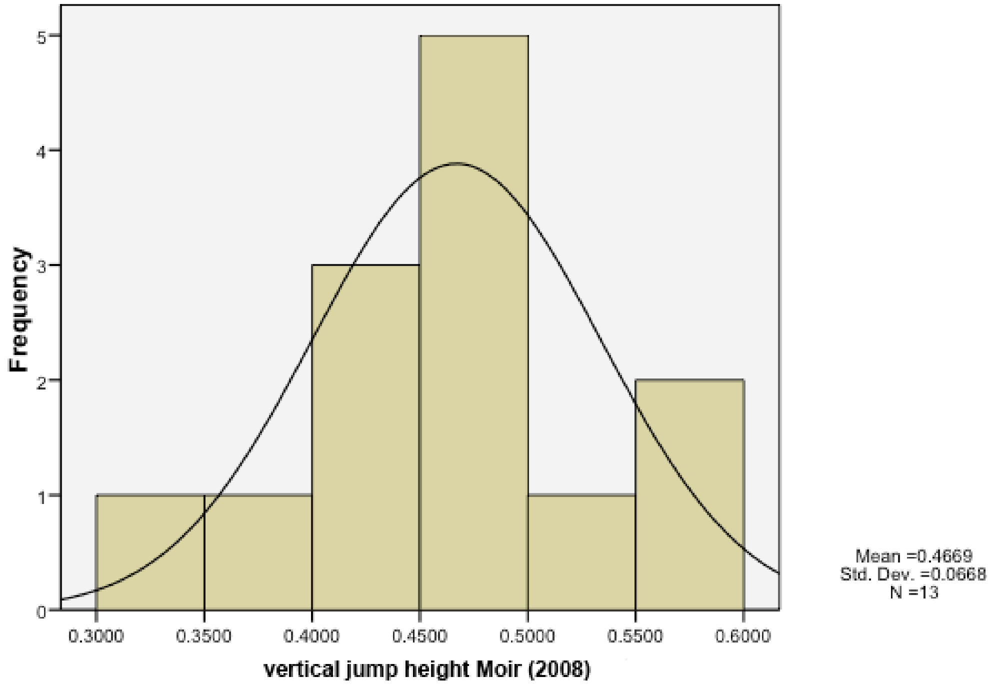

Figure 18: Moir (2008) jump height frequency distribution relative to normal distribution

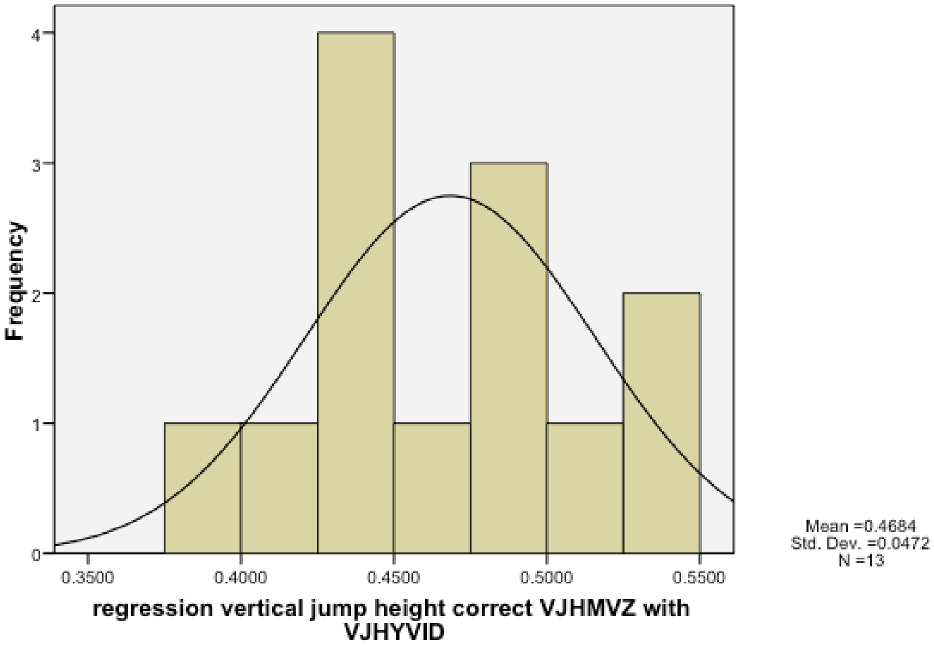

Figure 19: Maximum center of mass velocity regression jump height frequency distribution relative to normal distribution

Appendix I

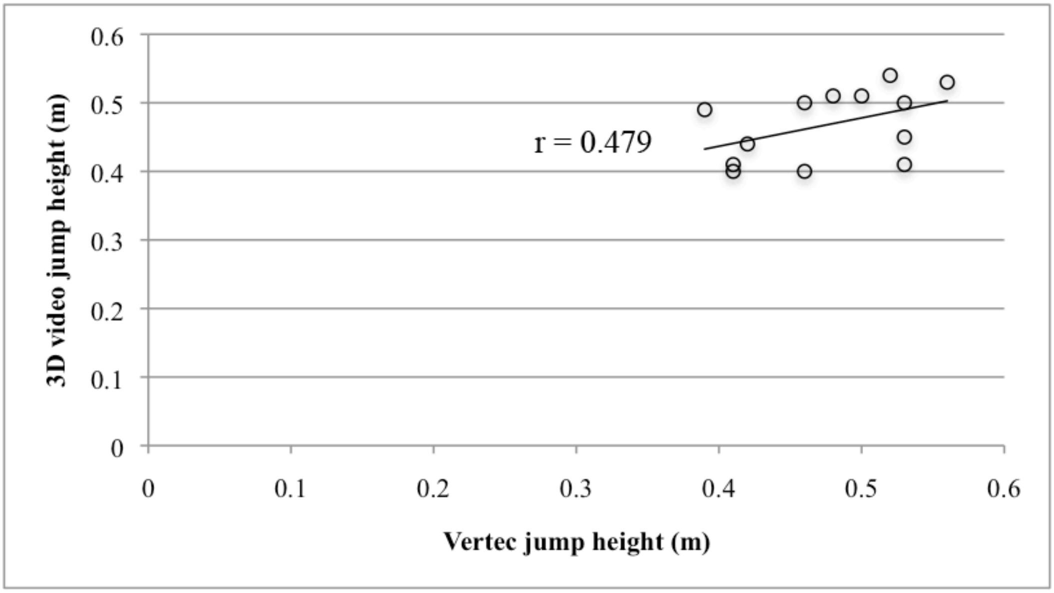

Figure 20: Vertec and 3D video jump height correlation

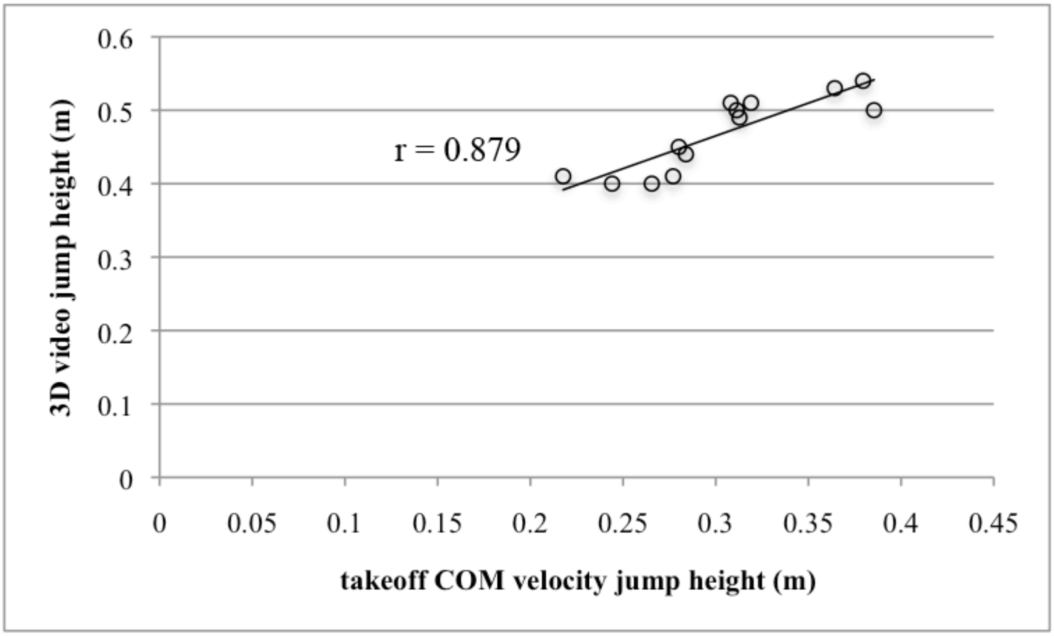

Figure 21: Takeoff center of mass velocity and 3D video jump height correlation

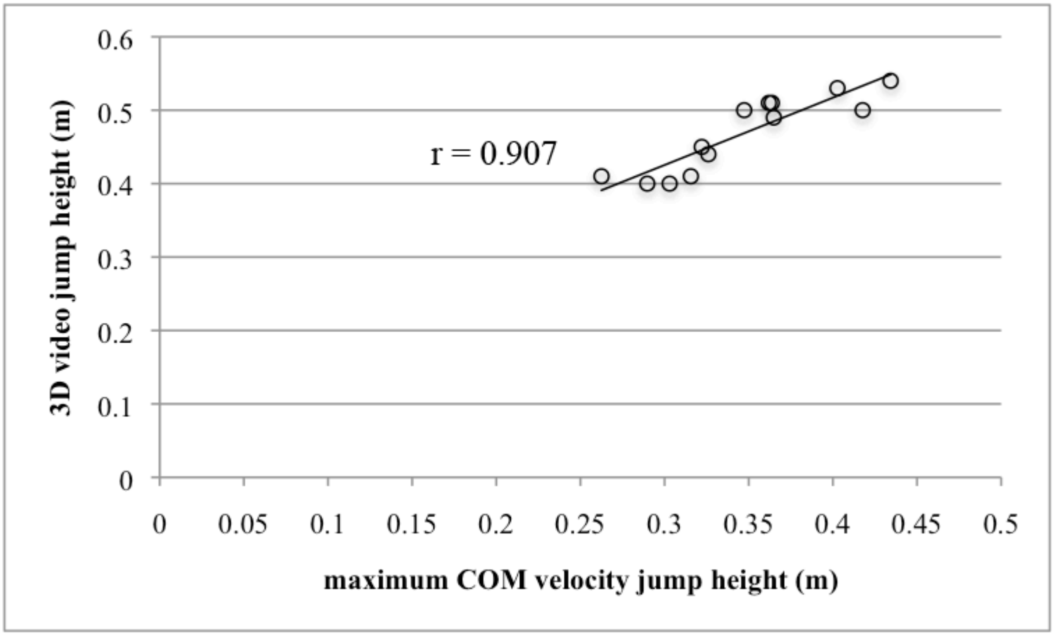

Figure 22: Maximum center of mass velocity and 3D video jump height correlation

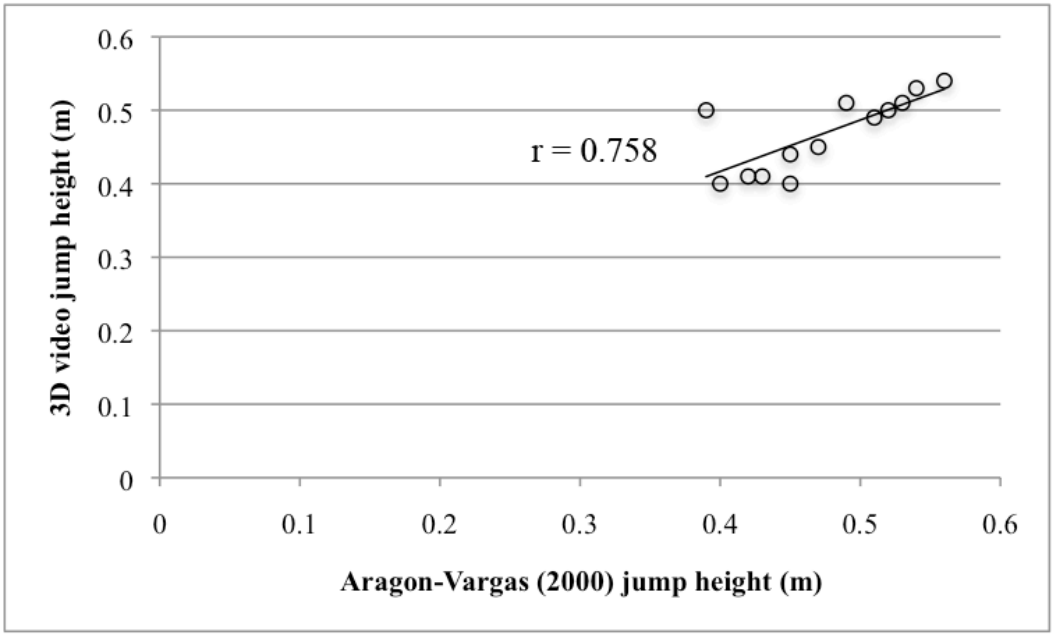

Figure 23: Aragon-Vargas (2000) method and 3D video jump height correlation

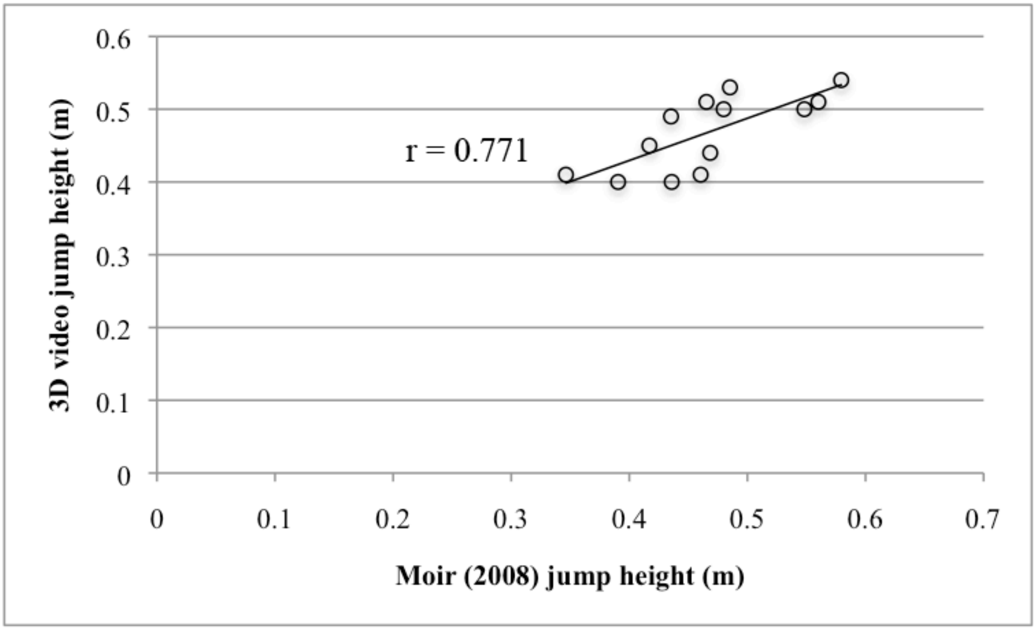

Figure 24: Moir (2008) method and 3D video jump height correlation

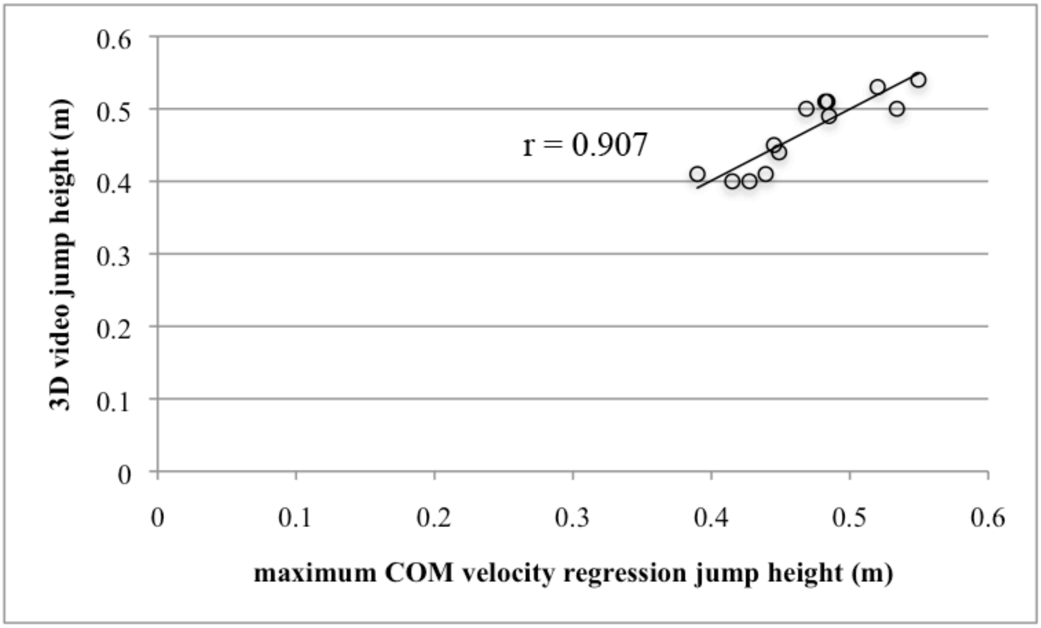

Figure 25: Maximum center of mass velocity regression equation and 3D video jump height correlation