Jumping Tasks and Athletic Performance

by

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B.Sc., University of Saskatchewan, 2010

M.Sc., University of Victoria, 2015

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We acknowledge and respect the Lək̓ʷəŋən (Songhees and Xʷsepsəm/Esquimalt) Peoples on whose territory the university stands, and the Lək̓ʷəŋən and W̱SÁNEĆ Peoples whose historical relationships with the land continue to this day.

Supervisory Committee

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Abstract

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The assessment and prediction of athletic performance is essential in research and sports science. The following series of studies systematically investigates the relationship between jumping performance and athletic tasks aimed at improving the accuracy and applicability of athletic assessments ranging from lab to field-based tests. Each study builds upon the findings of the previous research, moving from lab-based assessments to field-based applications, and demonstrates how advancements in technology and methodology can enhance athletic evaluation.

The squat jump (SJ) is a commonly used task in athletic assessment and the primary exercise used in vertical force-velocity profiling (v-FVP) of the lower extremities. Study 1 addresses a prevalent issue in SJ assessments, where identifying the unweighting phase

before the upward propulsive phase is often subjective. This subjectivity can lead to inaccuracies in evaluating SJ performance and, consequently, in designing training interventions. To resolve this, Study 1 set out to determine a quantitative threshold of unweighting amplitude that resulted in an increased jump height. In a laboratory setting, 56 athletes performed a total of 936 SJs under four different external loads. The SJs were categorized based on the amplitude of unweighting relative to bodyweight (BW) into six groups. Using an Analysis of Covariance with jump height as the dependent variable and external load as the covariate, the study found a significant difference in jump height across unweighting groups ($F(5,930) = 13.65$, $p < 0.01$). The results indicated that at a threshold of 2% BW for unweighting amplitude jump height was significantly increased compared to the <1% BW threshold. This finding is critical as it provides a standardized threshold for ensuring the validity of SJ assessments and reduces the subjectivity of previous studies utilizing the squat jump. This threshold not only aids in accurate assessment but also paves the way for the automation of detecting valid SJs.

Study 2 follows from Study 1 by focusing on enhancing the practicality of performance assessments in field settings. While Study 1 established an objective threshold for SJ assessments, the next step is to explore how other jumping metrics can be reliably measured using more portable equipment. This study evaluates the predictive validity of the peak-speed measurements from a linear position transducer (LPT) for estimating takeoff speed in hexagonal-bar (hex-bar) jumps. Twenty-one rowing athletes performed hex-bar jumps in accordance with national testing protocols, and the peak-speed data collected from the LPT were compared to criterion measure obtained from force plates. The study demonstrated a high association between takeoff speed and estimated takeoff speed (r =

0.98, $p < 0.05$), with a mean difference of only 0.18%, indicating minimal bias. The Bland-Altman plot further confirmed that there was no systematic bias in the predictions. This study's findings are significant because they show that LPTs, which are more portable and less costly than force plates, can accurately estimate takeoff speed. This capability is crucial for field-based assessments where the availability of "gold standard' equipment may be limited due to logistical or financial reasons.

Study 3 builds on Study 1 by utilizing a novel exercise for force-velocity profiling of the lower extremities and further advances Study 2 by introducing a computational model to calculate average force, velocity, and power from hex-bar jumps. While Study 2 validated the use of LPTs to calculate takeoff speed, Study 3 aims to extend this by validating a three-factor computational model that utilizes takeoff speed from the hex-bar jumps to derive comprehensive v-FVP. Using 21 university varsity rowing athletes, the study compared the computational model's outputs with criterion measures from force plates. The results confirmed that the model accurately computed force, velocity, and power with the mean biases of 85.38 N, 0.00 $m \cdot s^{-1}$, and 73.36 W. This study's findings are important as they demonstrate that a highly accessible and common training exercise can be used in conjunction with a simple computational model to replace expensive force plate measurements. This offers a cost-effective and field-applicable solution for assessing key performance metrics. The ability to calculate these metrics using the hex-bar jump is particularly advantageous for sports where traditional jump tests may be less specific or feasible.

Study 4 follows from Study 3 by focusing on applying these advanced metrics to sport specific contexts. While Study 3 demonstrated the feasibility of a computational model for deriving performance metrics, Study 4 applies these insights to understand how v-FVP metrics can predict sprint performance in female rugby athletes. This study explores the relationship between v-FVP metrics and 40 m sprint times in female university rugby athletes. Data were collected from 50 athletes (mean age 20.30 ± 2.02 years, weight 74.86 ± 12.10 kg, height 1.69 ± 0.05 m, 40 m time 6.15 ± 0.36 s). First, Pearson correlation coefficients were used to determine the strength of the relationship between 40 m time and v-FVP metrics. Second, redundant metrics defined as moderately correlated independent metrics, or metrics with negligible correlation to 40 m time were removed from the analysis. The remaining metrics were then entered into a linear mixed model to examine the effect of v-FVP metrics on 40 m time while accounting for individual differences. Significant correlations ($p < 0.01$) were found between 40 m time and several v-FVP metrics. Maximal Mechanical Power (P_{max}, $W \cdot kg^{-1}$) and the Slope of the Force-Velocity Relationship (S_{FV}, $N \cdot s \cdot m^{-1} \cdot kg^{-1}$) were significant predictors of 40 m time in the linear mixed model ($p < 0.01$). The model explained 93% of the variance, with fixed effects accounting for 46.79%. When examining the correlation of fixed effects, P_{max} showed a strong negative relationship with 40 m time, while S_{FV} had a low positive correlation. These findings suggest that practitioners should focus on improving and monitoring P_{max} and S_{FV} to enhance sprint performance over 40 m. The study's application of v-FVP metrics offers a refined approach to enhancing sprinting speed by focusing on individual v-FVP metrics, thus bridging the gap between lab-based measurements and sport-specific training applications.

Study 5 culminates this series by utilizing even simpler jumping tests, addressing a practical challenge in the NFL Combine testing process. While the previous studies have focused on improving measurement techniques and predictive models, Study 5 extends these concepts to a large dataset from the NFL Combine to develop predictive models for sprint performance utilizing simple jumping tasks. Using data from 4,149 NFL Combine athletes, the study developed regression models to predict sprint times for different segments of the 36.58 m sprint based on vertical jump, broad jump, height, and weight. The models demonstrated high accuracy with statistically significant predictions for segmental and overall sprint times. This study's findings are significant because they provide alternative methods for predicting sprint performance when direct testing of speed utilizing lab-based measures is not possible (e.g. injury). Further, the formulae presented in Study 5 allow practitioners to predict sprinting time, enabling comparisons between an athlete's actual and predicted performance to identify areas of opportunity and inform training strategies aimed at improving short (36.58 m) sprint speed.

In summary, this series of studies collectively advances the field of athletic performance assessment by progressing from the establishment of standardized testing thresholds to the development of portable and practical measurement solutions. Each study logically builds on the previous one, transitioning from lab-based validations to field-applicable techniques and demonstrating how these advancements can be utilized across various sports contexts.

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Dedication

This thesis is dedicated to Jill and Mila. What a wild ride this PhD has been, two houses, a marriage, three dogs, too many deer and grouse, three bears, one global pandemic, one child, one major shooting, the nightmare of Work Safe but now we have one less thing on our plate… until I do another degree. Proof that late nights, weekends and early mornings do pay off, thank you for everything.

1. General Introduction

1.1 Athlete Profiling

The cost of Olympic medals has been estimated at $8 million per medal (1998 dollars) with a linear relationship between money spent and medals won (Hogan & Norton, 2000). However, there is the potential to change the slope of the relationship between money spent and medals won by increasing the efficiency of service provision and improving the talent identification process. For example, physical characteristics have been shown to predict selection in junior rugby players (Till et al., 2011) and simple ballistic testing such as a standing long jump has shown the potential to identify sprinting talent in female rugby athletes (Agar-Newman & Klimstra, 2015). Further, improving specific ballistic tasks such as vertical jumps (e.g. countermovement jump, spike approach jump) appear to be sensitive to change across the season and important to improve longitudinally in sports such as volleyball to ensure transition from the junior to senior level (J. M. Sheppard et al., 2009, 2012; J. M. Sheppard & Newton, 2012). Through identifying the specific neuromuscular and morphological adaptations that can improve specific sporting actions, practitioners can be more targeted in their investments of money, time and training interventions to improve athletic performance.

Objective assessment of athletes' physical performance supports the development of physical profiles, which in turn allows sport practitioners to identify specific training areas of opportunity (Young, 1995). This allows an appropriate stimulus to be applied to drive training adaptations and assess athletic progress (DeWeese et al., 2015). Further, assessment of physical performance allows the identification of physically gifted athletes, which is important for talent identification purposes. An important physical capacity for many practitioners across various sporting contexts is the “strength” of the lower limbs. To assess an athlete’s lower body mechanical capabilities there are many tools available for practitioners such as force plates, linear position transducers, accelerometers, video motion capture (McMaster et al., 2014), timing gates, in addition to several other options. Whereas the movement and directions chosen by practitioners during testing should be influenced by the muscle groups, movement patterns, contraction type and velocity of the targeted sporting movement (Young, 1995). The overall process of test selection and the quantification of relevant physical capacities have been termed “performance diagnosis” (James et al., 2023). A potentially useful tool in performance diagnosis is ballistic actions, e.g. jumping tasks, as they minimize the ‘deceleration subphase’ of the movement being tested, resulting in higher mechanical outputs and muscle activation than their non-ballistic counterparts (Thompson et al., 2023). This makes jumping tasks a particularly attractive option when assessing an athlete’s lower body physical capabilities.

1.2 Testing & Assessment of ‘Strength’

Strength is a word often associated with athletic performance, however there are subtleties to defining it. Therefore, the purpose of this section is to clearly define strength and its derivatives. In simple terms, strength is an athlete’s ability to apply force in a single action (Siff, 2000; Suchomel et al., 2016). However, it is important to note that an athlete’s ability to apply force is dependent on external constraints (James et al., 2023), such as joint angle, joint orientation, speed of contraction, muscles utilized and time (Siff, 2000). Depending on the sporting context practitioners may be more concerned with the absolute force an athlete can produce (i.e. sports where athletes must move an opponent or heavy load, e.g. an offensive lineman in football) or the amount of force the muscles can produce normalized to body mass (i.e. sports where the athlete must move their own body mass, e.g. sprinting), termed relative strength (Siff, 2000). It has been suggested that testing athletes under various constraints gives practitioners a more comprehensive profile of an athlete to guide training decisions, for example five distinct strength qualities have been identified that share limited commonality ($R^2 < 0.5$) (James et al., 2023). These qualities are:

1. Maximal Isometric Strength: The greatest amount of force an athlete can apply to an unyielding object regardless of time, measured in newtons (N). In the lower body this is typically assessed with isometric squats or pulls.
2. Heavy Dynamic Strength: The force expressed at heavier loads and therefore low speeds. In the lower body this is typically assessed using proxy measures such as 1 repetition maximum (RM), 3 RM back squat or deadlift, but can be done on force plates to collect force directly. The outcome of this measure is kilograms (kg) or N.
3. Explosive Strength: A measure of the early stages (0.03 – 0.15 s) of force production from an isometric test. This is typically gathered from isometric squats or pulls when athletes are instructed to push or pull “fast” and “hard”. Explosive strength is measured in N at a specific time point. However, it is important to note that explosive strength could also be derived from isoinertial tasks such as loaded jumps, which have higher level of face validity (i.e. more like the dynamic tasks that explosive strength likely helps).
4. Reactive Strength: The ability to produce force in a short stretch shortening cycle action (<0.25 s). This measure is often collected by preforming a drop jump (DJ) or rebound

jumps (e.g. 10/5 repeat jump test). Reactive strength is typically measured in reactive strength index (RSI), which is measured in $m \cdot s^{-1}$.

5. Fast Dynamic Strength: The ability to produce force against little or no load. Often collected from squat jumps (SJ) and countermovement jumps (CMJ) and measured in height jumped (m) but can also be assessed using takeoff velocity ($m \cdot s^{-1}$).[1]

It is important to note that the above strength classifications rely primarily on the constraints of contraction type and time. Further, the definitions above do not always align with the original definition of strength, which refers to the ability to produce force (i.e. Ns) and often rely on proxy measures for force (e.g. kgs lifted) or secondary measures such as jump height. Further, there are a myriad of strength qualities that can be assessed under different constraints and readers are directed to works by Young (1995), Zatsiorsky & Kraemer (2006), Siff (Siff, 2000) and Verkhoshansky & Siff (Verkhoshansky & Siff, 2009). Decisions on what and how to measure performance should be based on validity, reliability, precision of the measurement needed, cost, sport specificity and practicality (Jennings et al., 2005). Although jumping performance likely depends on all five strength qualities listed above, jumping tasks are typically used to assess reactive strength and fast dynamic strength when performed unloaded and heavy dynamic strength when performed at loads close to 1 RM. Through comparison of different strength qualities, practitioners can better understand the training needs of the populations they are working with (J. M. Sheppard et al., 2011) and achieve better training outcomes through targeted strength training interventions (Jiménez-Reyes et al., 2019; Jiménez-Reyes, Samozino, Brughelli, et al., 2017).

[1] The above definitions are from Strength Classification and Diagnosis: Not All Strength is Created Equal (James et al., 2023)

1.3 Simple Lower Body Diagnostics

Unfortunately, practitioners may not have access to technology such as force plates, often used to assess the previously mentioned strength qualities due to a myriad of reasons such as financial barriers, or logistical barriers. This makes the need to identify cost effective alternatives to monitor athlete performance and physical constraints of paramount importance.

1.3.1 Horizontal Jumps

Jump tests are an example of ballistic movements, which allow the athlete to accelerate through a greater range of motion than non-ballistic movements such as a squat (McMaster et al., 2014), thus making them an attractive tool for practitioners. A commonly used ballistic assessment is horizontal jump tests. Horizontal jumps relate to performance in athletic tests such as 100 m sprint (r = -0.81) (Loturco, Pereira, et al., 2015), with faster athletes having further jumps than their slower counterparts and could be useful in talent identification settings where speed is an important quality (Agar-Newman & Klimstra, 2015). Typically, horizontal ability is collected using a standing long jump (Agar-Newman & Klimstra, 2015; Kleeberger et al., 2024; Loturco et al., 2015), which consists of an athlete starting in the standing position and then jumping for maximal horizontal distance while using an arm swing. Distance is then measured from the place the athlete started the jump (i.e., front of the toes) to the place the athlete lands (i.e., back of the heels). Another horizontal jumping variation that is used is the triple broad jump which requires the athlete to do three consecutive broad jumps, minimizing the time on the ground between jumps (no reset allowed), which has shown higher associations with sprinting ability than the standing long jump (Agar-Newman & Klimstra, 2015; Kleeberger et al., 2024). Surprisingly horizontal jumping ability has similar or larger association to sprinting ability than more complex methods of lower body assessment requiring tools such as a linear position transducer (LPT) or force plates

(Loturco, Pereira, et al., 2015), making horizontal jumps an attractive tool for practitioners to monitor. Further, horizontal jump tests only require a tape measure to be implemented and require little post-hoc analysis making them an appealing measure to be included in a testing and assessment battery for athletes.

1.3.2 Vertical Jumps

There are many variations of vertical jumps that can be used for assessing strength qualities such as the SJ (see Figure 1a), jump squats or CMJ (see Figure 1b), as well as depth jumps and DJ (see Figure 1c) (Young, 1995). In the SJ the athlete holds a squat position with a knee angle of ≈ 90 degrees and without a downwards motion of the body (i.e. unweighting) jumps for maximal height utilizing only the propulsive phase of the jump. The SJ measures an athlete's fast dynamic strength under primarily concentric conditions (James et al., 2023; Young, 1995); however, the load (i.e. constraints) can be manipulated safely (Janssen et al., 2012), to gain an insight into the athlete's heavy dynamic strength. In contrast, during the CMJ athletes start in the upright position and utilize a countermovement (i.e. unweights) which allows a pre-stretch of the leg extensors prior to beginning the propulsive phase of the jump (Young, 1995). Due to the pre-stretch of the muscles, storage and utilization of elastic energy and the fact that the propulsive phase begins with higher forces (Van Hooren & Zolotarjova, 2017) athletes typically jump higher when performing a countermovement, with some notable exceptions (e.g. speedskaters), which is likely attributable to sport-specific training histories (Kozinc et al., 2022). The difference in height achieved in the SJ and CMJ can be used to identify potential training areas of opportunity (e.g. athletes with compromised abilities to reduce muscle slack or athletes with poor stretch-shortening cycle performance) and changes in training status (McGuigan et al., 2006; Van Hooren & Zolotarjova, 2017).

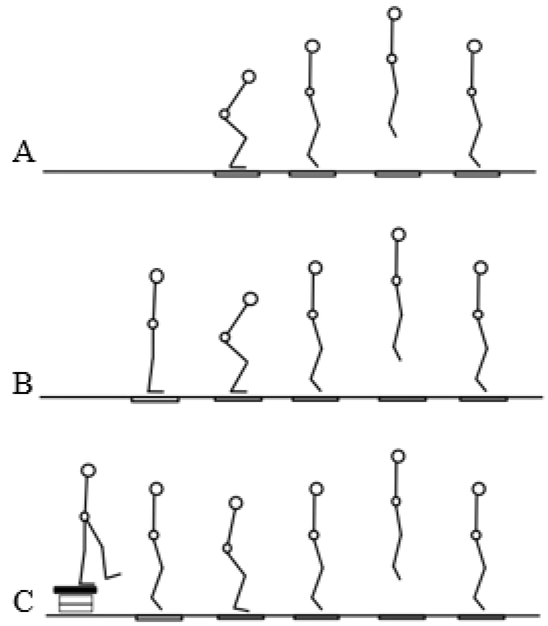

Figure 1. Vertical Jump Variations[2], A is an example of a SJ, B is an example of a CMJ and C is an example of a DJ

SJ and CMJ height, collected with a contact mat, also correlate to sprinting performance (r = -0.82 and -0.85 respectively) and can be useful to monitor fatigue in athletes (Marco-Contreras et al., 2021). In recent years the accessibility of utilizing vertical jumps in athlete assessment have increased with the development and validation of cost-effective tools such as mobile applications that are able to assess jump height, reactive strength index and leg asymmetry (Balsalobre-Fernández et al., 2015; Whiteley et al., 2023). Unfortunately, these cost-effective tools are

[2] Stick figures modified from Richter, A. (2011). Aspekte der Sprungkraft und Sprungkraftdiagnostik unter besonderer Berücksichtigung der Entwicklung im Kindes- und Jugendalter. https://doi.org/10.5445/IR/1000023198 (Richter, 2011)

currently unable to provide insight into an athlete's movement strategy, which is potentially important when using vertical jumps to monitor fatigue (Gathercole et al., 2015).

The DJ (Figure 1c) is a third variation of a vertical jump that is used in research and testing settings, used to measure reactive strength. DJs have a high correlation to athletic tasks such as sprinting performance (M. J. Barr & Nolte, 2011) with elite sprinters having higher DJ heights than their sub elite counterparts (Coh & Mackala, 2013). In the DJ, the athlete steps directly off a box and aims to jump as high as possible as quickly as possible. The instructions given to the athlete, when performing DJs, can have a large impact on the test results (Bobbert et al., 1987; Young et al., 1995). When DJs are performed without instructions to minimize ground contact time, often referred to as depth jumps, they closely resemble a countermovement jump in both their kinetics and kinematic characteristics (Bobbert et al., 1987) and highly correlate to CMJ height (Young et al., 1995). Depth jumps can be used in training settings to develop stretch-load tolerance due to the high forces athletes are subjected to while landing from high heights. It is suggested that improved stretch-load tolerance may transfer to athletic tasks which require high levels of eccentric strength (J. Sheppard, 2016). However, in testing settings, to measure the unique quality of reactive strength or the ability to utilize the stretch shortening cycle under time constraints DJ are often used and ground contact time is usually restricted to under 0.25s (James et al., 2023; Young, 1995). An argument could be made to adjust the ground contact time restriction to be applicable to the time available to produce force in a sport specific context e.g. under 0.10 s in sprinting (Young, 1995). Most often reactive strength is measured by dividing the jump height by the ground contact time, but different versions of this formula are used in the literature such as height in centimeters divided by time in seconds (M. J. Barr & Nolte, 2011; Young, 1995) or more often meters divided by seconds (Byrne et al., 2016; James et al., 2023).

There are some subtleties when using vertical jump assessments, such as the role of arm-swing, how jump height is calculated and regression-based approaches to determine power outputs of the athletes. For example, three commonly used ways to calculate jump height are:

1. The standing reach method often conducted using a Vertec (Buckthorpe et al., 2012) or by marking the highest position on a wall positioned beside the jumper (Sayers et al., 1999). The difference between the height the athlete can reach while standing is subtracted from the highest vane reached or height touched during the jump.
2. The flight time method using video, contact mat or force plate to calculate the time the athlete is in the air (flight time). Due to the constant gravitational acceleration jump height can be calculated: $jump\ height = 9.81\ \cdot flight\ time^2 \cdot 8^{-1}$.
3. The impulse momentum method using force plates. Assuming the athlete starts with zero velocity (i.e. standing still), the resultant force applied over the course of the jump can be used to calculate impulse (i.e. force · time) and impulse can then be used to calculate change in momentum (i.e. mass · velocity). Knowing the athlete started at zero velocity (i.e. no momentum) and the mass remained constant, take off velocity can be calculated. Take off velocity can then be converted to jump height using the laws of projectile motion where $jump\ height = take\ off\ velocity^2 \cdot (2 \cdot 9.81)^{-1}$

It is worth noting that the starting position can influence the standing reach method if the initial measurement of reach heigh is not conducted with the athlete on their toes and the arm extended fully above the head (i.e. the position the athletes would takeoff from). As the calculated jump height would include the distance the athlete covers from standing flat footed to a plantar flexed position and any additional gained by fully extending their arm. With the flight time method, there is an assumption that the athlete takes off and lands in the same position. If the athlete dorsiflexes their foot prior to landing or bends their knees, or the arms are in a different position, this can modify the flight time and therefore the jump height calculations. Error with the impulse momentum method is typically caused by an incorrect calculation of body mass, resulting in an incorrect resultant force. A second source for error is incorrect identification of the start of the jump, resulting in the calculations beginning while the athlete is moving (i.e. has an upwards or downwards velocity at the beginning of the calculations).

A further confounding factor to the assessment of vertical jumps is the use of an arm swing. Arm swing plays a substantial role in jumping across many sports such as volleyball, basketball and track and field. The use of the arms in jumping has been shown to increase jump distance by 21.2% in the standing long jump (Ashby & Heegaard, 2002) and 7 - 38% in the countermovement jump (Chiu et al., 2014; Mosier et al., 2019; Vaverka et al., 2016). It should be noted that Mosier et. al (2019), utilized a unique starting position with one arm overhead and the second arm on the hip for their tests which likely explains the large difference between the arm swing and no arm swing conditions. Nonetheless, the increase in jumping performance observed when arms are utilized is the result of increased ground reactions forces (Ashby & Heegaard, 2002; Chiu et al., 2014; Mosier et al., 2019; Vaverka et al., 2016) which is likely achieved through a more advantageous proximal to distal sequencing of joints (Chiu et al., 2014) and the ability to eliminate counterproductive rotation around the center of mass (Ashby & Heegaard, 2002). Due to the role that arms play in increasing ground reaction forces and changing the sequencing of joints, practitioners utilizing jump tests will likely have to make a judgement on whether to make their jump tests more context specific to some sporting tasks by allowing the use of the arms or to eliminate the arms to isolate the lower body for diagnostic purposes. Further, practitioners may compare jumps with and without arm swing to assess the athlete’s ability to coordinate the upper and lower body, to quantify the upper body's relative contribution to jumping performance in sport specific contexts.

Vertical and horizontal jumps serve as both general assessments of athletic ability and sport-specific tools for identifying individuals' strengths and weaknesses. To optimize jumping performance, practitioners often manipulate load to influence force production across different velocities. This approach forms the basis of a vertical force velocity profile (v-FVP), which provides deeper insight into an athlete's capacity to generate force and power under varying speed or velocity conditions, which has become a popular form of strength assessment.

1.3.3 Force Velocity Profiling

A hyperbolic relationship between force and velocity at the level of a single muscle fiber was first described by A.V. Hill, demonstrating a reduction in force production with increasing shortening velocity (Hill, 1938). However, in multijointed movements, such as the leg press, the relationship between force and velocity appears to be linear or quasi-linear rather than hyperbolic due to segmental dynamics (Bobbert, 2012; Jennings et al., 2005). Understanding the body's ability to produce force at different velocities has important implications for the development of both instantaneous power (i.e. force · velocity) and average power (i.e. (force · distance · time^{-1}). Research has shown correlations between have an athlete's ability to produce power in jumping tasks and sport specific tasks such as sprinting (Loturco, D'Angelo, et al., 2015; Loturco, Pereira, et al., 2015; Swinton et al., 2014; Vanezis & Lees, 2005). Further high-level performers have been shown to have higher power outputs during jumping than their lower-level counterparts (Edwards et al., 2023). As training emphasis can manipulate an athlete's ability to produce force at specific velocities (Cormie et al., 2010; Jiménez-Reyes et al., 2019; Jiménez-Reyes, Samozino, Brughelli, et al., 2017) it is recommended that training be geared to optimize force production at the velocities present in an athlete's sport (Zatsiorsky & Kraemer, 2006). This approach has shown promise in sporting tasks such as jumping, by biasing training to work on an athlete's ability to produce force at low or high speeds, depending on the athlete's needs (Jiménez-Reyes et al., 2019; Jiménez-Reyes, Samozino, Brughelli, et al., 2017).

An athlete's ability to produce force, and power at various velocities can easily be measured using force plates, however practitioners may be limited in their ability to access this technology. Some studies have attempted to calculate power using jump height, body mass and regression equations (Johnson & Bahamonde, 1996; Sayers et al., 1999). However, these equations lack a mathematical rationale, raising concerns around their generalizability when applied to diverse populations (Samozino et al., 2008). Further, leg length must be accounted for when estimating average power, as a longer push-off distance (h_{po}) increases the time available to produce force influencing measured power (Samozino et al., 2008). Due to these issues, Samozino et al. (2008) introduced a simple three-factor computational model for vertical jumps that estimates force, velocity and power outputs. By incorporating system mass, h_{po}, and takeoff velocity, the model allows for the construction of a v-FVP, providing insight into an athlete's capacity to generate force and power across varying velocities. As noted above, the primary advantage of the three-factor computational model is: increased accessibility for practitioners as force, velocity and power can be calculated using cheap technological solutions (e.g. tape measure, scale and a tool to measure jump height). Unfortunately, many of the tools to measure jump height may not be logistically feasible to utilize in a gym setting with multiple athletes or may be time intensive (e.g. the flight time method from video).

1.4 Cost Effective Technology to Measure Lower Body Performance

Force, velocity and power measurements of the lower body can be calculated using Samozino's method (2008), utilized in conjunction with accelerometers, linear position transducers, contact mats or high-speed cameras and force plates (Giroux et al., 2015). The purpose of this section is to provide a brief overview of some of the more commonly used technologies that are used to assess lower body jumping performance that range from low to moderate cost.

1.4.1 Contact Mats and Optical Measurement Grids

Contact mats and optical measurement grids represent a moderate cost option for assessing jumping performance. Using microswitches or light-emitting diodes communicating on an infrared frequency, a timer is triggered when the athlete leaves the ground and stopped when the athlete lands on the ground. Using the athlete's flight time (i.e. time athlete is in the air), jump height is calculated using the flight time method (see page 10). The assumption when using contact mats and optical measurement grids is that the athlete's center of mass is in the same position at takeoff and landing, i.e. they land and leave the ground in the same position. However, athletes often land in a different position from takeoff, with their hips slightly flexed and ankles dorsiflexed resulting in inflated jump heights (Linthorne, 2001). However, infrared grids may underpredict jump height relative to the force plate method in some contexts. This discrepancy likely arises due to the light-emitting diodes being located above the ground, causing a delay at takeoff, before the timer is started and premature interruption of the beams prior to the athlete touching the ground, resulting in an early interruption of the receiver circuit (Xu et al., 2023). The advantage of contact mats and optical measurement grids for practitioners is cost, ease of use and moderate portability. However, contact mats and optical measurement grids may not be ideal for large groups of athletes due to the space they require on a gym floor, the subjectiveness of determining if an athlete landed in an appropriate position and the staffing requirements to monitor the athlete's landing position.

1.4.2 High Speed Cameras

Due to the abundance of high-speed cameras (e.g. cameras with a frame rate >120fps) in cell phones and specific applications developed to assess jumping performance (e.g. MyJump 2), the use of cell phones to assess jumping performance has seen an increase in recent years (see Figure 2). High speed cameras utilize the flight time method, however due to images of the athlete's landing position it is easier to assess whether the athlete took-off and landed in a similar position, potentially removing one issue of the flight time method. A recent review of 21 studies comparing the My Jump 2 application to other flight time-based jump height measurement tools found no differences in jump height versus the criterion measures and near perfect reliability (Gençoğlu et al., 2023). When compared to the criterion measure of jump height calculated using a force plate, no between instrument differences and high associations ($r = 0.99$) between the My Jump 2 application and force plates were found (Bagchi et al., 2024). However, issues with this method are first, the determination of the takeoff and landing position is still subjective (e.g. the likely cause of outliers in the Bland-Altman plots in Gençoğlu et al., 2023 article) and second, the requirement to manually analyze the video to identify the takeoff and landing frames in the video. The manual interface with the software slows down the time from testing to the practitioner, athlete and coach receiving the results. This makes this solution untenable when working with large groups of athletes (e.g. team of invasion sport athletes), although advances in artificial intelligence to identify the takeoff and landing frames may speed up this process (Tan et al., 2024).

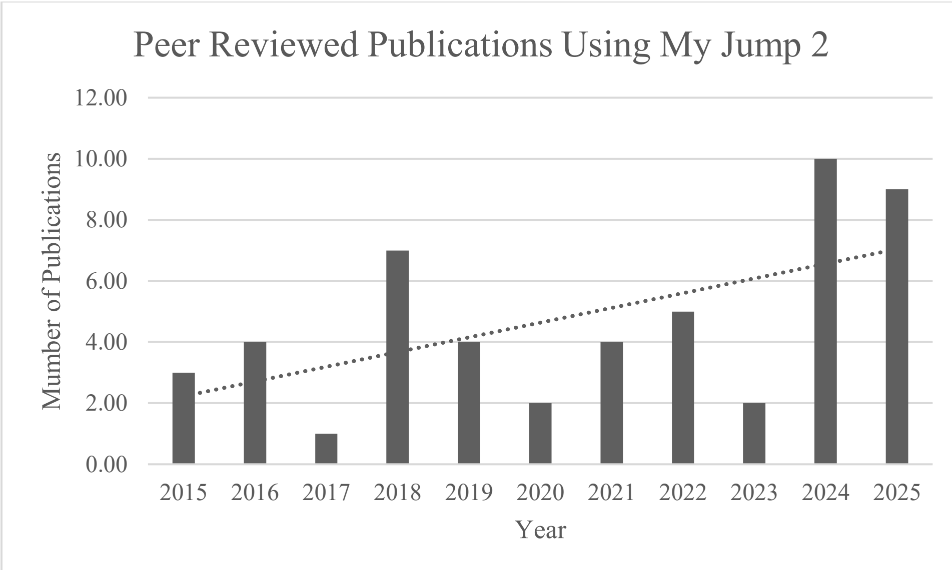

Figure 2. Number of publications per year using My Jump 2 iPhone application. Results from Pubmed, search date August 17, 2025, using search terms "My Jump 2".

1.4.3 Accelerometers

Accelerometers represent a low-cost option for monitoring athletic performance, with the added benefit of extreme portability. Accelerometers utilize an electro-mechanical sensor which detects the acceleration of the unit and resulting change in voltage. The acceleration detected by the unit is then often converted into velocity by integrating acceleration. Commercial accelerometers are often combined with other technology such as magnetometers and gyroscopes to better determine the orientation of the unit. Despite the potential of accelerometers for the purposes of assessing lower body performance there have been questions around the commercially available options validity, accuracy and reliability (Beckham et al., 2019; Gomez-Piriz et al., 2013; Lorenzetti et al., 2017; Orser et al., 2024). While issues with accelerometer vary by model, it has been suggested that sampling rate (Gomez-Piriz et al., 2013), unit orientation (Lorenzetti et al., 2017) and possibly start phase detection of the movement combined with proprietary algorithms contribute to the above issues. Accelerometers have been shown to have lower reliability than linear position transducers at assessing velocity for the purposes of athletic assessment (Lorenzetti et al., 2017).

1.4.4 Linear Position Transducers

Linear position transducers (LPT) offer a moderate cost option for monitoring athletic performance, with the added advantage of portability and ease of operation. This makes LPTs well-suited for both travel and implementation in a gym setting by athletes and practitioners. Linear position transducers consist of a flywheel and cable that connects to the object of interest, calculating the speed of movement by directly measuring the displacement of the cable relative to the sampling frequency (i.e. time between samples). Using inverse dynamics some models calculate force and power (Ruiz-Alias et al., 2024; A. Turner et al., 2024), however these values can be overestimated due to double differentiation of barbell displacement (Garnacho-Castaño et al., 2015) and not all models calculate force and power.

Practitioners must be aware of the type of movement that is being monitored and some of the limitations of LPTs. First, LPTs underestimate velocity in field application (i.e. free weights) as they only analyse linear velocity (Lorenzetti et al., 2017). Therefore, practitioners should be aware of utilizing movements that have significant displacement in the horizontal plane, for example movements where a barbell must navigate around the body such as a barbell deadlift. Due to the potential impact of horizontal displacement, movements utilizing in a smith machine, which restricts the movement to only the vertical plane, appear to have higher validity and reliability than free-weight movements (Moreno-Villanueva et al., 2021; Ruiz-Alias et al., 2024). Second, movements that begin from a pause or isometric position prior to initiating the propulsive phase exhibit higher levels of precision and reliability making it easier for the technology to identify the start of the movement, impacting the calculations to determine the velocity of the object of interest

(Moreno-Villanueva et al., 2021). Third, movements with different rates of acceleration and technical requirements throughout the propulsive phase may exhibit less accuracy and increased measurement error when examining the average velocity over the movement. For example, the clean and snatch consist of a transition phase as the bar clears the knees and the velocity of the bar slows down (Garnacho-Castaño et al., 2015; Suchomel et al., 2025), therefore for Olympic lifting variations, peak velocity, i.e. the highest velocity of the propulsive phase may be a better measure to monitor. Unfortunately, peak velocity appears to have a larger root mean square error than average velocity when using LPTs and may not be as robust of a measure as the average velocity (Lorenzetti et al., 2017). Due to the above reasons (i.e. linear bar path, movement starting from a pause, consistent rate of acceleration) a simple movement like a hexagonal-bar jump may be an ideal option for the purposes of lower body diagnostics. A fourth limitation that practitioners should be aware of is the sampling frequency of their technology. Some models of LPTs may use a consistent sampling frequency whereas other units may have a variable sampling frequency that is dependent on the speed of the movement; in other words, sampling frequency increases as the rotary encoder spins at higher speeds and lowers as the rotary encoder spins slower. This is likely why researchers have found differences between units such as the Tendo and T-Force (Garnacho-Castaño et al., 2015). For example, when using a Tendo weightlifting analyzer practitioners can expect a 5% measurement error with loads between 10 - 70% 1RM but this jumps to 10 - 12% at 80 - 90% 1RM when examining bench press (Stock et al., 2011). Although some of this measurement error may be due to a reduced sampling frequency as the rotary encoder slows, the error is more likely driven by alterations in the bar path and the appearance of sticking regions at higher loads (Wilson et al., 2016). For example, similar findings to those of Stock et al. were observed in the bench press at heavier loads; however, when using a machine-based based leg press which has a linear path, the mean difference and standard error of measurement did not increase at heavier loads (Miller et al., 2020). When assessing jump squats and squats, Tendo units appear to be a reliable measurement device (Garnacho-Castaño et al., 2015; Lorenzetti et al., 2017) and can generate repeatable v-FVPs (Jennings et al., 2005), making them a potentially useful assessment tool for practitioners. Finally, practitioners utilizing a LPT may be constrained by the limited number of metrics provided by their specific device, highlighting an opportunity for academic research focused on the identification and validation of novel performance metrics.

1.5 Gaps in the Research

Examining the research around strength and jumping assessment in athletes several gaps arise, specifically:

1. It is well established that a countermovement can increase jump height (Bobbert et al., 1996; Kozinc et al., 2022). However, despite the frequent use of SJs in the research[3], there is no consensus on a standardized threshold for a countermovement. Furthermore, the reporting of a threshold to determine a valid SJ is rare in the literature and often subjective (see Table 1). Remedying this gap in the research is important as commercial software and custom algorithms to analyse SJs are becoming more common, and practitioners need to be aware that an incorrect threshold could decrease the ability to generalize the results of their research.

[3] A search of the *Journal of Strength and Conditioning Research* on May 22, 2024, for the term "squat jump" returned 727 studies.

Table 1. Example of methodologies used to detect unweighting in the SJ in the most recent 17 studies in the *Journal of Strength and Conditioning Research.*

Article	Visual (Subjective)	Visual Force Time Trace- Threshold Not Specified (Subjective)	Force Time Trace- Threshold Specified	Not Stated
Agreement in Squat Jump Force-Time Characteristics Between Smith Machine and Free-Weight Squat Jump Force-Time Characteristics (Kotani et al., 2023)		✓		
Reliability of the Squat Jump Force-Velocity and Load-Velocity Profiles (Kotani et al., 2022)		✓		
Effects of Repeated Jump Testing and Diurnal Changes on Subsequent Countermovement Jump and Squat Jump Output and Force-Time Characteristics (Harrison et al., 2024)			>10% BW	
Countermovement Jump and Squat Jump Force-Time Curve Analysis in Control and Fatigue Conditions (Hughes et al., 2022)			>5% BW	
Intrasession and Intersession Reliability of Isometric Squat, Midthigh Pull, and Squat Jump in Resistance-Trained Individuals (Ishida et al., 2023)				✓

Comparison of Countermovement Jump and Squat Jump Performance Between 627 State and Non-State Representative Junior Australian Football Players (Edwards et al., 2023)				✓
Positive Effects of Pre-exercise Metabolic Alkalosis on Perceived Exertion and Post-exercise Squat Jump Performance in World-Class Cyclists (Thomas et al., 2022)				✓
Quantifying Changes in Squat Jump Height Across a Season of Men's Collegiate Soccer (Sams et al., 2018)	✓			
Can Squat Jump Performance Differentiate Starters vs. Nonstarters in Division I Female Soccer Players? (Magrini et al., 2018)	✓			
Self-Preferred Initial Position Could Be a Viable Alternative to the Standard Squat Jump Testing Procedure (Petronijevic et al., 2018).			>5%	
Assessment of Loaded Squat Jump Height with a Free-Weight Barbell and Smith Machine: Comparison of the Takeoff Velocity and Flight Time Procedures (Pérez-Castilla et al., 2020)		✓		
Optimizing Half Squat Postactivation Potential Load in Squat Jump Training for Eliciting Relative Maximal Power in Ski Jumpers (Gołaś et al., 2017)	✓			

Specific Adaptations in Performance and Muscle Architecture After Weighted Jump-Squat vs. Body Mass Squat Jump Training in Recreational Soccer Players (Coratella et al., 2018)	✓			
Biomechanical Analysis of Squat Jump and Countermovement Jump From Varying Starting Positions (Mackala et al., 2013)				✓

Note: Three of the 17 studies purporting to use SJs used countermovement jumps and are not reported in the table above

2. LPTs appear to be a cost-effective tool for assessing ballistic performance. However, not all LPTs can calculate jump height and the ones that do (e.g. GymAware) require an extra step prior to use, to determine the takeoff position of the athlete, which may not be logistically feasible in a training setting. Further, units that can calculate jump height come at an increased cost, which may pose a financial barrier for practitioners. Therefore, if other commonly reported metrics from an LPT, such as peak speed, can be used to estimate takeoff speed, jump height could subsequently be calculated. This capability would be crucial for field-based assessments where the availability of 'gold standard' equipment may be limited due to logistical or financial reasons.

3. Constructing a v-FVP of athlete's lower limb extensor capabilities has become increasingly popular in the assessment of athletic populations. However, much of the v-FVP research uses only a SJ or a countermovement jump, limiting the movements that practitioners can chose from. The ability to calculate v-FVP metrics using other exercises such as hexagonal bar (hex-bar) jump could be particularly advantageous for sports where traditional jump tests may be less specific or feasible (e.g. injury). If other movements such as a hex-bar jump could be utilized practitioners would have more movement options to chose from to better suit their situation.

4. In field-based sports sprinting performance can often delineate levels of performance and therefore practitioners in strength and conditioning should have a robust understanding of how metrics in the gym impact an athlete's ability to sprint. In the literature the relationship between metrics from a v-FVP metrics and sprint performance is unclear and there is a lack of research in highly trained female athletes. Therefore, determining what v-

FVP metrics relate to sprint performance would better allow practitioners to target their training interventions.

5. In the literature there are many studies investigating the strength and direction of the associations, between jumping tasks and sprinting performance. However, very few studies examine the relationship between jumping tasks and sprinting performance (i.e. how one metric changes in relation to another). Determine if simple jump tests, can be used to predict sprint performance would allow practitioners to inform their training prescription when lab-based tests are not available.

1.6 Dissertation Objectives

Despite the widespread use of jumping tasks in athlete assessment there are issues with the accuracy, applicability and accessibility of many tests. Therefore, the purpose of this dissertation is to increase the robustness of field-based jump assessments, examine the potential for more accessible field-based applications, and demonstrate how jumping assessments can enhance athletic evaluation.

Therefore, the specific objectives of this dissertation are:

1. Increase the robustness of SJ assessments through determining a quantitative threshold of unweighting amplitude, to allow practitioners to ensure they only include valid SJs in their analysis.

2. Determine if time efficient and cost-effective technology such as a linear position transducer (LPT) can estimate takeoff speed. This capability would be crucial for field-

based assessments where the availability of "gold standard' equipment may be limited due to logistical or financial reasons.

3. Determine if other vertical jumping variants (hex-bar jump) can be used to derive a v-FVP. The ability to calculate these metrics using the hex-bar jump could be particularly advantageous for sports where traditional jump tests may be less specific or feasible (e.g. injury).

4. Determine if v-FVP metrics can predict sprint performance in elite/international level female athletes. This would allow a refined approach to bridge the gap between lab-based measurements and sport-specific training applications in addition to assist practitioners in determining what metrics to focus on.

5. Determine if simple jumping tests, can be used to predict sprint performance. This would be significant as direct testing utilizing lab-based measures is not always feasible, thus offering practical solutions.

2. Determining the Threshold of Unweighting in Squat Jumps: A Study on Jump Height and Unweighting Amplitude[4]

2.1 Abstract

Squat jumps (SJs), involving only an upward propulsive phase, are commonly used in athletic assessment and research. Unfortunately detecting an unweighting phase prior to the upward propulsive phase is typically done subjectively by observing the athlete or inspecting the force-time trace, and there is no clearly established threshold of unweighting for a valid SJ. This reliance on subjectivity to determine a valid SJ has the potential to result in misleading findings or incorrect training interventions. Therefore, the aim of this study was to determine at what threshold of unweighting does SJ height increase.

To answer this question, 56 female athletes, mean (± *SD*) bodyweight (BW) 76.26 ± 12.40 kg, height 1.68 ± 0.06 m, age 22.23 ± 1.47 years performed 936 SJs, under four different external loads. SJs were divided into 6 separate groups based on the amplitude of unweighting relative to BW and an Analysis of Covariance was run with jump height as the dependent variable, unweighting group as the fixed factor and external load as a covariate.

There was a significant difference in jump height ($F(5,930) = 13.65$, $p < 0.01$) between unweighting groups whilst controlling for external load. Post hoc testing utilizing Dunnett's Test showed that all SJ unweighting thresholds >2% BW ($p < 0.01$) resulted in an increased jump height from the threshold of ≤1% BW.

[4] Published: Agar-Newman DJ, Funk S, Cavin E, Geneau MC, Tsai MC, Klimstra M (2024). Determining the Threshold of Unweighting in Squat Jumps: A Study on Jump Height and Unweighting Amplitude. J Strength Cond Res, 39(3), 295-299. doi: 10.1519/JSC.0000000000005019. Epub 2024 Nov 26. PMID: 39977020.

Therefore, to maintain the validity of SJs as a measure, a threshold of ≤2% BW for unweighting amplitude is recommended. Adhering to this threshold will eliminate subjectivity in identifying valid SJs and potentially enable practitioners to automate the process using algorithms.

2.2 Introduction

Comprehensive strength testing to determine an athlete's strengths and weaknesses is essential for effective training program design (McGuigan et al., 2013; McMaster et al., 2014; Newton & Dugan, 2002). Strength is defined as an individual's ability to produce force and can be expressed in multiple ways such as maximal isometric strength, explosive strength, maximal heavy dynamic strength, fast maximal dynamic strength, and reactive strength (James et al., 2023). Ballistic actions involving jumping and throwing tasks (McMaster et al., 2014) are one method of assessment utilized by practitioners to gain insight into an athlete's force production abilities and various methods to collect data using these tasks exist.

Jumping tasks, often performed on force plates, are used to measure fast maximal dynamic strength (James et al., 2023), power (Jiménez-Reyes, Samozino, Pareja-Blanco, et al., 2017; J. M. Sheppard & Doyle, 2008) and neuromuscular status (Claudino et al., 2017). The squat jump (SJ) and countermovement jump (CMJ) are common jumping tasks used by practitioners and have been shown to be valid and reliable (Markovic et al., 2004). The SJ is used to measure an athletes' rate of force development and ability to produce power utilizing primarily a concentric muscle action (McGuigan et al., 2013; Newton & Dugan, 2002; Young, 1995). To complete a SJ an athlete assumes a squat position with a knee angle of ≈90 degrees held under isometric conditions for 3-seconds prior to jumping as high as possible (J. M. Sheppard & Doyle, 2008). Maintaining this static position and ensuring the absence of an unweighting phase (i.e., period where the force trace drops below bodyweight [BW]) before the upward propulsive phase is essential, as it constrains the muscle's ability to produce force by removing the ability to utilize the stretch-shortening cycle (Bobbert et al., 1996; Earp et al., 2010; Van Hooren & Zolotarjova, 2017). Conversely, in a CMJ the athlete begins the movement with an unweighting phase, lowering their center of gravity rapidly prior to jumping a high as possible. This unweighting phase may allow the athlete to store and utilize elastic energy in the parallel and series elastic components present in the muscle and tendon, operate through a more optimal region of the force-muscle-length curve, allow the muscle to work at an optimal velocity, produce more work, increase electrical activity in the muscle and reduce muscle slack (Bobbert & Casius, 2005; Van Hooren & Zolotarjova, 2017) resulting in higher jump heights when compared to the SJ (Bobbert et al., 1996; Bobbert & Casius, 2005; Kozinc et al., 2022; J. M. Sheppard & Doyle, 2008; Van Hooren & Zolotarjova, 2017).

It is posited that a comparison of an athlete's SJ and CMJ ability (often called the eccentric utilization ratio, EUR) provides unique insights into an athlete's neuromuscular status and adaptations to training (Hawkins et al., 2009; McGuigan et al., 2006). The difference in height between the SJ and CMJ potentially highlight an athlete's ability to utilize the stretch shortening cycle action (Young, 1995) or other training areas of opportunity such as poor muscle activation (Van Hooren & Zolotarjova, 2017) and rate of force development (Kozinc et al., 2022) in the case of a poor SJ performance relative to the CMJ. Further tracking training induced adaptations through monitoring EUR has shown potential in highly trained populations (McGuigan et al., 2006) but not college level athletes (Hawkins et al., 2009). As completing an unweighting phase prior to jumping leads to an increased jump height relative to starting from a static position, it is paramount practitioners check for an unweighting phase in SJs to prevent an inflation of jump height and ensure that the measurement is unique from the CMJ.

Unfortunately, achieving compliance with SJ protocols is challenging (J. M. Sheppard & Doyle, 2008) and there is a lack of consensus on how to define the unweighting phase. For example, studies utilizing force plates employ different method to assess the validity of SJs. These include a downwards displacement of 0.02 m (Secomb et al., 2016), an unweighting in the ground reaction force of 5% BW (Hughes et al., 2022; Petronijevic et al., 2018) or 10% BW (Harrison et al., 2024). Further, an unweighting greater than or equal to 10% BW or decrease of greater than or equal to 10% in squat displacement prior to the initiation of the upward propulsive phase has been used (Mitchell et al., 2017). Other more subjective methods such as no visible unweighting determined by inspection of the force time trace by a practitioner (Kotani et al., 2022, 2023; Kozinc et al., 2022; Pérez-Castilla et al., 2020) and subjective visual observations for downwards motion (Coratella et al., 2018; Gołaś et al., 2017; Magrini et al., 2018; Sams et al., 2018) have also been employed. Lastly, some studies do not specify exclusion criteria for valid SJs (Edwards et al., 2023; Harrison et al., 2024; Ishida et al., 2023). This reliance on subjectivity to determine a valid SJ has the potential to result in misleading findings or possibly incorrect training interventions. As 99.2% of SJs have some unweighting phase (J. M. Sheppard & Doyle, 2008), it is important to determine at what threshold of unweighting jump height becomes inflated. Establishing a clear threshold for unweighting in the SJ would allow the use of algorithms for the detection of unweighting and remove the potential for subjectivity in detecting valid SJs. Therefore, the purpose of this study was to determine at what amplitude of unweighting, determined as percentage of BW, does SJ height increase. As an unweighting phase leads to increased jump height, it was hypothesized that SJ height would increase with larger amplitudes of unweighting (Ha) with the null hypothesis that amplitude of unweighting would not increase SJ height (Ho).

2.3 Methods

2.3.1 Approach to the Problem

To assess at what threshold of amplitude of unweighting jump height increases during the SJ a retrospective cohort study design was used. Anonymized SJ testing data was utilized from pre- and post-season testing sessions in a group of varsity rugby athletes. Amplitude of unweighting was defined as the lowest point in the force-time trace prior to the upward propulsive phase and expressed as a percentage relative to BW. This method has previously been used to determine unweighting (Mitchell et al., 2017) and is more robust to different algorithms used to identify the start of a jump, such as unweighting impulse. SJs were then grouped based on the amplitude of unweighting. The dependent variable was jump height, and the independent variable was unweighting group. External load (weight on a barbell) was included as a covariate, as practitioners often perform SJs under loaded conditions (Baker et al., 2001; Samozino et al., 2008; A. P. Turner et al., 2011). As 99.2% of SJ have some unweighting phase (J. M. Sheppard & Doyle, 2008), the unweighting threshold of ≤1% BW was used as the measure of a "good" SJ to which other unweighting thresholds were compared to.

2.3.2 Subjects

Fifty-six university female rugby athletes, mean ± *SD,* BW 76.26 ± 12.40 kg, height 1.68 ± 0.06 m, age 22.23 ± 1.47 years were sampled for this study. Athletes were strength training 2 times per week (see Table 2 for a sample program) and regularly utilized bilateral jumps as part of their training regime and testing battery. To be included in the study all athletes were required to be free of injury and were allowed to stop testing at any point. All subjects gave their informed consent to partake in this study and ethical approval for the study was obtained from the University of Victoria's Human Research Ethics Board and complied with the principles outlined in the Declaration of Helsinki.

Table 2. Typical Strength Session

Exercise	Number of Sets	Number of Repetitions
Jumping Action	2-3	3-6
Clean Variation	5-6	3-5
Lower Body Push or Pull	5-6	3-7
Upper Body Push or Pull	5-6	3-7
Individual Supplemental Exercise 1	2-3	11-15
Individual Supplemental Exercise 2	2-3	11-15
Individual Supplemental Exercise 3*	2-3	11-15

Note: Second year athletes performed the higher set ranges and lower repetition ranges.

*Only second year athletes performed the third supplemental exercise.

2.3.3 Procedures

Testing was conducted during the pre-season and post-season periods when rugby volume was minimal. The testing was part of a wider test battery conducted as the only session of the day, taking place between 16:00 – 18:30 PM. The testing day consisted of a 20-minute warm up consisting of 10 minutes of general activity through multiple planes to elevate body temperature and a 10-minute specific warm-up consisting of A-Skips, A-Runs, Straight Leg Runs and 3 sprints of increasing intensity. Testing consisted of 2 x 40 m sprints of maximal intensity, with approximately 5 minutes between sprints; heights were collected during the rest period. This was followed by a 5-minute walk to the biomechanics lab where athletes performed the jump testing. Jump testing was preceded by a specific warm-up of 3 CMJs arms akimbo, 3 minutes rest, then 3 CMJs arms akimbo, approximately 3 minutes prior to commencing testing.

Jump Testing. Bodyweight was measured using 2 bilaterally mounted force plates (AMTI©, OR6-7, Watertown, USA) prior to each jump. The plates were zeroed prior to the subject stepping on and once on the plates the average force during the quiet standing period was selected then divided by 9.81 $m \cdot s^{-2}$ to determine the system weight (BW + external load), the external load was then subtracted from the system weight to determine BW.

The testing consisted of 3 CMJs with arms akimbo as part of the subjects regular testing battery. This was followed by the SJs. For the SJs, the subjects lowered themselves to a standardized depth of 0.50 m, confirmed by a rubber band positioned over the posterior edge of the force plate, which equated to a knee angle of ≈ 90 degrees. A 3-second pause was initiated prior to commencing the upward propulsive portion of the jump. The subjects were instructed to jump for maximal height. The SJs were performed across 4 loads, beginning at 0.50 kg (doweling across the shoulders), and progressed by 15 kg increments unless the athlete was unable to jump over 0.10 m or technical proficiency was compromised as assessed by a NSCA Certified Strength and Conditioning Specialist. At each load, the subject performed 3 attempts with 10-15 seconds between jumps and 3 minutes between loads. Rogue Fitness barbells and plates (Columbus, OH) were used for all loaded SJs. All jumps were collected using AMTI (AMTI©, OR6-7, Watertown, USA) force plates sampling at 1000Hz, and data was processed using custom script written in LabVIEW 2015 National Instruments (Austin, Texas) software using the impulse-momentum method (Linthorne, 2001). Raw force-time data from each jump trial were filtered using a fourth-order Butterworth filter with a low-pass cutoff frequency of 50Hz. The end of the unweighting period was identified as the first BW crossing moving backwards from the peak force of the jump. The start of the unweighting period was identified as the next BW crossing moving backwards from the end of the unweighting period. The amplitude of unweighting was the lowest point in the force-time trace between the start and end of unweighting period and presented as a percentage of BW. Test-retest reliability in our laboratory for SJ height demonstrated an ICC of 0.98 (0.93 – 1.00) and TEM of 0.02 m for jump height.

2.3.4 Statistical Analysis

Nine-hundred and thirty-seven SJs were used for the analysis. The statistics were conducted in JASP® (version 0.17.1, Netherlands). The SJs were grouped by unweighting amplitude into six groups by increments of 1% with the last group consisting of jumps with an unweighting amplitude >5% BW (see Table 3). The external loads ranged between 0.5 kg and 45 kg. To determine the threshold of unweighting that effected jump height an Analysis of Covariance (ANCOVA) was run with jump height as the dependent variable, unweighting group as the fixed factor and external load as a covariate. Alpha was set at 0.05. Assumptions were checked utilizing Levene's test for equality of variance and investigating the Q-Q Plot for normality. Dunnett's Test was used to determine significant differences between parameter estimates at each unweighting threshold and the amplitude of unweighting ≤1% BW group due to the risk of Type I error while making multiple comparisons.

Table 3. Descriptives - Flight Height

Unweighting Group	N	Mean (±*SD*)
≤1% BW	316	0.14 ± 0.05
>1% and ≤ 2% BW	290	0.15 ± 0.05
>2% and ≤ 3% BW	152	0.16 ± 0.05
>3% and ≤ 4% BW	59	0.16 ± 0.06
>4% and ≤ 5% BW	36	0.19 ± 0.06
>5% BW	84	0.20 ± 0.06

Note: Measurements in meters

2.4 Results

The one-way ANCOVA compared the different unweighting thresholds while controlling for external load. Levene's test and the Q-Q Plot showed normality in jump height. There was a significant difference in jump height between unweighting thresholds whilst adjusting for external load (F(5,930) = 13.65, $p < 0.01$), however the effect ($\eta_p^2 = 0.03$) is trivial (Hopkins, 2002). External load also had a significant effect ($\eta_p^2 = 0.62$) on jump height (F(1,930) = 1648.46, $p < 0.01$). Dunnett's test showed that the SJ unweighting threshold of ≤1% BW was significantly different from all groups >2% BW threshold ($p < 0.01$) (refer to Table 4). Comparing the estimated marginal means showed that the unweighting thresholds >2% BW resulted in higher jump heights when compared to the ≤1%BW threshold, refer to Table 5.

Table 4. Post Hoc Comparisons for Unweighting Groups

Comparison Groups		Mean Difference (m)	*SE* (m)	*t*	p_{dunnett}
≤1% BW to	>1% and ≤ 2% BW	$5.28 \cdot 10^{-3}$	$4.21 \cdot 10^{-3}$	1.26	0.66
	>2% and ≤ 3% BW	0.02	$5.11 \cdot 10^{-3}$	3.47	$2.68 \cdot 10^{-3}$*
	>3% and ≤ 4% BW	0.02	$7.34 \cdot 10^{-3}$	3.33	$4.48 \cdot 10^{-3}$*
	>4% and ≤ 5% BW	0.05	$9.10 \cdot 10^{-3}$	5.04	<0.001**
	>5% BW	0.06	$6.35 \cdot 10^{-3}$	9.25	<0.001**

Note: *p<0.01, **p<0.001

Table 5. Marginal Means for Unweighting Group

Unweighting Group	Marginal Mean	95% CI for Mean Difference Lower		95% CI for Mean Difference Upper	*SE*
≤1% BW	0.15	0.14	-	0.15	1.76×10^{-3}
>1% and ≤ 2% BW	0.15	0.15	-	0.15	1.83×10^{-3}
>2% and ≤ 3% BW	0.15	0.15	-	0.16	2.52×10^{-3}
>3% and ≤ 4% BW	0.16	0.15	-	0.17	4.05×10^{-3}
>4% and ≤ 5% BW	0.17	0.16	-	0.18	5.20×10^{-3}
>5% BW	0.18	0.17	-	0.18	3.44×10^{-3}

Note: Measurements in meters

2.5 Discussion

The purpose of this study was to determine at what threshold of unweighting, jump height increases. The results rejected the null hypothesis and confirmed the alternative hypothesis, indicating that SJ with an amplitude of unweighting >2% BW result in significantly higher jumps than SJ with an amplitude of unweighting ≤1% BW while controlling for the effect of external load (see Table 4). This finding has an impact on practitioners seeking to remove subjectivity from their identification of “good” SJs to use in research or to influence the design of training programs. Furthermore, the threshold of >2% BW could also be used in algorithms to automate the process of detecting SJs where athletes fail to adhere to the SJ protocol.

The difficulty of detecting compliance to SJ protocols has previously been noted with gross visual observation by practitioners only detecting 61.6% of trials with unweighting, despite 89.6% of SJ trials containing a small unweighting (J. M. Sheppard & Doyle, 2008). Further, it has been found that approximately 45.8% of jumps have unweighting amplitudes >10% BW as detected by force plates, highlighting the high frequency that unweighting occurs prior to the upward propulsive phase of the SJ (J. M. Sheppard & Doyle, 2008). In contrast our study found that only 8.96% of trials had an unweighting amplitude >5% BW. The reduced frequency of large unweighting periods found in our study likely highlights the importance of having subjects perform jumps as part of their regular training regime and familiarity with the testing protocol, as the presence of a large unweighting period presents a unique threat to the validity of the SJ height. As this study showed, even small unweighting amplitudes results in an increase in jump height while holding constant the effect of external load (see Table 5).

Including SJ trials with small unweighting periods outside of the >2% threshold could influence practitioners’ interpretation of SJ data. For example, force velocity profiles constructed utilizing a countermovement jump result in larger calculated maximal power output, force, and velocity values (Jiménez-Reyes et al., 2014). Furthermore, inflating the SJ height would impact the calculation of EUR, masking training induced adaptations if practitioners are tracking EUR longitudinally like other studies (McGuigan et al., 2006). As this study showed SJs with an unweighting >1% to 2% BW do not result in increased jump height when compared to the criterion condition of ≤1% BW, it is likely that practitioners can include jumps in their analysis when investigating SJ data or for comparison to CMJ when investigating EUR. This aligns with findings utilizing different methodology for detecting unweighting that determined a small downwards displacement of 0.01-0.03 m did not increase jump height significantly (Hasson et al., 2004).

One limitation of this study is that only the impact of unweighting on the primary outcome of a SJ height was investigated. It is possible that practitioners may want to do further investigations on the impact of unweighting on tertiary measures such as force, power, or average velocity collected from the SJ as these measures are often used in research (Jiménez-Reyes et al., 2018, 2019; Jiménez-Reyes, Samozino, Brughelli, et al., 2017; Sleivert & Taingahue, 2004). A second limitation of this study is that it was completed with a sample consisting of only female rugby athletes. Significant differences in the impact of unweighting on jump height have been found in different sports and genders (Hawkins et al., 2009; Kozinc et al., 2022). However, gender was found to have only a small effect on the difference between SJ and CMJ jump heights with males having larger differences than females (Kozinc et al., 2022). Further, unweighting will likely impact individual athletes differently, as evidenced by observations from the Australian Institute of Sport (J. M. Sheppard & Doyle, 2008). It is possible that these findings could impact the generalizability of the unweighting amplitudes found in this study. However, until such time as further research is conducted, it is recommended that an unweighting amplitude of 2% BW be used as the threshold to determine SJ compliance as it removes subjectivity in the detection process and unweighting >2% BW have been shown to significantly increase jump height.

2.6 Practical Applications

For the SJ to be a valid measure it is essential that it is unaffected by an unweighting period prior to the upward propulsive phase and therefore a standardized threshold is required. Based on the findings of this paper an amplitude of unweighting threshold of 2% BW is recommended for practitioners. SJs with an unweighting >2% BW should be excluded from analysis due to the impact this unweighting can have upon jump height. The adoption of this threshold will remove subjectivity from the analysis process and allow practitioners to utilize this threshold in algorithms to automatically detect valid SJs.

3. Predicting Hexagonal-Bar Jump Takeoff Speed using Peak Speed from a Linear Position Transducer[5]

3.1 Abstract

To evaluate if takeoff speed can be predicted using peak-speed from a linear position transducer (LPT), twenty-one rowing athletes performed hexagonal-bar jumps in line with the National Team testing protocol. Predictive validity was assessed by comparing peak-speed from a LPT to the criterion measure takeoff speed collected from force plates. The relationship between peak-speed and takeoff speed was: Takeoff Speed = 1.21 · Peak-Speed - 0.68, and the correlation was statistically significant ($r = 0.98$, $p<0.05$). The Bland-Altman plot indicated that the 95% limits of agreement ranged from -0.13 $m \cdot s^{-1}$ to 0.13 $m \cdot s^{-1}$, with points above and below the zero line, suggesting there is no systematic bias. The mean difference in speed was 0.18%. This research shows that takeoff speed can be accurately predicted from peak-speed using a LPT. This allows practitioners to quickly and accurately estimate jump height when accessibility and portability of testing equipment are limiting factors in the field.

3.2 Introduction

Specialized ballistic movement testing of athletic populations can be useful to enable within and between athlete comparisons, direct training interventions and assess changes in performance. For example, jumping and sprinting performance may partially explain or influence selection in rugby players (Gabbett et al., 2011b; Till et al., 2011) and simple ballistic tests such

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as a standing long jump has shown potential to identify sprinting talent in female rugby athletes (Agar-Newman & Klimstra, 2015). Furthermore, force-velocity profiling examining the relationship between velocity and the athletes' force producing capabilities, using jumps across a spectrum of loads has proven useful for the development of individualized training interventions to minimize force-velocity imbalances and improve ballistic (Jiménez-Reyes et al., 2019; Jiménez-Reyes, Samozino, Brughelli, et al., 2017).

To produce an athlete's force-velocity profile, kinetic and kinematic values are derived from measures taken during ballistic tests. While research grade equipment, such as force plates, provide optimal testing accuracy and reliability, issues such as cost, accessibility and portability limit their use in the field. Fortunately, several cost effective and portable tools, such as linear position transducers (LPT), accelerometers and video cameras, have the potential to collect accurate and reliable metrics in the field and gym (McMaster et al., 2014). Additionally, Samozino et al. (2008) developed a simple three-factor computational method for calculating mean values for force, power and speed during a squat jump. This three-factor computational method uses system mass, flight time derived from a GRF-time signal, and push-off distance, calculated as the difference between the distance from the greater trochanter to the ground at the bottom of a squat and the distance between the greater trochanter and ground with the lower limb fully extended with maximal plantar flexion (Samozino et al., 2008). This method makes the need for a force plate theoretically unnecessary for calculating mean force, speed and power values. This has since been validated with flight time being derived from other simple cost-effective tools such as video from a cell phone (Balsalobre-Fernández et al., 2015; Driller et al., 2017). However, jump height calculated from flight time may be inflated due to differences in takeoff and landing posture of the athlete (Aragón-Vargas, 2000; Kibele, 1998; Linthorne, 2001). Furthermore, manually detecting takeoff and landing events may be time prohibitive when working with large groups of athletes in a training setting.

Other tools show potential for use to calculate peak speed or takeoff speed (TS) such as inertial measurement units (IMU). IMU based products such as the Push Band (PUSH Inc., Toronto, CAN) and Bar Sensai (Assess2Perform, Montrose, USA) are inexpensive and easy to use and some research shows that the Push Band 2.0 may be used to measure mean and peak speed (Lake et al., 2018). However, the band tends to overestimate speed when compared to the force plates and may be influenced by the athlete's performance level (Lake et al., 2018). Furthermore, the reliability and validity of IMU to assess jump height has yet to be determined. Potentially imprecise values inputted into the three-component model mentioned previously (Samozino et al., 2008b) could result in erroneous kinematic and kinetic predictions and result in inaccurate force velocity profiles.

LPTs are another tool that show the potential to calculate jump height. Some models determine height directly utilizing a method similar to a tape measure (GymAware, 2019). Although this method has been found to be reliable, it over-predicts jump height (O'Donnell et al., 2018; Wadhi et al., 2018). Further, the GymAware system in Wadhi et al.'s (2018) and O'Donnell et al.'s (2018) studies were recalibrated prior to each jump, making the protocol unrealistic in a team setting where training efficiency is a priority. Practitioners working in a daily training environment may be limited by the tools available, time available for post-hoc analysis or sport specific coaches' views on technological assessments, making the ability to test athletes in numerous ways a key priority. Another simple and reliable output measure from many commercially available LPTs is peak speed (PS) (Garnacho-Castaño et al., 2015; Lorenzetti et al., 2017); which occurs approximately 0.27 ms prior (Lake et al., 2018) to the instance of takeoff in the standing vertical jumps (see Figure 3).

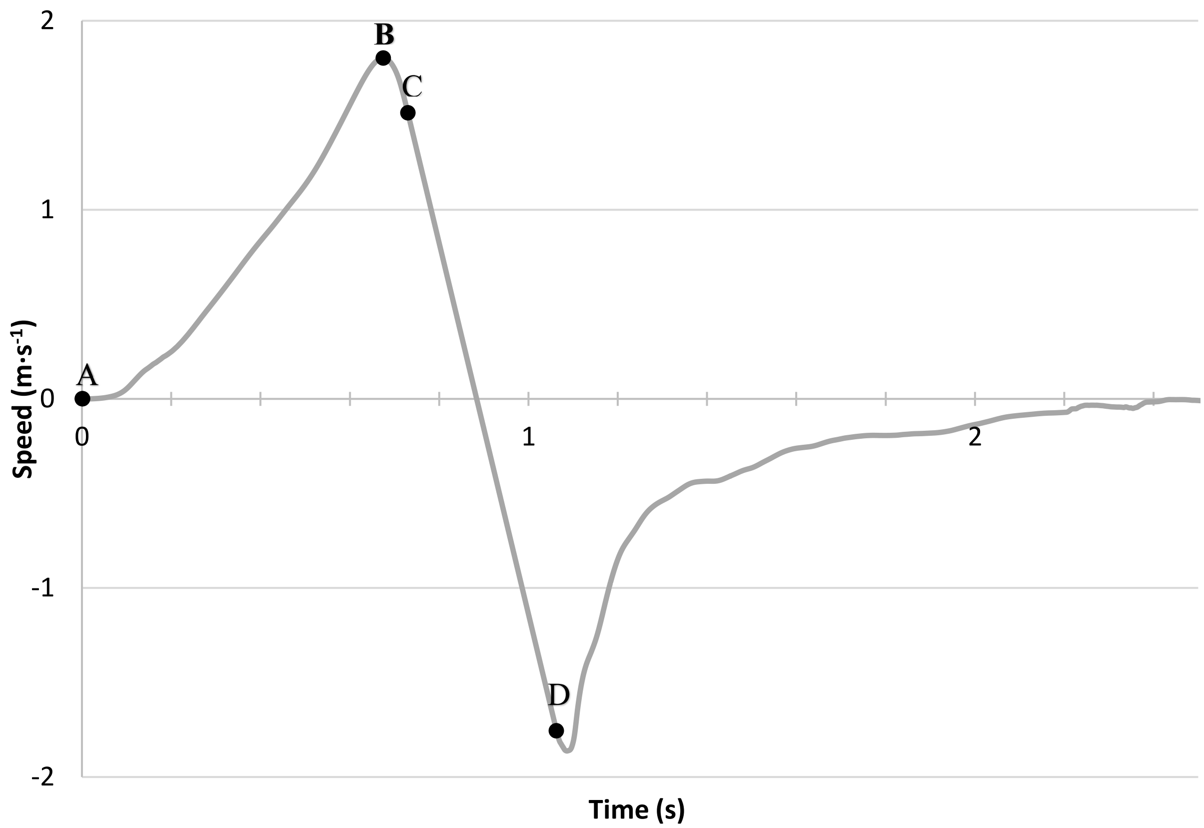

Figure 3. Speed-time curve of a hex-bar jump with key positions labelled (A) Initiation of the movement, (B) PS, (C) Takeoff and TS, (D) Touch Down

If TS can be determined utilizing PS from an LPT, the maximum height achieved by the center of mass can easily be calculated using simple Newtonian physics. This would allow practitioners to utilize LPTs that do not directly calculate jump height with the three-factor model developed by Samozino et al. (2008) and hexagonal bar (hex-bar) jump (Agar-Newman et al., 2020).

Furthermore, this method would eliminate the need to recalibrate the LPT prior to each jump opening another avenue of assessment for strength and conditioning practitioners working in the daily training environment. Therefore, the purpose of this study was to determine if TS calculated using the impulse-momentum method from force plates can be predicted using PS from a simple LPT during hex-bar jumps. Based on the previous literature, there is not enough evidence to assume that TS can be computed from PS and therefore the null hypothesis (Ho) is: there will be no difference between the estimated TS calculated from PS and TS speed calculated using the impulse-momentum method and our alternative hypothesis (Ha) is: there is a difference between the estimated TS calculated from PS and TS speed calculated using the impulse-momentum method.

3.3 Methods

3.3.1 Approach to the Problem

To determine if PS from a LPT can predict TS calculated from force plates during hex-bar jumps the cross- validation technique was utilized by partitioning the data into a training set to develop a model and predict TS using the test set to evaluate the model's performance. PS and TS were collected from the force plates (AMTI©, OR6-7, Watertown, MA, USA) and PS was simultaneously collected from a LPT during hex-bar jumps. Half of the data (training set) was utilized to develop a linear mixed model. Then, predictive validity was assessed using the second half of the data (test set) by comparing the predicted TS to the criterion measure TS from the force plates using the impulse-momentum method.

3.3.2 Subjects

Twenty-one athletes (12 females, 9 males) were sampled from the varsity rowing team. The subjects had a mean age of 20.40 ± 2.60 years and a range from 18.47-27.63 years (females 20.28 ± 2.54 years, males 20.55 ± 2.82 years), a body mass of 78.56 ± 13.68 kg (females 77.19 ± 14.47 kg, males 80.40 ± 13.16 kg) and height 177.02 ± 8.27 cm (females 174.14 ± 6.84 cm, males 176.32 ± 8.81 cm). Subjects had a strength training history of 3.57 ± 2.69 years (females 3.63 ± 2.89 years, males 3.50 ± 2.57 years) and were in their specific preparation period, rowing 150 km – 180 km per week, with two sessions per day, six days per week. All subjects volunteered for this study, gave their informed consent to partake in this study and ethical approval for the study was obtained from the University of Victoria's Human Research Ethics Board and complied with the principles outlined in the Declaration of Helsinki. Subjects were allowed to withdraw from the study at any time.

3.3.3 Anthropometric Measures

Body mass was measured using bilaterally configured force plates (AMTI Watertown, USA) which were zeroed prior to the subject stepping onto the plates for the initial 28.55 kg load. The average force during a quiet period of standing was selected and divided by 9.81 $m \cdot s^{-2}$ to determine the system mass and the hex-bar mass was subtracted from the system mass to determine the subjects' body mass. Height was collected using a Seca 213 portable stadiometer (Hamburg, Germany) using the ISAK stretch method (Stewart et al., 2011).

3.3.4 Kinetic and Kinematic Measures

Subjects performed the testing between 15:00 and 18:00 hours. Kinetic and kinematic measures were collected using previously published methods (Agar-Newman et al., 2020). Briefly, subjects performed a ten-minute general warm-up prior to performing a specific warm-up of three jumps of increasing intensity at the initial 28.55 kg load. Hex-bar jumps were performed using a 23.55 kg hex-bar and Eleiko weightlifting plates (Halmstad, Sweden). The testing consisted of two jumps at each load, starting at 28.55 kg and increased by 10 kg increments to 78.55 kg, averaging 4.5 minutes rest between loads. These loads were chosen as they were in line with the national teams testing battery and theoretically would cover a spectrum of takeoff velocities. At the start of the movement a 3 second pause was counted aloud by the tester after which the subjects were directed to "explode from the ground as fast as possible." If the subjects' technique was compromised (flexion of the spine or valgus of the knees) or if they were unable to leave the ground the testing was stopped. Subjects were instructed to hold the hex-bar's low handles (0.225 m from the ground) and lifting straps were recommended to securely fasten the subject to the hex-bar and minimize the risk of dropping a hex-bar directly onto the force plate. Force-time data was collected using the bilateral force plates noted above sampling at 1000 Hz using custom software (LabView 2015) and filtered using a Double Butterworth filter at 20 Hz. The force plates were zeroed prior to each jump, system mass (subject mass and bar mass) was calculated using the quiet stationary period prior to the jump, and TS was calculated using the impulse-momentum method (Linthorne, 2001). Briefly this method uses the subjects' body weight from the quiet stationary period (zero velocity), subtracts the subject's body weight from the force-time curve, divides the force time curve by the subject's body mass to determine the acceleration-time curve and then numerically integrates the acceleration-time curve utilizing the trapezoid rule to calculate velocity. The with-in session reliability of TS calculated using the impulse-momentum method was ICC = 0.98 (95% CI 0.97 – 0.99), *SEM* = 0.12 $m \cdot s^{-1}$. PS was measured using a LPT (Tendo Power Analyzer v.314, Trenčín, Slovak Republic) fastened to the right sleeve of the hex-bar, with the sensor unit positioned directly below. The Tendo's sensor unit consisted of a cable surrounding a slotted disk at standardized distances. When the cable was extended, the disk rotated and a light shine through the slots. An optic sensor then converts the light into electronic impulses. Velocity, which was calculated by dividing the standardized distance of the slots by the time between impulses and was transferred to the microcomputer. The sampling rate was determined by the speed of the discs rotation (Garnacho-Castaño et al., 2015). PS data was collected directly from the microcomputer attached to the sensor unit. The with-in session reliability of the LPT was ICC = 0.97 (95% CI 0.95 – 0.98), *SEM* of 0.05 $m \cdot s^{-1}$ with the unit's displacement cutoff set to 0.35 m (i.e. the smallest size of movement the unit records). All ICCs were calculated using a Two-Way Mixed Model with Absolute Agreement.

3.3.5 Statistical Analysis

220 Jumps were collected of which 14 jumps were excluded prior to analysis due to technical failure or failure to follow protocol. The analysis consisted of three parts. First, the data was separated into "Jump 1" and "Jump 2" with "Jump 1" used as training set while "Jump 2" was used as the test set. Second, a linear mixed model was built using the training set data to determine the relationship between TS and PS, while accounting for individual athlete variance. Alpha was set to 0.05. Investigation of the residual plot showed a random scatter of points and normality plot showed the residuals fall on a straight-line indicating the normality assumption was appropriate for TS. Finally, a correlation and Bland-Altman analysis was used to assess the level of agreement between measured TS and estimated TS in the test set (i.e. Jump 2). A range of agreement was defined as mean bias ± 2 SD with 95% of values within the limits (Giavarina, 2015). The limit of agreement of difference was defined a priori as 5% of TS, which is clinically acceptable. All statistics were calculated using R (Version 3.4.3; Vienna, Austria).

3.4 Results

The speeds of the hex-bar jump decreased in a linear fashion across loads (Table 6). However, it should be noted that only 2 jumps were performed by the female subjects at the heaviest load due to technical proficiency. The linear mixed model determined that the relationship between TS and PS was:

$$TS = 1.21 \cdot PS - 0.68$$

This relationship was shown to be statistically significant ($p<0.05$), with $r = 0.98$ and a *RMSE* of 0.05 $m \cdot s^{-1}$ (df = 103). This equation was then used to estimate TS on the test set of data. There was a statistically significant correlation ($r = 0.98$, $p<0.05$) between TS and estimated TS using the training set (Figure 4) with an *RMSE* of 0.07 $m \cdot s^{-1}$ with df = 103.

Table 6. PS and TS Across Loads & Genders

	Females							Males						
Load (kg)	*n*	PS	*SD*	CV	TS	*SD*	CV	*n*	PS	*SD*	CV	TS	*SD*	CV
28.55	24	2.12	0.17	8%	1.56	0.16	10%	18	2.69	0.18	7%	2.07	0.16	8%
38.55	24	1.92	0.14	8%	1.34	0.18	13%	18	2.53	0.23	9%	1.93	0.17	9%
48.55	22	1.74	0.13	8%	1.18	0.16	14%	18	2.37	0.23	10%	1.79	0.19	11%
58.55	20	1.56	0.13	8%	0.94	0.20	21%	18	2.17	0.19	9%	1.64	0.21	13%
68.55	14	1.42	0.14	10%	0.81	0.17	21%	18	2.01	0.22	11%	1.48	0.21	14%
78.55	2	1.12	0.01	1%	0.49	0.01	2%	13	1.94	0.22	11%	1.34	0.26	19%

Note: All speeds in $m \cdot s^{-1}$

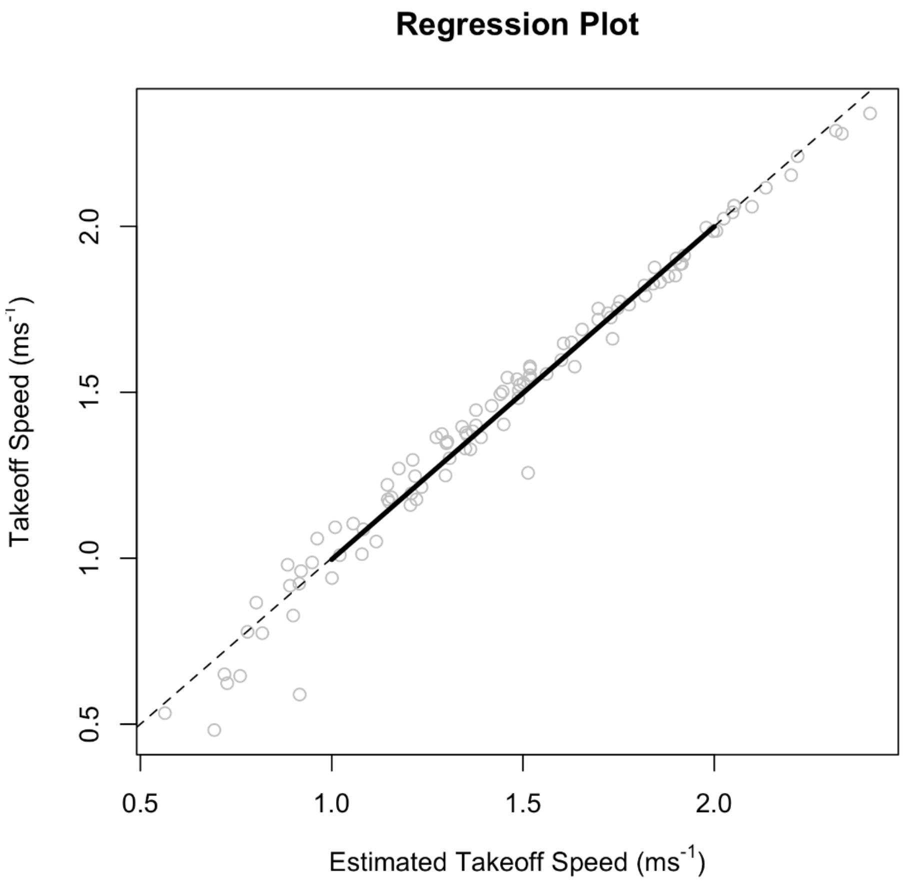

Figure 4. Scatterplot of TS vs estimated TS

Bland-Altman plot (Figure 5) indicated that the 95% limits of agreement ranged from -0.13 $m \cdot s^{-1}$ to 0.13 $m \cdot s^{-1}$, with a mean difference in speed of 0.18%. This range is within the value of ± 5% of TS defined a priori as acceptable. The plot showed points above and below the zero line, suggesting there is no systematic bias of one metric versus the other.

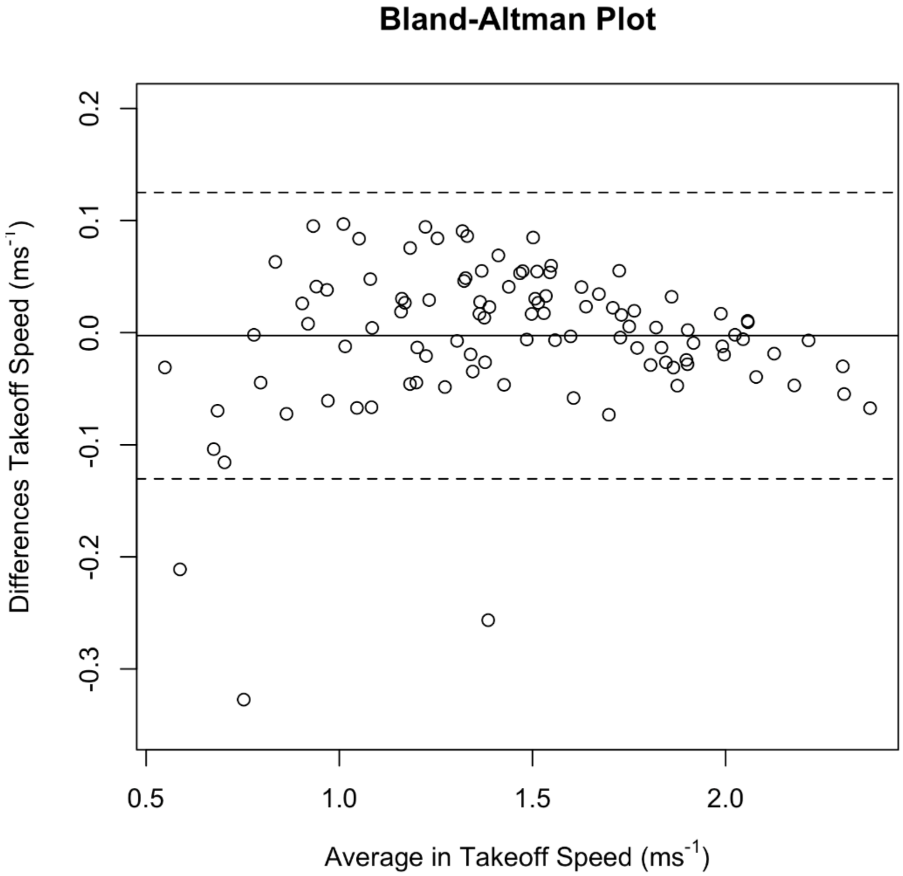

Figure 5. Bland-Altman plot of differences in TS and estimated TS

3.5 Discussion

The aim of this study was to determine if TS calculated using the impulse momentum method from force plates can be predicted using PS from a simple LPT during hex-bar jumps. It was hypothesized that there would be no difference between the estimated TS calculated from PS and TS speed calculated using the impulse-momentum method. This research shows that TS can be predicted from PS utilizing a hex-bar jump and an LPT. This suggests that values from a LPT, measuring PS, may be used to calculate jump height. This finding makes the requirement to determine the takeoff position of individual athletes prior to jumping unnecessary, decreasing the time testing will take practitioners.

To the authors' knowledge this is the first study to predict TS using PS during a ballistic loaded task. Aragon-Vargas (2000) compared their criterion measure, center of mass displacement calculated using cinematography and segmental center of masses, to calculated jump height from a force plate and the flight time method. Interestingly, jump height calculated using TS predicted a 0.02 m lower jump than their criterion measure (Aragón-Vargas, 2000). They found that predictions using flight time, while reliable were inaccurate, as it operates on the assumption that the center of mass travels upwards and downwards for equal time. However, Aragon-Vargas determined that participants travelled downward for a significantly longer period during their flight phase (average difference = 0.02 s, $p < 0.01$). This major limitation was attributed to different takeoff and landing postures, consistent with Kibele (1998) who noted, subjects often land with a lower center of mass due to flexed ankles and knees prior to landing, leading to an over-prediction of jump height calculated from flight time. Unfortunately, in the statistical analysis Aragon-Vargas (2000) did not provide a Bland Altman analysis which is a simple way to quantify the level of agreement between two quantitative variables (Giavarina, 2015). This would have helped determine if the magnitude of error was consistent across jump heights. As Bui et al.'s (2015) paper suggests, error in the calculation of vertical jump height may vary with level of jump height, which could make mathematical corrections difficult. Changing kinematic landing strategy may be another way to minimize error while utilizing the flight time method, however this could be difficult to modify and monitor in a training environment with multiple athletes. A solution for this problem could be the collection of high-speed video to visually assess compromised technique post-hoc. However, this can be prohibitive and time-consuming with multiple athletes such as testing a large team. These results, taken together with the present work, support the importance of using kinematic measures, over temporal measures to predict jump height.

Another interesting finding of this study was the discovery of three points outside of the limits of agreement on the Bland-Altman plot at low speeds. This warrants further investigation into possible discrepancies in precision at low speeds when using a LPT combined with a hex-bar jump. It is possible that a discrepancy may be present at heavier loads due to the inverse relationship between sampling rate and movement speed present in the model of LPT used in this research. Another possibility for the values outside of the 95% limits of agreement at the slower speeds is due to changes in movement strategy as the load increases. This investigation could easily be undertaken by comparing heavier loads (lower velocities) and lighter loads (higher velocities), analyzing accuracy or movement strategies using a motion capture system.

We determined that TS calculated using the impulse-momentum method from force plates can be predicted using PS from a LPT during a hex-bar jump. This will allow a quicker way to assess jump height where equipment and time may be a limiting factor, such as a team setting. As an extension, this equation may allow a quicker way to assess mean velocity, power and force using Samozino et al's (2008) three factor model. However future research will need to be conducted assessing the validity and accuracy of such an application. Further, practitioners should be aware that when using simple LPT there is the possibility that precision may be compromised at lower speeds.

4. The Validity of Applying a Simple Three-Factor Computational Model to Calculate Force, Power and Speed Utilizing Hexagonal Bar Jumps[6]

4.1 Abstract

The development of athlete specific force-speed profiles can be accomplished through testing ballistic movements, enabling athlete comparisons and to inform training interventions. However, field based assessments relying on the squat jump or countermovement jump may lack specificity for some sports or be contraindicated for some athletes. Therefore, the purpose of this study was to assess the validity of a three-factor computational model using system mass, push-off distance and jump height to calculate force, speed and power for the hexagonal bar (hex-bar) jump.

Twenty-one university varsity rowing athletes (12 females and 9 males, 20.40 ± 2.60 years, 78.56 ± 13.68 kg, 1.77 m ± 0.08 m and strength training history of 3.57 ± 2.69 years) were purposefully sampled. Testing consisted of jumps at loads starting at 28.55 kg and increasing by 10 kg increments to 78.55 kg or until technical failure occurred. Validity was assessed by comparing the three-factor computational model to the criterion force-time measures from a force plate.

The results show force (mean bias = 85.38 N, *SE* = 5.41, 95% confidence limit 1576.85 - 1598.19), speed (mean bias = 0.00 m·s^{-1}, *SE* = 1.25^{-5}, 95% confidence limit 0.72 - 0.72) and power

[6] Published: Agar-Newman, D. J., Tsai, M.-C., & Klimstra, M. (2020). The Validity of Applying a Simple Three-Factor Computational Model to Calculate Force, Power, and Speed Using Hexagonal Bar Jumps. *Journal of Strength and Conditioning Research*, *Ahead of P*(00), 1–7. https://doi.org/10.1519/jsc.0000000000003581

(mean bias = 73.36 W, *SE* = 3.90, 95% confidence limit 1166.61 - 1181.97) can be computed using a three-factor computational model utilizing the hex-bar jump.

In conclusion, jump height from a hex-bar jump can be used with a simple three-factor computational model to calculate valid measures of force, speed and power. This allows practitioners in the field to utilize a movement that may be more sport specific or safe, to calculate kinetic and kinematic measures without encountering the issues of cost and portability associated with force plates.

4.2 Introduction

McMaster et al. (2014) recommend that profiling of athletes should include physiological, biomechanical, anthropometric and physical performance measures. Physical performance assessments are useful to separate levels of athletes (Agar-Newman & Klimstra, 2015; Durandt et al., 2006; Till et al., 2011), playing positions (Agar-Newman et al., 2015; Hene et al., 2011) and guide training interventions (Claudino et al., 2016; Jiménez-Reyes, Samozino, Brughelli, et al., 2017). Although not new, the accessibility of the work of Samozino et al. (Samozino et al., 2008b, 2012) and the development of athlete and movement specific force speed profiles has gained popularity in the field of strength and conditioning.

Athlete specific force-speed profiles calculated through testing ballistic movements and utilizing Samozino et al.'s three factor computational model, requiring body mass, jump height and push-off distance, allows force, speed and power to be calculated (Samozino et al., 2008). The three-factor model has led to the validation of smartphone applications that provide a simple way to test and profile athletes (Balsalobre-Fernández et al., 2015; Driller et al., 2017). This can then be compared to an optimal profile in the squat jump (Samozino et al., 2012). The efficacy of guiding training around manipulating an athlete's force speed profile around their force-speed imbalance has been shown to be advantageous to improve vertical jump (Jiménez-Reyes et al., 2019; Jiménez-Reyes, Samozino, Brughelli, et al., 2017). However, much of the research utilizing the three-factor computational model and optimal slope utilize a concentric only squat jump.

Testing novel exercises, despite similar movement patterns may result in erroneous interpretations of the assessment. For example, Jiménez-Reyes et al. (Jiménez-Reyes et al., 2014) investigated the effect of a countermovement jump on the lower limb force-speed profile. They noted that the countermovement jump performance was 15.4% higher than the squat jump, resulting in a large upwards shift in the theoretical force at zero velocity (20.6%) than velocity at zero force (13.3%) values when utilizing the countermovement (Jiménez-Reyes et al., 2014). Further, field based assessments relying on the squat jump or countermovement jump may not be a relevant sport specific movement for all sports, due to the position of the center of mass, posture and how the weight is manipulated.

A solution for this could be utilizing the hex-bar jump for force-speed profiling. This lower body pulling action has the athlete starting in a stable position with a low center of mass. Swinton et al. noted an enhanced mechanical profile using hex-bar jumps when compared to barbell jumps (Swinton et al., 2012). This could be due to an increased contribution of trunk extension as the load can move independently of the torso and remains closer to the center of mass (Swinton et al., 2012). Trunk extension has been shown to contribute as much as 10% to jump performance and can be restricted when using a regular barbell (Luhtanen & Komi, 1978). Further, the hex-bar jump significantly alters the technique when compared to the deadlift resulting in lower peak moments at the lumbar spine, hip and ankle and an increased moment at the knee (Swinton et al., 2011). This could be useful for athletes with a history of lower back pain (Swinton et al., 2012). Therefore, the purpose of this study was to assess the validity of Samozino et al.'s computational model to calculate force, speed and power for the hex-bar jump. Based on the previous literature, there is not enough evidence to assume that the computational model will not be correct; therefore, the null hypothesis (Ho) is: there will be no difference between the computational model and the measured force plate metrics, and our alternative hypothesis (Ha) is: there is a difference between the computational model and the measured force plate metrics.

4.3 Methods

4.3.1 Approach to the Problem

Predictive validity was assessed by comparing Samozino et al.'s (2008) previously published three factor computational model using calculated jump height (flight time method), push-off distance (h_{po}) (height at takeoff (h_{to}) minus height of squat (h_s)), and system mass (body mass + bar load) to the criterion force-time measures from a force plate (AMTI©, OR6-7, Watertown, MA, USA) sampling at 1000Hz. The force, speed and power measures from the three-factor computational model were the predictor variables and the force, speed and power measures from the force plate were the criterion variables. The cross- validation technique was utilized to assess the accuracy of the model.

4.3.2 Subjects

Twenty-one athletes (12 females, 9 males) were purposefully sampled from the varsity rowing team. The subjects had a mean age of 20.40 ± 2.60 years (females 20.28 ± 2.54 years, males 20.55 ± 2.82 years), a body mass of 78.56 ± 13.68 kg (females 77.19 ± 14.47 kg, males 80.40 ± 13.16 kg) and height 1.77 ± 0.08 m (females 1.74 ± 0.07 m, males 1.76 ± 0.9 m). Subjects had a strength training history of 3.57 ± 2.69 years (females 3.63 ± 2.89 years, males 3.5 ± 2.57

years). Subjects performed a total of 220 hex-bar jumps. All subjects volunteered for this study, gave their informed consent to partake in this study and ethical approval for the study was obtained from the University of Victoria's Human Research Ethics Board and complied with the principles outlined in the Declaration of Helsinki. Subjects were allowed to withdraw from the study at anytime.

4.3.3 Anthropometric Measures

Body mass was measured using two bilaterally mounted force plates (AMTI©, OR6-7, Watertown, USA) which were zeroed prior to the subject stepping onto the plates for the initial 28.55kg load (hex-bar (23.55kg) + 5kg). The average force during a quite standing period was selected, divided by $9.81 m \cdot s^{-2}$ to determine the subjects' body mass. Height was collected using a portable stadiometer (Seca® 213 Hamburg, Germany) using the International Society for the Advancement of Kinanthropometry (ISAK) stretch method. The vertical push off distance (h_{po}) was calculated using the difference between the moment of toe off (h_{to}) and the initial starting position (h_s) (see Figure 6). h_{to} and h_s were measured using a segmometer (Rosscraft Innovations, Vancouver, Canada). h_{to} was collected using a similar protocol to Giroux et al. (Giroux et al., 2015) and the starting position (h_s) was measured using the vertical distance between the anterior iliac crest and the ground in the initial starting position of the hex-bar jump.

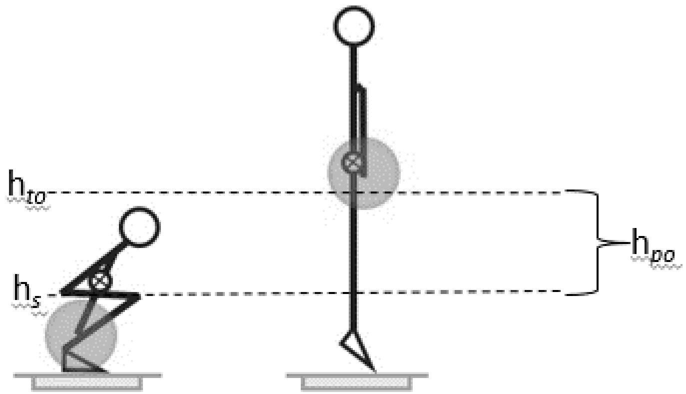

Figure 6. The key measurements needed to calculate h_{po} from the hex-bar jump.

4.3.4 Kinetic and Kinematic Measures

Subjects performed a ten-minute individual warm up prior to performing a standardized warm up of three jumps of increasing intensity at the initial 28.55 kg load. Hex-bar jumps were performed using a 23.55 kg hex-bar and Eleiko weightlifting plates (Halmstad, SWE). The testing consisted of 2 jumps starting at 28.55 kg and increasing by 10 kg increments to 78.55 kg, which is in line with the country's rowing National Team testing protocols. Subjects averaged four and a half minutes rest between loads. If the subjects' technique was compromised (flexion of the spine or valgus of the knees) or if they were unable to leave the ground the testing was stopped. Subjects were instructed to hold the hex-bar's low handles (0.23 m from the ground) and lifting straps were recommended to firmly fix the athletes to the hex-bar and minimize the risk of loss of grip. A 3 second pause was counted out loud by the tester at the start of the movement after which the subjects were directed to "explode from the ground as fast as possible."

The criterion kinetic and kinematic measures were collected using two force plates sampling at (1000Hz) and run through custom script written in LabVIEW 2015, National Instruments™ (Austin, Texas). The force plates were zeroed prior to each jump, system mass (subject mass and bar mass) was calculated using the quiet stationary period prior to the jump, the force was taken directly from the force plates, and the impulse-momentum method was used to calculate speed from the force plates with the stationary period prior to the jump used to begin the calculations. Power was calculated as the product of the force and speed time points.

The predictor kinetic and kinematic variables were calculated using Samozino et al.'s (2008) previously published three-factor computational model. The h_{po} was calculated using the method detailed in the anthropometric section, the system mass was the sum of the subject's body mass and bar mass taken from the force plate and the jump height was calculated using the flight time method using the time from takeoff to touch-down on the force plates.

4.3.5 Statistical Analysis

Two hundred and twenty jumps were collected, of which 14 jumps were excluded prior to analysis due to either subjects' technical failure or failure to follow the experimental protocol. Simple linear regressions were used to determine the linear relationship between calculated and measured metrics (force, power, and speed) in R (version 3.4.3, Vienna, Austria). The slope was tested against 1 (instead of 0 as in standard regression model) to show the deviation from identity. Coefficient of Determinations (R^2) were reported as a measure to evaluate the goodness-of-fit of the model. Alpha was set to 0.05. A Bland-Altman analysis was used to assess the level of agreement between the computational method and the criterion measures from the force plate. A range of agreement was defined as mean bias ± 2 SD with 95% of values within the limits. The limit of agreement for difference was defined a priori as 5% for takeoff speed, force and power.

4.4 Results

There were statistically significant coefficients of determination ($p < 0.05$) for force, speed and power (see Table 7). This shows that force ($SE = 5.41$, 95% confidence limit 1576.85 - 1598.19 N), speed ($SE = 1.25^{-5}$, 95% confidence limit 0.72 - 0.72 m·s^{-1}) and power ($SE = 3.90$, 95% confidence limit 1166.61 - 1181.97 W) can be accurately computed for a hex-bar jump using Samozino et al.'s three-factor computational model. The Bland-Altman plots showed less than 5% of the points outside of the limits of agreement (see Figures 7-9). The slope against identity (i.e. force-plate to calculated) for the regression is significantly different than 1 ($p < 0.05$) for force and power (see Figures 10 and 11).

Table 7. Comparison of Samozino et al.'s computational method and the force plate method

	Force plate method ($\bar{x}$)	Computational method ($\bar{x}$)	R^2	Slope	y-Intercept of Linear Regression Line
$\bar{F}$ (N)	1502.15	1587.52	0.92*	1.06**	-0.57
$\bar{v}$ (m·s^{-1})	0.73	0.73	1.00*	1.00	0
$\bar{P}$ (W)	1100.93	1174.29	0.99*	1.14**	-81.92**

Note. *$p < 0.05$ against 0, **$p < 0.05$ against 1.

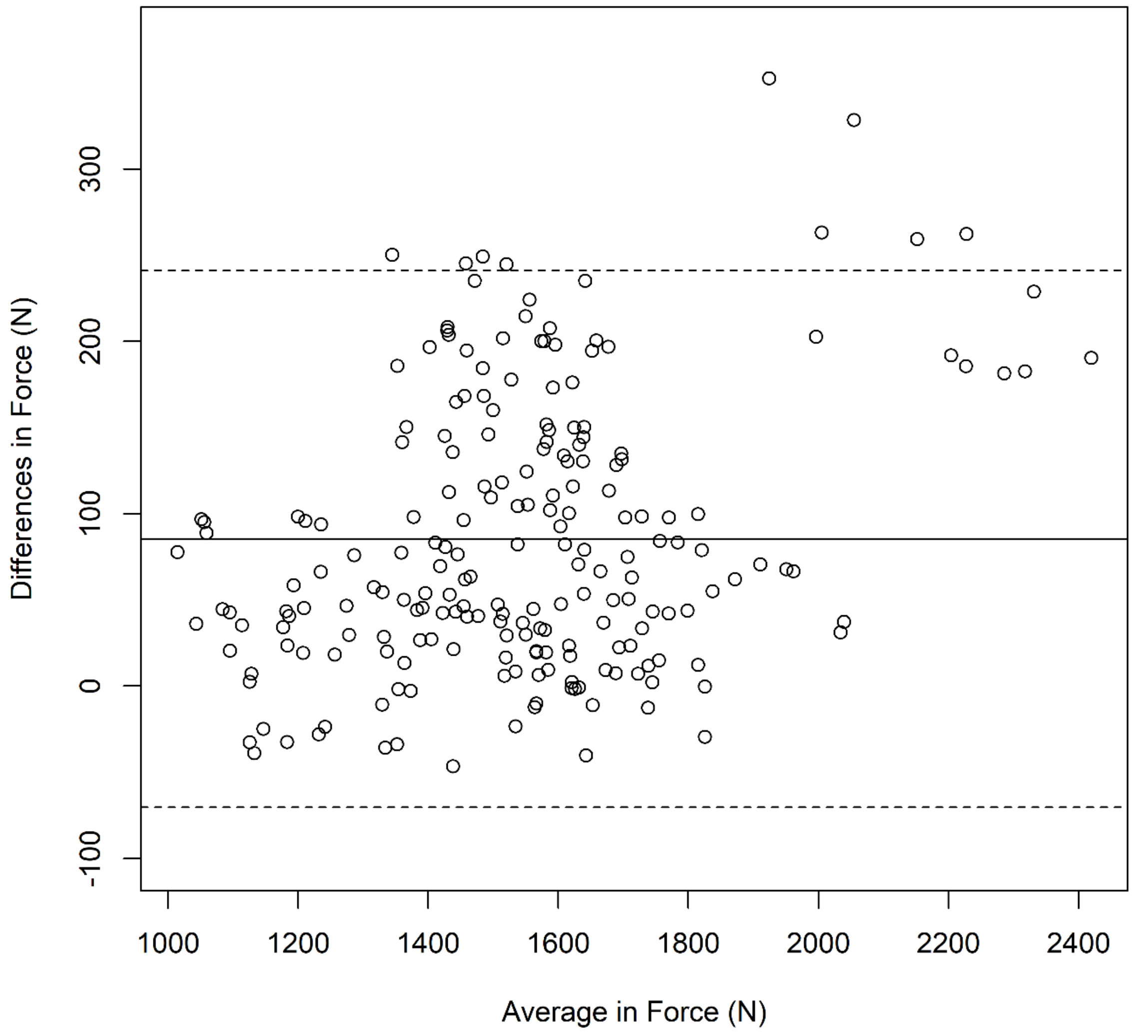

Figure 7. Bland-Altman Plot showing the mean difference and the limits of agreement for force. Solid line represents the mean bias. Dotted lines represent the upper and lower limits of agreement (mean ± 2 *SD*).

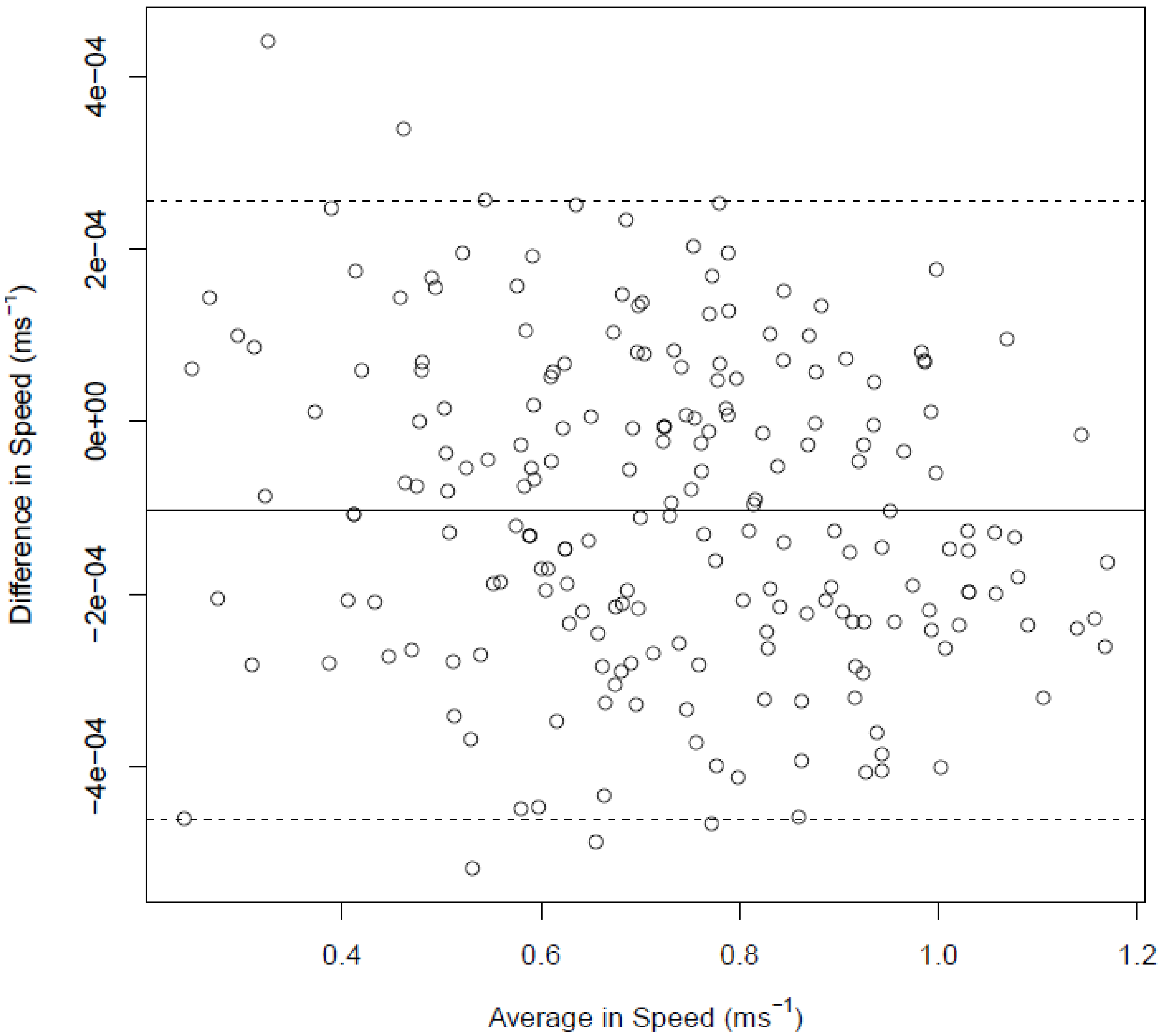

Figure 8. Bland-Altman Plot showing the mean difference and the limits of agreement for speed. Solid line represents the mean bias. Dotted lines represent the upper and lower limits of agreement (mean ± 2 *SD*).

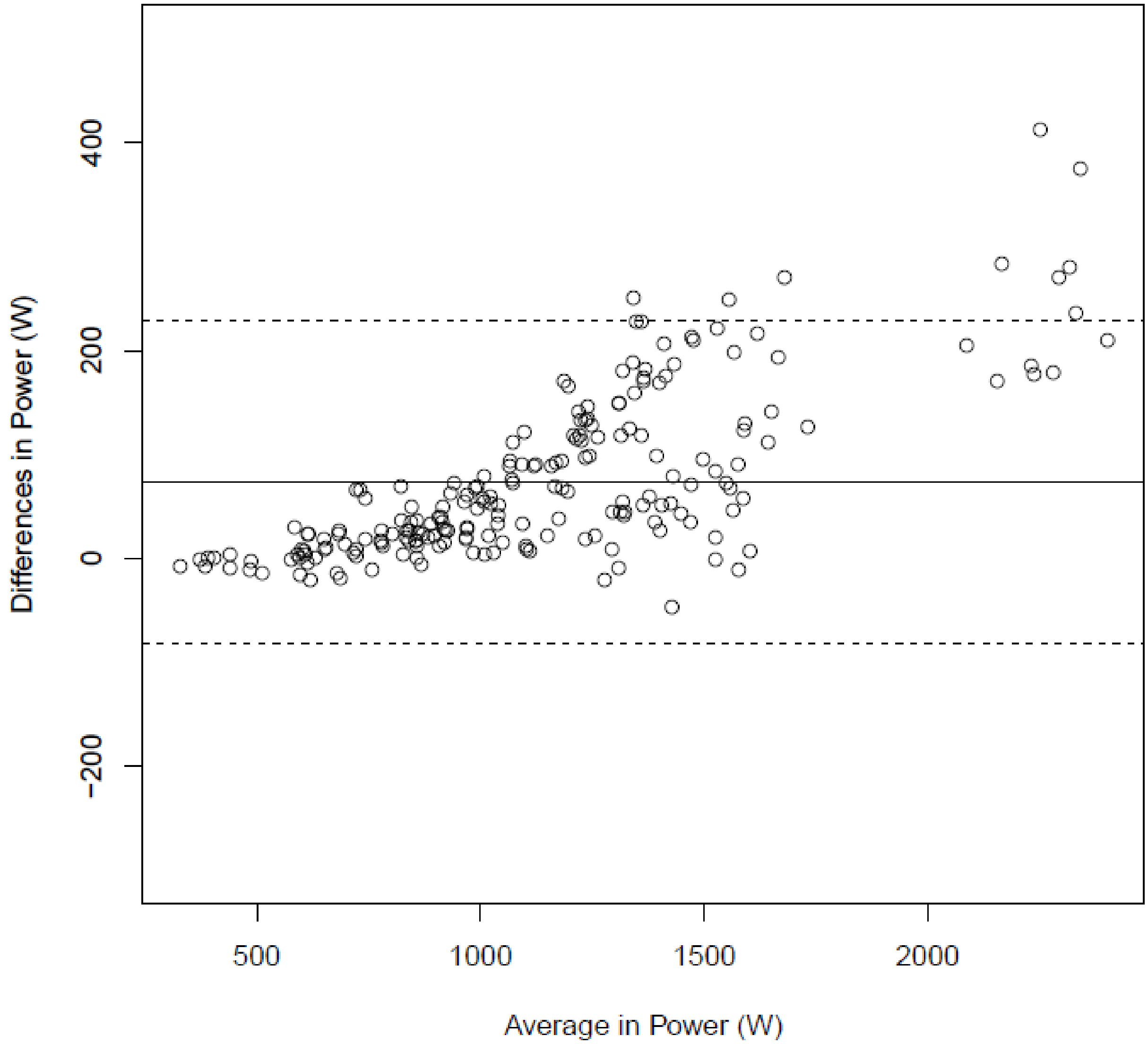

Figure 9. Bland-Altman Plot showing the mean difference and the limits of agreement for power. Solid line represents the mean bias. Dotted lines represent the upper and lower limits of agreement (mean ± 2 *SD*).

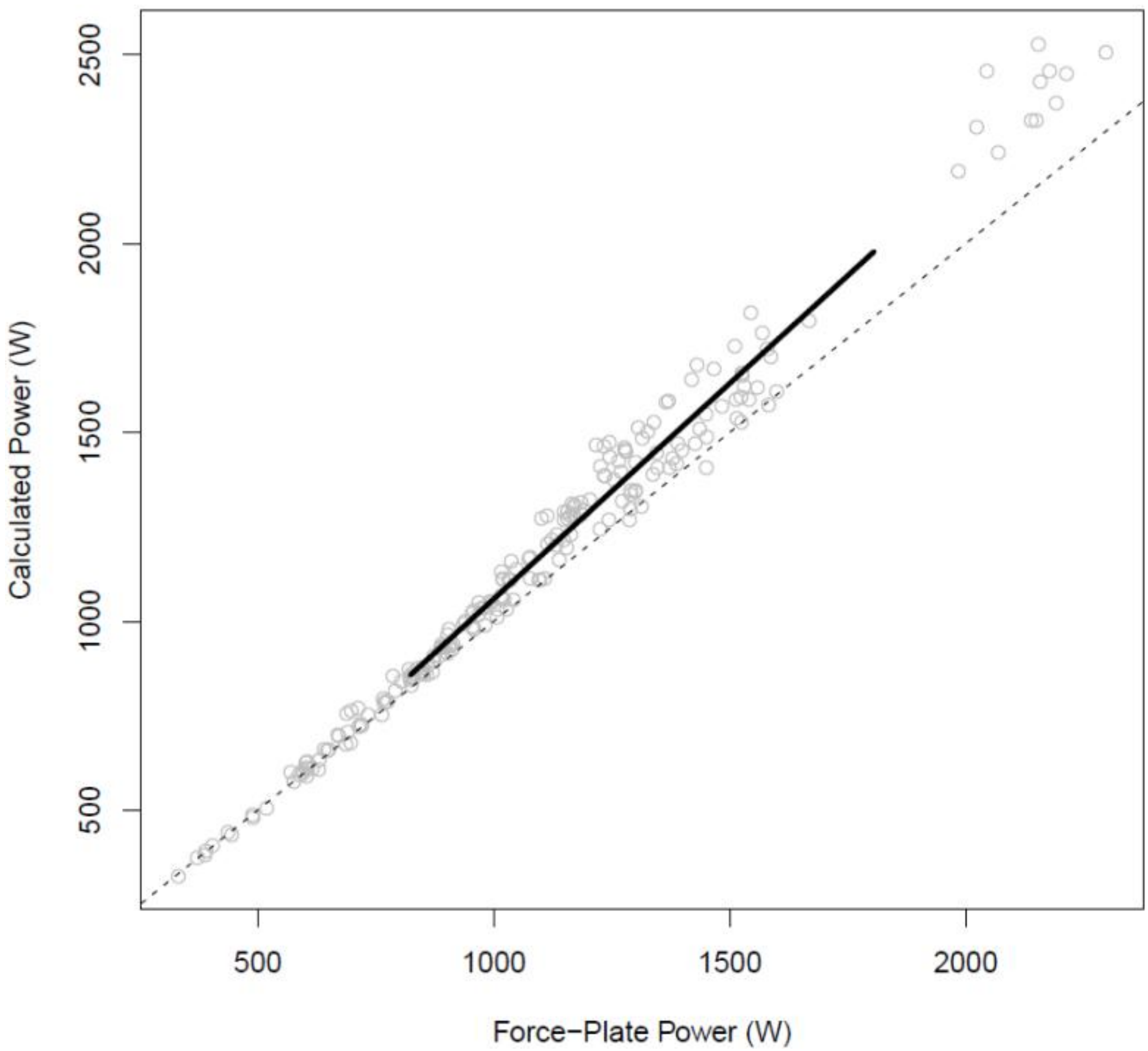

Figure 10. Regression plot of power during hex-bar jumps calculated using Samozino et al.'s Three-Factor Model and the criterion measure from the force plate. The dashed line represents the identity line (y = x) and the solid line represents the slope tested against 1, $p < 0.05$.

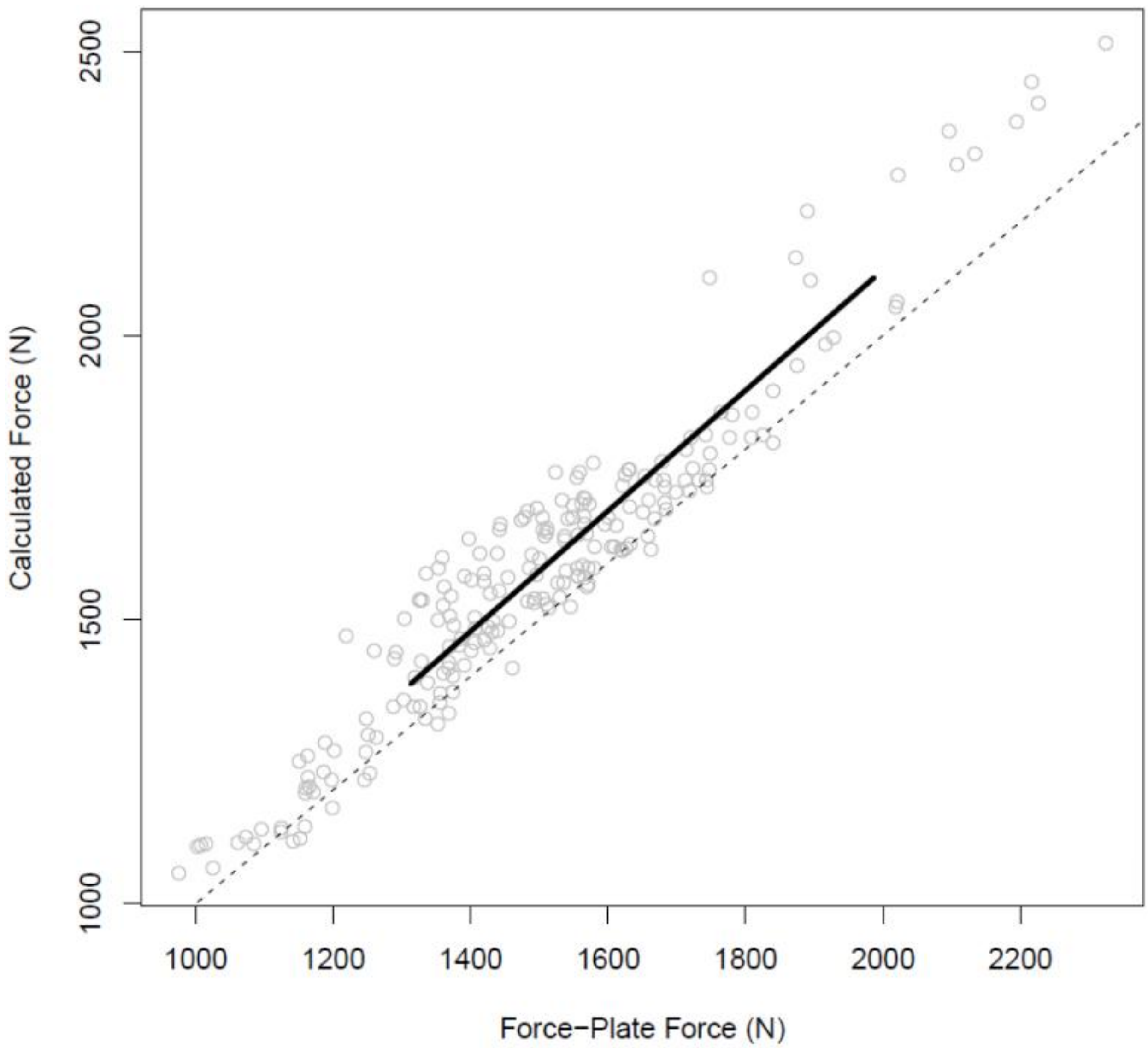

Figure 11. Regression plot of force during hex-bar jumps calculated using Samozino et al.'s Three-Factor Model and the criterion measure from the force plate. The dashed line represents the identity line (y = x) and the solid line represents the slope tested against 1, $p < 0.05$.

4.5 Discussion

A simple three-factor computational model utilizing h_{po}, body mass and jump height values collected from a hex-bar jump produces valid measures of force, speed and power. Both the coefficients of determination ($p < 0.05$) and the Bland-Altman Plots (less than 5% of points outside of the limits of agreement) show high agreement between the three-factor computational model and the criterion measures calculated from the force plate. This provides another lower body ballistic exercise that may be used besides the commonly used squat jump (Jiménez-Reyes et al., 2014; Samozino et al., 2008), to create force-speed profiles using the three-factor computational model. The hex-bar jump may be better suited to specific sports due to the position of the center of mass, posture and how the weight is manipulated. Further, subject may be able to utilize a more natural movement of the torso, as less rotational torque must be overcome compared to a barbell squat jump when the load is positioned on the shoulders (Swinton et al., 2012). This may make the hex-bar jump an ideal alternative when a squat or countermovement jump is contraindicated.

When compared to a hex-bar, a barbell positioned across the shoulders (barbell squat) or in front of the shins (barbell deadlift) may create a larger moment arm between the lifted mass and the hip joint which may increase shear force on the lumbar spine (Swinton et al., 2011, 2012). This could put athletes who already experience large loads on their lumbar spines (e.g. rowers) or previously injured athletes at an increased risk for back injuries (Swinton et al., 2011). Furthermore, a barbell positioned across the shoulders may be deemed less sport specific for athletes that need a low center of mass or engage in pulling actions. Further, a hex-bar jump may be a superior alternative to a straight barbell for loaded jump training interventions aimed at improving countermovement jump height (Weakley et al., 2018). This is due to the higher kinematic and kinetic markers athletes can exhibit utilizing the hex-bar when compared to a straight barbell jump (Swinton et al., 2012) and deadlift (Swinton et al., 2011).

The selection of the lower body ballistic exercise can have a significant impact on the kinetic and kinematic outputs. Jiménez-Reyes (Jiménez-Reyes et al., 2014) showed that a countermovement jump resulted in an increased force (theoretical force at zero speed) and speed (theoretical speed at zero force) values by 20.6% and 13.3% respectively when compared to a squat jump. This could impact interpretation of force speed profiles to guide training decisions (Jiménez-Reyes et al., 2019; Jiménez-Reyes, Samozino, Brughelli, et al., 2017). This is likely due to the greater uptake of muscle slack, higher muscle activation as well as storage and utilization of elastic energy (Van Hooren & Zolotarjova, 2017) during the countermovement resulting in higher take off velocities. Even a small amplitude countermovement jump can have significant effects on take off speed in elite athletes and visually is only identified correctly 61.6% of the time by a practitioner (J. M. Sheppard & Doyle, 2008). It is likely that a hex-bar jump would restrict the ability to engage in a small amplitude countermovement as the bar mass rests on the floor, minimizing the athletes' ability to dip. This could positively impact the reliability and validity of the metrics calculated from smartphone applications utilizing video and the flight time method and is an interesting avenue for future research.

It should be noted that there was no bias for speed ($0 \text{ m} \cdot \text{s}^{-1}$) however there were clear biases for force 85.38 N and power 73.36 W. This means that a practitioner must be aware that the three-factor computational model utilizing a hex-bar over predicts force and power (see Figures 7 and 9). As power is calculated from force, it is possible that this bias has a common origin. Swinton et al. (Swinton et al., 2012) utilizing a forward dynamics approach noted that hex-bar jumps resulted in higher force and power possibly due to the positioning of the load closer to the center of mass and the ability to move the load independently of the torso. It is possible that both the biases and the difference in the slope against identity (i.e. force-plate to calculated) could be due to the ability of the shoulder girdle and hex-bar load to move independently of the body's center of mass. As the upwards movement of the shoulder girdle in a hex-bar jump is probably impossible to eliminate, the inclusion of a "shrug" distance in the calculation of h_{po} could potentially increase the precision of the model. Interestingly, visual inspection of the Bland-Altman plot for power (Figures 9) shows that the majority of the points outside of the limits of agreement occur only at the higher power outputs, this may be due to the above point where a higher percentage of the system mass is comprised of the shoulder girdle + barbell unit in relation to the body; future research utilizing a more powerful and stronger population of subjects would be of interest to determine if points at higher power outputs and relative loads continue to fall outside the limits of agreement or if these points were due to chance.

Samozino et al's (2008) three factor computational utilizing a hex-bar jump has good agreement with the force-plate derived criterion measures. This provides a simple way for a practitioner to calculate kinetic and kinematic measures utilizing a ballistic lower body pulling action if jump height, push off distance and system mass are known. However, further investigation is needed to determine why the slope against identity for power and force is significantly different than 1 ($p < 0.05$) and to tighten the precision of the method at higher power. Furthermore, future work needs to determine if force, power and velocity derived in the field using a scale, tape measure, and smartphone or jump mat produces similar results.

4.6 Practical Application

A simple three-factor computational model utilizing values collected from a hex-bar jump validly allows the calculation of force, speed and power. This allows a practitioner in the field to easily calculate kinetic and kinematic measures with simple measures such as push off distance, jump height and system mass. Furthermore, this supports the use of a movement that may be more specific to sports requiring a low center of mass, a lower body pulling action, or when squat and countermovement jumps are contraindicated for the calculation of force-speed profiles utilizing the three-factor computational model.

5. Relationship between Vertical Force-Velocity Metrics and Sprinting Performance in Female Rugby Union Athletes[7]

5.1 Abstract

Sprinting ability is important across field sports and research in females is deficient; therefore, the aim of this study was to investigate the relationship between gym-based vertical force-velocity profile (v-FVP) metrics and 40 m time in female rugby athletes. Data from 50 athletes, mean (± SD) age 20.30 ± 2.02 years, weight 74.86 ± 12.10 kg, height 1.69 ± 0.05 m and 40 m time 6.15 ± 0.36 s were sampled. First, Pearson correlation coefficients were examined between 40 m time and v-FVP metrics and second, v-FVP variables were input into a linear mixed model to examine their effect on 40 m time, accounting for individual differences (random effects). There were significant correlations ($p < 0.01$) between 40 m time and several v-FVP metrics, leading to the inclusion of Maximal Mechanical Power (P_{max}, $W \cdot kg^{-1}$) and the Slope of the Force Velocity Relationship (S_{FV}, $N \cdot s \cdot m^{-1} \cdot kg^{-1}$) in the linear mixed model. The linear mixed model showed P_{max} ($\beta = -0.09$) and S_{FV} ($\beta = 0.02$) as significant predictors ($p < 0.01$) of 40 m time. The model explained a substantial proportion of the variance (conditional $R^2 = 0.93$), with fixed effects accounting for 46.79% of the variance. Correlations of the fixed effects indicated a strong negative relationship between P_{max} and baseline 40 m times, while S_{FV} showed a low positive correlation with baseline 40 m times. These results suggest that practitioners utilizing a v-FVP in their test battery should seek to improve and monitor changes in P_{max} and S_{FV} for the purposes of improving sprint performance over 40 m.

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[7] Agar-Newman, D. J., Tsai, M.-C., Phillips, K., Patterson, R., & Klimstra, M. Accepted for publication in the Journal of Strength and Conditioning Research November 19th, 2025

5.2 Introduction

Sprinting ability is an important performance factor in many field sports. In collision-based sports such as American football (Fry & Kraemer, 1991), rugby union (Smart et al., 2013) and rugby league (Gabbett et al., 2011a), sprinting ability has been shown to differ across both performance levels and positions. Due to the importance of sprinting ability across many sporting contexts, strength and conditioning coaches often seek to improve sprinting ability utilizing gym-based interventions. Therefore, it is important for practitioners to confirm the relationships between gym-based assessments of strength and sprinting ability.

Linear sprints can be broken up into different phases (Nagahara et al., 2014) which have unique kinetic determinants (Nagahara et al., 2018). Knowledge of the kinetic contributors to performance and their relationship to an observed phase or technique can assist practitioners in understanding the underlying factors constraining an athlete's speed. For example, when examining acceleration ability during a sprint, better sprinters produce greater net horizontal impulse (J.-B. Morin et al., 2015; Nagahara et al., 2018) and at top speed, sprinters produce greater relative vertical ground reaction forces earlier in the stance than non-sprinters (Clark & Weyand, 2014; Nagahara et al., 2018). To develop these propulsive forces, the musculature around the knee and hip (e.g. quadriceps, adductors, hamstrings and gluteus maximus) play a critical role (Wiemann & Tidow, 1995), with sprinters having greater thigh musculature and psoas major cross-sectional area than their untrained counterparts (Ema et al., 2018). Due to the important role that lower body musculature plays in sprinting, specific lower body strength training appears to positively impact aspects of sprinting performance (M. Barr et al., 2014; Keiner et al., 2014). For example, youth soccer players that engaged in strength training over a 2-year period displayed greater improvements in their change of direction performance than their untrained counterparts (Keiner et al., 2014).

Cross-sectional research has also identified associations between absolute and relative strength as demonstrated by clear relationships between back squat strength and sprinting performance over 5 m, 10 m, 20 m and 30 m (Comfort et al., 2014; Wisloff et al., 2004). In addition, vertical (Kale et al., 2009) and horizontal (Agar-Newman & Klimstra, 2015; Kleeberger et al., 2024) jumps are associated with sprinting ability and have been shown to contribute to predicting sprint time (e.g. 9.14 m, 9.14 – 18.29 m, 18.29 – 36.58 m and 36.58 m times) in contact sport athletes (Agar-Newman et al., 2024). It is important to highlight that associations between lower body exercises and sprint performance increase when expressing performance relative to body mass, such as relative strength and power (Baker & Nance, 1999). This is supported by research in rugby union that found large differences between fast and slow athletes in the power clean (kg · body mass^{-1}), a lift that requires relatively high levels of force to be applied with speed, and horizontal jumping ability (M. Barr et al., 2014). In addition, changes in relative strength in the power clean leads to improvements in specific kinematic factors such as stride length, which could be considered a positive adaptation for sprinting performance (M. Barr et al., 2014). Therefore, these findings support the use of lower body exercise assessments, with a focus on relative strength and power, to identify physical and neuromuscular constraints that can be used to guide training to improve sprint performance (Young, 1995).

One test that assesses an athlete's absolute and relative lower body force, velocity and power production is the squat jump (SJ) vertical force velocity profile (v-FVP). Although the force velocity relationship in single muscle fibers is not new (Hill, 1938), a new interpretation looking at performance in multijointed movements has increased the accessibility of profiling the lower body's force, velocity and power capabilities with Samozino et al.'s three factor computational model (Samozino et al., 2008). The three-factor computational model utilizes jump height, system mass and push-off distance to estimate an athletes' force, and power capabilities across varying velocities and can be performed using cost-effective technology such as a contact mat or video (Balsalobre-Fernández et al., 2015). It is suggested that the v-FVP could give an indication of the physical capabilities of the lower limb extensor musculature by allowing practitioners to examine the athletes theoretical maximal force at zero velocity (F_0), theoretical maximal velocity at zero force (V_0), relationship between F_0 and V_0 (slope of the force velocity relationship, S_{FV}) and maximal mechanical power (P_{max}) (J. B. Morin & Samozino, 2016). Further, when combined with other sprint-based tests, such as a horizontal force velocity profile (h-FVP), the v-FVP is suggested to potentially give an indication of the athlete's ability to transfer their assessed vertical physical capabilities to the specific task of sprinting (J. B. Morin & Samozino, 2016). However, in a cohort of male academy rugby league athletes, found no associations between P_{max} from the v-FVP and P_{max} from the h-FVP, as well as sprint time (Nicholson et al., 2021). This contrasts other studies utilizing elite female soccer players which have found significant associations between v-FVP metrics and 20 m sprint time (e.g. V_0, $r = 0.63$ and P_{max}, $r = 0.73$) and some metrics from the h-FVP (F_0, $r = 0.76$ V_0, $r = 0.80$ and P_{max}, $r = 0.99$) (Marcote-Pequeño et al., 2019). The lack of agreement in the research could be attributed to the different sexes, sports and levels of athletes used in the studies. In other words, the relationship between v-FVP metrics and sprint performance may be defined by the interactions of the specific sport, athlete sex and performance level and therefore extrapolating current v-FVP research findings from higher or lower-level athletes or highly homogenous groups should be undertaken with caution (Jiménez-Reyes et al., 2018). This lack of agreement in the research could also be attributed to differences in methods as some of the recent criticism around force velocity profiling has noted that the profiles created from various tests are task specific (Bobbert et al., 2023). As the usefulness of v-FVP to guide training recommendations is based on potential associations between v-FVP variables and sprint performance there is a need for more research into the relationship between v-FVP and sprinting performance within specialized cohorts. Further, some coaches may not be interested in conducting the horizontal force velocity profiles due time constraints or the recent criticism surrounding them (Ettema, 2023) and instead may be more interested in their athletes' sprint times directly and how they could potentially be impacted by manipulations in the v-FVP within a specific population of athletes.

Therefore, an important question is what v-FVP metrics impact sprinting performance as this would allow practitioners to target the development of specific attributes in the weight room setting. Unfortunately, there is a paucity of research in female athletes and no research investigating v-FVP in collegiate female rugby union athletes. Therefore, the purpose of this research was to determine the effect of v-FVP metrics on sprinting performance in female rugby union athletes. Relevant finding can be used to determine recommendations and limitations of using v-FVP to assess sprint ability in collegiate female rugby union athletes.

5.3 Methods

5.3.1 Approach to the Problem

To assess the ability of v-FVP variables to predict sprinting performance, a retrospective cohort study utilizing university level varsity female rugby athletes and regularly occurring pre- and post-season testing data was used. Athletes conducted a 40 m sprint test and a v-FVP using SJs was calculated using the three-factor computational model within the same week. As strength and power relative to body mass appears to be associated with sprinting performance, variables from a v-FVP expressed relative to body mass (e.g. F_0, N·kg^{-1}, P_{max}, W·kg^{-1} and S_{FV}, $F_0 \cdot BM^{-1} \cdot V_0^{-1}$) in addition to V_0 (m·s^{-1}) were the independent variables, Athlete (random effects) and 40 m time (dependent variable) were selected for the analysis. Part 1 of the analysis consisted of using a single testing date randomly selected from each athlete to investigate the associations between the independent and dependent variables using scatterplots and Pearson's correlations. Part 2 of the analysis consisted of determining the effect of the v-FVP variables on 40 m time using a linear mixed model while accounting for individual athlete variance.

5.3.2 Subjects

50 female, Tier 3 Highly Trained (McKay et al., 2021), collegiate rugby athletes, which included 4 athletes with international caps were sampled. To be included, athletes were required to be free of injury at the time of testing and have performed both a v-FVP with a goodness of fit ≥ 0.95 (Samozino et al., 2022) and 40 m sprint test within one week. The subjects had a mean (± *SD*) age 20.30 ± 2.02 years, weight 74.86 ± 12.10 kg, height 1.69 ± 0.05 m. The mean 40 m time of the subjects was 6.15 ± 0.36 s. Leading up to the testing, athletes were strength training two to three times per week (see Table 8 for sample program) and regularly incorporated bilateral jumps and sprints into their training regime. All subjects gave their informed consent to partake in this study and ethical approval for the study was obtained from the University of Victoria's Human Research Ethics Board and complied with the principles outlined in the Declaration of Helsinki. Subjects were allowed to withdraw from testing at any point.

Table 8. Subjects Typical Strength Session

Exercise	Sets	Reps
Plyometric Movement	2 -3	3-6
Clean Variation	5-6	3-5
Lower Body Push or Pull	5-6	3-7
Upper Body Push or Pull	5-6	3-7
Individual Supplemental Exercise 1	2-3	11-15
Individual Supplemental Exercise 2	2-3	11-15
Individual Supplemental Exercise 3*	2-3	11-15

Note: Year 2 and above athletes performed higher set ranges and lower rep ranges. * Year 2 athletes and above performed a 3rd Supplemental Exercise

5.3.3 Procedures

Testing was conducted during the pre-season and post-season period when rugby volume was minimal.

Anthropometrics. Body mass was measured using two bilaterally mounted force plates (AMTI©, OR6-7, Watertown, USA) prior to each jump. The plates were zeroed prior to the subject stepping onto them with the dowel or barbell and the average force during a quiet standing period was selected, divided by 9.81 $m{\cdot}s^{-2}$ to determine the system mass. The dowel or barbell mass was then subtracted from the system mass to determine body mass and the average measure across all jumps was taken for analysis. Height was collected between repetitions during the sprint testing using a portable stadiometer (Seca® 213 Hamburg, Germany) using the

International Society for the Advancement of Kinanthropometry stretch-stature method (Stewart et al., 2011).

Sprint Testing. The testing was part of a wider test battery conducted as the only session of the day, in the afternoon between 4:00 – 6:30 PM. The testing day consisted of a 20-minute warm up consisting of 10 minutes of general activity through multiple planes to elevate body temperature and a 10-minute specific warm up consisting of A-Skips, A-Runs, Straight Leg Runs and 3 sprints of increasing intensity.

The sprint assessment was conducted using Brower Timing TC-System (Utah). Subjects started with the middle of their front foot positioned 0.75 m behind the first set of timing gates with the first gate set to the height of 0.50 m to minimize the chance of false signals (hand or torso prematurely breaking the beam). The remainder of the gates were set to a height of 1.00 m at intervals of 5 m, 10 m, 20 m, 30 m and 40 m. Testing consisted of 2 x 40 m maximal sprints with approximately 5 minutes between sprints. The average 40 m time was taken for analysis; this protocol has shown an ICC of 0.98 (95% CI = 0.97 – 0.99) and TEM of 0.04 s in our laboratory.

Jump Testing. Jump testing was conducted within a week of the sprint testing around the athletes' class schedules between the hours of 10:00 AM - 4:00 PM as the first session of the day to minimize the influence of fatigue. Jump testing started with a general warm up consisting of 5-10 minutes of skips in multiple directions (forwards, backwards and sideways) to elevate muscle temperature and 5 minutes of dynamic mobility. Then a specific warm up consisting of 10 m low amplitude hops forward, 10 m low amplitude hops backwards and followed by three countermovement jumps with arms akimbo, three minutes rest, three countermovement jumps with arms akimbo. The warmup was completed approximately three minutes prior to commencing testing.

For all vertical jump testing the athletes were instructed “to jump as high as possible”. The testing started with three countermovement jumps with arms akimbo (used to answer another research question). This was followed by three SJs at four loads, beginning at 0.50 kg (doweling across the shoulders), progressing by 15 kg increments until 45 kg. Testing was terminated early if the athlete was unable to jump over 0.10 m or technical proficiency was compromised as assessed by a National Strength and Conditioning Association Certified Strength and Conditioning Specialist. Rogue KG Competition Plates (International Weightlifting Federation approved) and barbells (Rogue Fitness, Columbus, OH) were used for all loaded SJs. To standardize push off distance across the SJ attempts, the subjects squatted to a depth where their gluteal muscles lightly touched a rubber band positioned over the posterior edge of the force plate and 0.5 m above the ground. This depth equated to a knee angle of ≈ 90 degrees. This was done to eliminate any changes in push off distance between attempts or as the loads increased. Prior to initiating the propulsive phase of the jump, a three second pause was counted aloud by the tester and then the athletes were commanded to “jump”. A 10-15 second rest was given between jumps and three minutes rest was given between jump types or loads. All jumps were collected using AMTI (AMTI©, OR6-7, Watertown, USA) force plates sampling at 1000Hz, and data was processed using custom script written in LabVIEW 2015, National Instruments (Austin, Texas) software. As a countermovement has been shown to impact jump height (Agar-Newman et al., 2025; Harman et al., 1990) and v-FVP (Nishioka & Okada, 2022), the script identified any unweighting greater than 2.5% body mass prior to the propulsive phase as assessed by the force-time trace (i.e. countermovement) and these jumps were removed from the analysis. Jump height was then calculated using the impulse-momentum method (Linthorne, 2001). The average jump height was chosen for further analysis as it is more reliable than a single trial (Claudino et al., 2017). Test-retest reliability in our laboratory for SJ height demonstrated an ICC of 0.98 (95% CI = 0.93 – 1.00) and TEM of 0.02 m.

Force Velocity Profile. To increase the accessibility of this research to practitioners without access to force plates, the previously validated three-factor computational model was utilized (Samozino et al., 2008). For the sake of brevity, the three-factor computational model uses system mass of the athlete (athlete mass + external load), jump height and push-off distance (distance the center of mass travels from initiation of the jump to takeoff, h_{po}) to calculate the athletes' average force (N), average velocity ($m \cdot s^{-1}$), and average power (W) for each jump. Average force (N), average velocity ($m \cdot s^{-1}$), and average power (W) are then plotted against each other to calculate two key values: the y-intercept, which represents the theoretical maximal force an athlete can produce at zero velocity and the x-intercept, which indicates athlete's theoretical maximal velocity at zero force (V_0). Additionally, maximal mechanical power (P_{max}) is calculated as ½ theoretical maximal force multiplied by ½ V_0, and slope of the force velocity relationship is determined by multiplying the theoretical maximal force by V_0^{-1}. Due to previous research highlighting the importance of relative strength for sprinting performance (Baker & Nance, 1999; M. Barr et al., 2014), theoretical maximal force, maximal mechanical power and the slope of the force velocity relationship were normalized to body mass (F_0 = theoretical maximal force $\cdot$ BM^{-1}, P_{max} = maximal mechanical power $\cdot$ BM^{-1} and S_{FV} = theoretical maximum force $\cdot$ BM^{-1} $\cdot$ V_0^{-1}). As h_{po} has been shown to be a potential source of error in the three-factor computational model (Samozino et al., 2022), h_{po} was calculated using the athletes' average velocity over the propulsive phase (from the initiation of the movement to toe off) multiplied by the time to complete propulsive phase

(Nishioka & Okada, 2022). This method demonstrated an ICC 0.95 (95% CI = 0.94 - 0.96) and TEM of 0.01 m.

5.3.4 Statistical Analysis

First, a single testing date was randomly selected for each athlete and the associations between each independent variable from the v-FVP and the dependent variable 40 m time were analyzed using scatterplots and Pearson's correlations using JASP (v. 0.19.2, Amsterdam, Netherlands). Associations were interpreted using previously suggested descriptors (Mukaka, 2012) and alpha was set to 0.05. Second, to examine the effect of the v-FVP on 40 m time while accounting for individual athlete differences, redundant variables (moderately correlated independent variables [e.g. Relative F_0], $r > 0.5$, or independent variables with negligible correlations to the dependent variable[e.g. V_0]), $r < 0.3$) were removed from the analysis and the remainder of the variables were inputted into a linear mixed model using R (version 4.4.2, Vienna, Austria). The model was specified as follows:

$$40\ m\ Time = \beta_0 + \beta_1 \cdot P_{max} + \beta_2 \cdot S_{FV} + (1|Athlete\ ID) + \varepsilon$$

Where 40 m time is the dependent variable, P_{max} and S_{FV} are the fixed effects and athlete is the random effect, accounting for variability between individual athletes (independent variables). Epsilon (ε) is the error term. The results were then checked for normality using Q-Q Plots to check that the residuals fell on a straight line and plotting the residuals against the fitted data to ensure a random scatter of points ensuring that normality assumption were appropriate for 40 m time.

5.4 Results

The first part of the analysis determined that several of the variables were significantly correlated (p < 0.01) with 40 m time and that P_{max} and F_0 were also significantly correlated (p < 0.01), see Table 9. This left P_{max} and S_{FV} to be inputted into the linear mixed model.

Table 9. Pearson's correlations for 40 m Time and v-FVP Variables

Variable	40m Time (s)	P_{max} (W·kg^{-1})	F_0 (N·kg^{-1})	V_0 (m·s^{-1})	S_{FV} (N·s·m^{-1}·kg^{-1})
40m Time (s)	—				
P_{max} (W·kg^{-1})	-0.72**	—			
F_0 (N·kg^{-1})	-0.66**	0.65**	—		
V_0 (m·s^{-1})	0.02	0.33*	-0.49**	—	
S_{FV} (N·s·m^{-1}·kg^{-1})	0.43**	-0.26	-0.90**	0.80**	—

Note: Correlation coefficients: *p <0.05 and **p < 0.01

The second part of the analysis determined that the fixed effects of P_{max} (β = -0.09, SE = 0.01, t(99.34) = -9.28, p < 0.01) and S_{FV} (β = 0.02, SE = < 0.01, t(78.51) = -4.02, p < 0.01) were significant predictors of 40 m time. The equation modeling these effects was:

$$(1)\ 40\text{ m Time (s)} = 7.83 - P_{max} \cdot 0.09 + S_{FV} \cdot 0.02 + u_{\text{Athlete ID}} + \varepsilon$$

The linear mixed-effects model explained a substantial proportion of the variance in the 40 m sprint time (conditional R^2 = 0.93), with the fixed effects alone accounting for 46.79% of the variance (marginal R^2 = 0.47). This highlights the importance of both the fixed predictors and random effects (e.g., individual differences) in explaining the data. The random intercept for athlete had a variance of 0.06 (*SD* = 0.24) and had a residual error variance of 0.01 with a *SD* of 0.09. When investigating the correlations of the fixed effects in Table 10, it was determined that P_{max} has a very high negative correlation with the intercept, suggesting that athletes with higher P_{max} values have lower baseline 40 m times and that the S_{FV} had a low positive correlation to baseline 40 m times (Mukaka, 2012). Further there was negligible correlations between the fixed effects which does not suggest any issues with multicollinearity in the model. Normal Q-Q Plot were visually checked for linearity and residuals vs. fitted data were checked for random distribution about zero, constant variance and outliers, shown in Figure 12.

Table 10. Correlation of Fixed Effects

Variable	β0	P_{max} ($W \cdot kg^{-1}$)
P_{max} ($W \cdot kg^{-1}$)	-0.91	—
S_{FV} ($N \cdot s \cdot m^{-1} \cdot kg^{-1}$)	0.50	-0.15

Note. β0 = the intercept

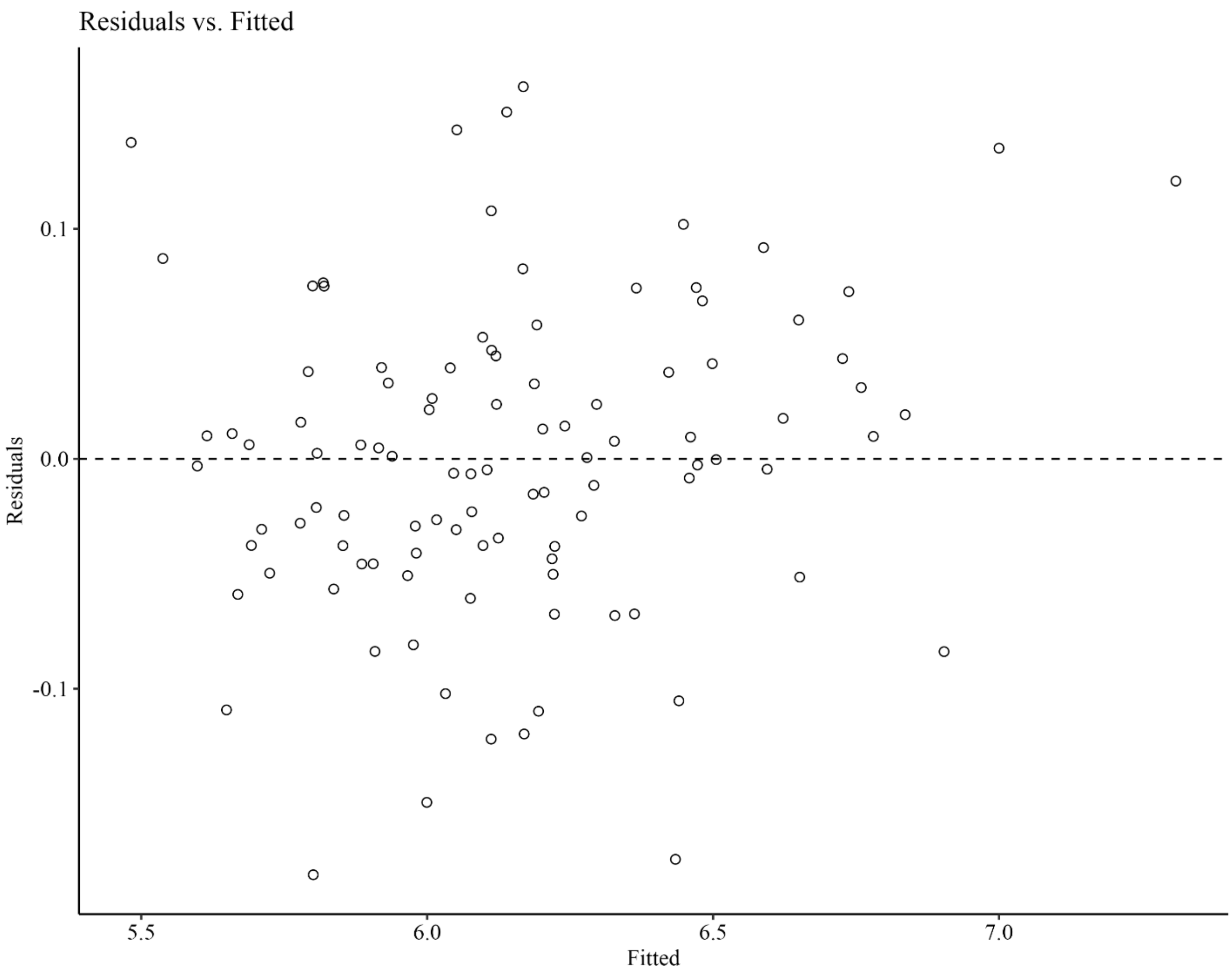

Figure 12. Residuals vs. fitted data

5.5 Discussion

From this investigation there are two main findings examining the relationships between v-FVP and 40m sprint time for a cohort of female collegiate rugby union athletes. First, when examining associations, it was observed that many v-FVP variables are correlated to each other and to 40 m time. Specifically, F_0 had a very high negative correlation with S_{FV} (r = -0.90) and a moderate positive correlation to P_{max} (r = 0.65). Further, 40 m time had a high negative correlation with P_{max} (r = -0.72), a moderate negative correlation with F_0 (r = -0.66) and low positive correlation with S_{FV} ($r = 0.43$). Overall, this first finding is not surprising as many variables of the v-FVP are correlated and have demonstrated associations with sprint performance. In the analysis of this specific cohort this result indicates that, with the consideration of all v-FVP variables, F_0 is redundant for use as a variable to include in a linear mixed model to predict 40 m time and that further analysis determining the effect of v-FVP variables on 40m sprint time should only include P_{max} and S_{FV}. The second finding of this study demonstrates that P_{max} ($\beta = -0.09$, $p < 0.01$) and S_{FV} ($\beta = 0.02$, $p < 0.01$) are both significant individual predictors of 40m sprint time with a combined (fixed effect) 46% variance explained. Further, when including individual effect (random effects) the complete model explains 93% of the variance in 40 m sprint time. Overall, these results highlight the importance of P_{max} and S_{FV} metrics from the v-FVP for the purposes of predicting sprint performance, in a cohort of collegiate female rugby union athletes, with individual athlete performance differences playing a critical role.

Further, there appears to be moderate to very high correlations between all metrics calculated from the three-factor computational factor model except for S_{FV} and P_{max}. The observed correlations are likely because the v-FVP metrics are calculated using the same input values (jump height, h_{po} and system mass) and therefore F_0 and V_0 are functions of each other and inversely related i.e. as V_0 increases, F_0 decreases. The lack of association between S_{FV} and P_{max} is likely due to the two variables representing distinct qualities of the athlete's lower limb performance in the squat jump across a spectrum of loads. Whereas P_{max} represents the maximal capacity of the lower limb to generate force across a spectrum of loads or velocities, the S_{FV} better describes how the lower limbs' ability to produce force is modulated by velocity. Similar to how F_0 and V_0 can be used together to define the entire v-FVP profile, P_{max} and S_{FV} can also be used together in this manner where P_{max} (and force and/or velocity at P_{max}) can be used as a bias and S_{FV} define the change from bias based on different levels of force or velocity. This finding is valuable not only for this cohort but may also support a useful approach for other cohorts when examining the relationships between v-FVP and sprint performance. These finding are important for practitioners for two reasons. First, if practitioners are using the v-FVP for the purposes of monitoring performance in athletes they may be able to reduce the number of metrics they are tracking by eliminating redundant variables. For example, the S_{FV} has a very high negative correlation with F_0 (r = -0.90) and high positive correlation with V_0 (r = 0.80) but only a negligible correlation with P_{max} (r = -0.26) therefore it may be possible to limit the number of variables that practitioners track to P_{max} and to one of F_0, V_0 or S_{FV}. Further, if practitioners are interested in the relationships between v-FVP metrics and performance tests such as 40 m sprint time, possible issues may arise with multicollinearity, making the model unstable and less reliable if all the v-FVP metrics are used.

To avoid potential issues with multicollinearity P_{max} and S_{FV} were used in the linear model over F_0. This decision was made as P_{max} and F_0 were moderately correlated, but P_{max} had a higher correlation with the dependent variable 40 m time. In addition, S_{FV} had a very large correlation with F_0 and low positive correlation to 40 m time. The linear mixed model showed that P_{max} and S_{FV} were significant predictors of 40 m time. Suggesting that for each 1 $W \cdot kg^{-1}$ improvement in power and change in the S_{FV} of -1 $N \cdot s \cdot m^{-1} \cdot kg^{-1}$ leads to a decrease in sprint time of 0.09 s and 0.02 s respectively. These findings align with previous research that showed low to moderate negative correlations between P_{max} (r = - 0.43 to -0.64) from a v-FVP and sprinting time over 5 m, 20 m and 10-20 m in multisport athletes (Junge et al., 2023). Like the current study which used loads between 0 - 45 kg, Junge et al. used similar loads (0 - 50 kg) (Junge et al., 2023). For practitioners, the current study suggests that to improve 40 m performance, training should be done to enable athletes to move loads fast and therefore improve power output across a spectrum of loads in the SJ. Specifically, a focus on heavier loads and therefore the lower velocity end of the force-velocity relationship in the squat jump is likely to bias the profile to be force dominant (Jiménez-Reyes et al., 2019) which could be a positive adaptation for 40 m performance. If training with these heavier loads includes a high intent to move the loads fast, positive adaptation such as increased motor unit recruitment and rate coding enhancements will likely occur (Behm et al., 2024) which could be considered positive adaptations for sprinting over 40 m.

Another interesting finding was that the linear mixed-effects model explained a substantial proportion of the variance in the 40 m sprint time (conditional R^2 = 0.93), with the fixed effects alone accounting for 46.79% of the variance (marginal R^2 = 0.47). The difference between the conditional and marginal R^2 values suggests that other factors outside of the v-FVP metrics may be at play such as initial sprint performance or training background of the athletes. This aligns with research showing that initial sprint speed needs to be accounted for when predicting sprinting ability from jumping tests (Kleeberger et al., 2024). Another interpretation could be improvements in other variables not measured in this study such as ability to utilize the stretch shortening cycle or technical improvements over the training period may contribute to the changes in sprinting performance.

When examining the correlations of fixed effects there is a very high negative correlation between the intercept and P_{max} suggesting athletes with higher P_{max} have lower 40 m times. This is consistent with cross-sectional studies showing that faster athletes have higher power outputs ($W \cdot kg^{-1}$) in 40 kg barbell jumps (Hori et al., 2008) and perform better in power cleans normalized to body mass, an exercise requiring high levels of force and speed, compared to slower athletes (M. Barr et al., 2014). Further, the low positive correlation between the intercept and S_{FV} may suggest that slower athletes have a more velocity biased profile. When interpreted alongside the findings of faster athletes having higher P_{max} values, this suggests that an emphasis should be placed on developing high levels of force at the higher loads (i.e. lower velocities), to shift the profile to be force biased. This aligns with research that showed high positive correlations with sprinting velocity between 10 to 50 m and the load at which athletes achieved their maximum power (Loturco, D'Angelo, et al., 2015), with faster athletes achieving more power at heavier weights. Finally, the negligible correlation between P_{max} and S_{FV} suggests no issues with multicollinearity.

This study is not without its limitations. First, this study used a cohort of collegiate level female rugby athletes consistently training, and caution should be taken when applying these results to other levels of athletes or sports with different training backgrounds. It is also worth noting that the v-FVP profile utilized a SJ, and the force velocity relationship cannot be generalized to different tasks such as v-FVPs constructed with a countermovement jump (Bobbert et al., 2023). Therefore, different findings may occur if using tasks such as a countermovement jump which will likely result in different S_{FV} values due to changes in F_0 and V_0 (Jiménez-Reyes et al., 2014; Nishioka & Okada, 2022), possibly due to an athlete's ability to utilize the stretch shortening cycle. Further, it is worth noting there is criticisms geared around training to achieve an optimal force-velocity profile for vertical jumps (Bobbert et al., 2024). This study does not suggest that athletes should be trying to achieve some "optimal" profile, but rather faster athletes have higher P_{max} and lower S_{FV}. Therefore, practitioners could likely use this knowledge to improve an athlete's ability to apply force at speed, especially at heavier loads for the purposes of improving 40 m performance. However, a training study would need to be conducted to confirm this. Finally, of interest for practitioners working in contact sports, future research should investigate the ability of v-FVP to predict sprint momentum using similar methods to this study as associations with F_0 and momentum have been found in male academy rugby league players (Nicholson et al., 2021).

5.6 Practical Applications

The findings of this study are useful for practitioners seeking to streamline their gym-based assessments for the purpose of improving 40 m sprinting ability. Specifically, this study suggests that P_{max} and S_{FV} from a v-FVP are the most important predictors of 40 m time, while F_0 is redundant. These findings highlight the importance of producing force across a spectrum of loads with a particular emphasis on developing force and speed at higher loads to bias the S_{FV} to be more force dominant. Further, interindividual differences account for a large proportion of the variance in predicting sprint time suggesting that other factors besides v-FVP metrics are influencing sprint performance. This could suggest that practitioners may want to include tests that assess other physical qualities in their testing batteries.

6. Predicting Sprint Performance from the Vertical and Horizontal Jumps in NFL Combine Athletes[8]

6.1 Abstract

Identifying fast athletes is an important part of the National Football League (NFL) Combine. However, not all athletes partake in the 36.58 m sprint and relying on this single test may miss potentially fast athletes. Therefore, the purpose of this study was to determine if sprinting times can be predicted utilizing simple anthropometric and jumping measures.

Data from the NFL Combine between the years 1999-2020 inclusive was utilized (n = 4,149). Subjects had a mean (± *SD*) height = 1.87 ± 0.07 m and body mass = 111.96 ± 20.78 kg. The cross-validation technique was used, partitioning the data into a training set (n = 2,071) to develop regression models to predict time over the 9.14 m, 9.14 - 18.29 m, 18.29 - 36.58 m segments and 36.58 m utilizing vertical jump (VJ), broad jump (BJ), height and mass as the independent variables. The models were then evaluated against a test set (n = 2,070) for agreement.

Statistically significant ($p < 0.01$) models were determined for 9.14 m time (Adjusted R^2 = 0.76, SEE = 0.05 s), 9.14 - 18.29 m time (Adjusted R^2 = 0.74, SEE = 0.04 s), 18.29 – 36.59 m time (Adjusted R^2 = 0.79, SEE = 0.07 s) and 36.58 m time (Adjusted R^2 = 0.84, SEE = 0.12 s). When evaluated against the test set, the models showed biases of -0.05 s, -0.04 s, -0.02 s and -0.02 s and root-mean-square error of 0.07 s, 0.05 s, 0.07 s and 0.12 s for the 9.14 m, 9.14 – 18.29 m, 18.29 - 36.58 m segments and 36.58 m, respectively. However, 5-6% of the predictions lay outside of the limits of agreement.

[8] Agar-Newman, D. J., Macrae, F., Tsai, M. C., & Klimstra, M. (2024). Predicting Sprint Performance from the Vertical and Horizontal Jumps in National Football League Combine Athletes. Journal of Strength and Conditioning Research, 38(8), 1433–1439. https://doi.org/10.1519/JSC.0000000000004799

This study provides four formulae that can be used to predict sprint performance when the 36.58 m sprint test is not performed, and practitioners can utilize these equations to determine training areas of opportunity when working with athletes preparing for the NFL Combine.

6.2 Introduction

Strength, power, and speed are of paramount importance to success in American football. However, the physiological demands vary across positions with sprinting speed and vertical jump (VJ) particularly important for wide receivers (WR), running backs (RB), and defensive backs (DB) (Edwards et al., 2018; Hoffman, 2008; Wellman et al., 2017). Players in these positions cover the most ground, spend the most time sprinting, and spend more time in the air than players of other positions (Edwards et al., 2018; Hoffman, 2008; Wellman et al., 2017). In addition, acceleration ability may be important for linemen that must perform repeated short sprints on each play. For players of these positions, acceleration ability may be more important than top speed ability. Therefore, coaches, scouts and media devote significant attention to a prospective player's sprint performance in the National Football League (NFL) Draft Combine.

The NFL Combine is a test battery designed to inform athlete selection. The Combine tests consist of the 36.58 m (40-yard) sprint with split times at 9.14 m (10-yard) and 18.29 m (20 yard), a 102.27kg (225 lb) maximum repetition bench press, vertical jump, standing broad jump, pro-agility shuttle test, and a 3-cone drill. Approximately 300 of the top draft prospects are invited each year to participate. While teams base draft selection primarily on competitive playing performance, NFL Combine results are a supplementary factor in the decision-making process (Hartman, 2011). This stems from predictive links between Combine performance tests and NFL athlete success in some positions; for example, sprint performance in the RB position is a valid predictor of an athlete's success in the NFL (Kuzmits & Adams, 2008). Therefore, many players spend significant time and resources in the off-season to prepare for the NFL Combine to increase their draft stock. Understanding the relationships between the various NFL Combine tests would better allow practitioners in preparing athletes by identifying potential training areas of opportunity.

In addition, understanding the relationships between the NFL Combine tests may aid teams in estimating sprint performance for those who do not perform a 36.58 m test. Further, there is also the possibility that measurement limitations may mask an athlete's potential sprinting performance. For instance, the 36.58 m timer is begun with a hand-trigger start from a three-point position in the NFL Combine which makes comparisons to sprints that include reaction time or other starting procedures (e.g., two-point start) difficult (T. Haugen & Buchheit, 2016). In addition, some athletes may have the physical capacity to achieve fast sprint times but may be limited by improper or inefficient technique, whereas simple jump tests (i.e., vertical, or horizontal jumps) are likely less limited by technical ability. Therefore, understanding the relationship between jumping performance and sprinting performance could potentially assist teams to make more educated decisions on draft day.

Several studies have examined the associations and relationships between jumping ability and sprint performance in a variety of sports; however, these studies often involve soccer or rugby athletes (Agar-Newman & Klimstra, 2015; Gunaydin, 2019; Köklü et al., 2015; Loturco et al., 2020; Merino-Munoz et al., 2021). Moderate correlations between vertical jump performance, change of direction without the ball, and sprint performance have been observed in male and female soccer players (Köklü et al., 2015; Merino-Munoz et al., 2021). Unfortunately, most studies that claim to investigate the relationship between jumping performance and sprinting ability in

NFL Draft eligible players only show the associations between variables (Robbins, 2012a) and not the relationship, which shows how a change in an independent variable will potentially impact a dependent variable. One of the few studies to report relationships between NFL Combine measures only used data from the 2003 and 2008 combines, was published as an abstract (Fairchild et al., 2011) and is likely out of date. As sprinting performance is likely important for certain NFL positions, the purpose of the present study is to determine if sprinting times can be predicted utilizing simple anthropometric and jumping measures in NFL Draft eligible players. Based on the previous literature, we hypothesized that sprinting time can be computed from vertical jump (VJ), broad jump (BJ) and simple anthropometric measures. Therefore, the null hypothesis (Ho) was: there will be no relationship between sprinting time and predicted sprinting time and our alternative hypothesis (Ha) was: there will be a relationship between sprinting time and predicted sprinting time.

6.3 Methods

6.3.1 Approach to the Problem

To determine if sprinting time can be predicted from jumping metrics and simple anthropometric measures, publicly available NFL Combine testing data were retrieved from http://draftscout.com/. The cross-validation technique was utilized, with the data partitioned into a training set to develop a multiple linear regression model to predict sprint time with vertical jump (VJ), broad jump (BJ) and basic anthropometric measures (height and mass) as the independent variables and sprint time over the 9.14 m, 9.14 -18.29 m, 18.29 - 36.58 m segments and 36.58 m as the dependent variables. The linear models developed were then used with the test set data to assess the agreement of the calculated times to the actual times.

6.3.2 Subjects

Data utilized for this study included players who partook in the NFL Combine between the years 1999-2020 inclusive. Data were collected from http://draftscout.com/ and has been utilized in other studies investigating combine performance and deemed accurate (Robbins, 2012b, 2012a). Data for 7,171 subjects were downloaded, and the study was limited to the subjects who had complete records for the 36.58 m sprint, height, body mass, VJ test and BJ test, $n = 4{,}141$. Subjects had a mean (± *SD*) height = 1.87 ± 0.07 m and body mass = 111.96 ± 20.78 kg, further descriptive statistics can be found in Table 11. In accordance with the Tri-Council Policy Statement on Ethical Conduct for Research Involving Humans (TCPS 2), human research ethics board approval was unnecessary due to the retrospective nature of the study, the availability of the information in the public domain and the anonymous nature of the results.

Table 11. Descriptive statistics for NFL Combine Athletes

	Mean (± *SD*)
Height (m)	1.87 ± 0.07
Mass (kg)	111.96 ± 20.78
VJ (m)	0.83 ± 0.11
BJ (m)	2.88 ± 0.24
9.14 m Time (s)	1.68 ± 0.11
18.28 - 36.58 m Time (s)	2.02 ± 0.15
36.58 m Time (s)	4.82 ± 0.31

Note. Data for all subjects ($n = 4141$)

6.3.3 Procedures

The procedures for collecting data at the NFL Combine have previously been published (Robbins, 2012a). For brevity purposes the following NFL combine tests were utilized for the analysis:

Vertical Jump. Subject stand with their dominant side against the Vertec and extend their arm upwards as far as possible. The Vertec is set with the bottom vane either 0.46 m or 0.61 m above the subjects' outstretched arm. With both feet firmly planted to the ground the subjects may utilize a countermovement and arm-swing, jumping as high as possible attempting to reach the highest vane on the Vertec from the floor. Any shuffling of the feet prior to takeoff results in a failed attempt and the jump did not count. After the first jump the subject then resets their feet and has a second attempt to touch a higher vane. The distance from the subjects' outstretched hand at the start of the movement to the highest vane touched of the two attempts is taken as their jump height and measured in 0.01 m increments.

Broad Jump. Subjects start with their toes behind the start line. Utilizing a countermovement and arm swing subjects jump as far as possible in the horizontal direction. Subjects then must land balanced with both feet planted, although falling forward is allowed; however, falling backwards disqualifies the jump. Jump distance is measured from the start line to the heel of the nearest foot to the start line. Jumps are measured to the nearest 0.03 m increment. Subjects receive two attempts, and the farther jump recorded is taken for analysis.

36.58 m Sprint. Timing gates are placed at the 9.14 m, 18.29 m, and 36.58 m marks. The subject holds a 3-point stance for 2 seconds and receives the command "you can go" from the tester. The subject then runs 36.58 m as fast as possible. The timer is started when the subject's down-hand separates from the turf. After running 36.58 m the subject jogs back to the starting area and takes approximately 10-15 minutes before commencing their second attempt. Rolling starts are not allowed.

6.3.4 Statistical Analysis

Data from 7174 athletes were downloaded and incomplete sets of data (missing any independent or dependent variables) were excluded from the analysis resulting in 4,141 complete sets of data. The analysis consisted of three parts. First, the data was randomized by position and testing date and divided into a training set (n = 2,071) and test set (n = 2,070) utilizing Microsoft Excel (Version 2209, Redmond, Washington). Second, backwards stepwise multiple regressions were conducted to determine the relationship between 9.14 m time, 9.14 – 18.29 m time, 18.29 – 36.58 m time, 36.58 m time and the jumping and anthropometric measures using the training set of data (IBM SPSS Statistics, Version 27.0.1.0, Armonk, NY) and alpha was set to 0.05. Finally, Bland and Altman plots were used to assess the level of agreement between measured sprinting times and calculated sprinting times using the test set of data. A range of agreement was defined as mean bias ± 2 *SD* with 95% of values within the limits (Giavarina, 2015). The limit of agreement of difference was defined *a priori* as 5% of sprinting time, which is clinically acceptable. The goodness of model fit was assessed using root-mean-square error.

6.4 Results

When predicting 9.14 m time there were significant standardized coefficients for mass (β = 0.50), VJ (β = -0.09) and BJ (β = -0.37). For 9.14 – 18.29 m time there were significant standardized coefficients for height (β = 0.06), mass (β = 0.48), VJ (β = -0.11), and BJ (β = -0.31). There were also significant standardized coefficients for 18.29 – 36.58 m time for mass (β = 0.53), VJ (β = -0.10) and BJ (β = -0.34). All previously noted coefficients were significant at the $p < 0.01$ level. For 36.58 m time there were significant standardized coefficients for height (β = 0.03, $p = 0.01$), mass (β = 0.52), VJ (β = -0.10), and BJ (β = -0.36) with mass, VJ and BJ significant at the $p < 0.01$ level. The equations for predicting 9.14 m time (1), 9.14 – 18.29 m time (2), 18.29 – 36.58 m time (3) and 36.58 m time (4) are presented below:

$$9.14\ m\ time = 1.941 + 0.003 \cdot mass - 0.90 \cdot VJ - 0.164 \cdot BJ \quad (1)$$

$$9.14 - 18.29\ m\ time = 1.15 + 0.06 \cdot height + 0.002 \cdot mass - 0.073 \cdot VJ - 0.093 \cdot BJ \quad (2)$$

$$18.29 - 36.58\ m\ time = 2.249 + 0.004 \cdot mass - 0.188 \cdot VJ - 0.231 \cdot BJ \quad (3)$$

$$36.58\ m\ time = 5.284 + 0.148 \cdot height + 0.008 \cdot mass - 0.300 \cdot VJ - 0.471 \cdot BJ \quad (4)$$

The Adjusted R^2 and *SEE* for Equation 1 was 0.76 and 0.05 s, for Equation 2 was 0.74 and 0.04 s for Equation 3 was 0.79 and 0.07 s and for Equation 4 was 0.84 and 0.12 s, respectively. These equations were used to estimate 9.14 m, 9.14 – 18.29 m, 18.29 – 36.58 m and 36.58 m times utilizing the test set of data (Figures 13 - 16). The goodness of the model fit was assessed in Figures 17 - 20 showed biases of -0.05 s, -0.04s, -0.02 s and -0.02 s and a root-mean-square error of 0.07 s, 0.05s, 0.07 s and 0.12 s respectively. However, 5.75% of observations in the 9.14 m sprint, 5.46% of observations for the 9.14 – 18.29 m sprint, 5.65% of observations in the 18.29 -36.58 m sprint, and 5.02% of observations in the 36.58 m sprint fell outside the limits of agreement.

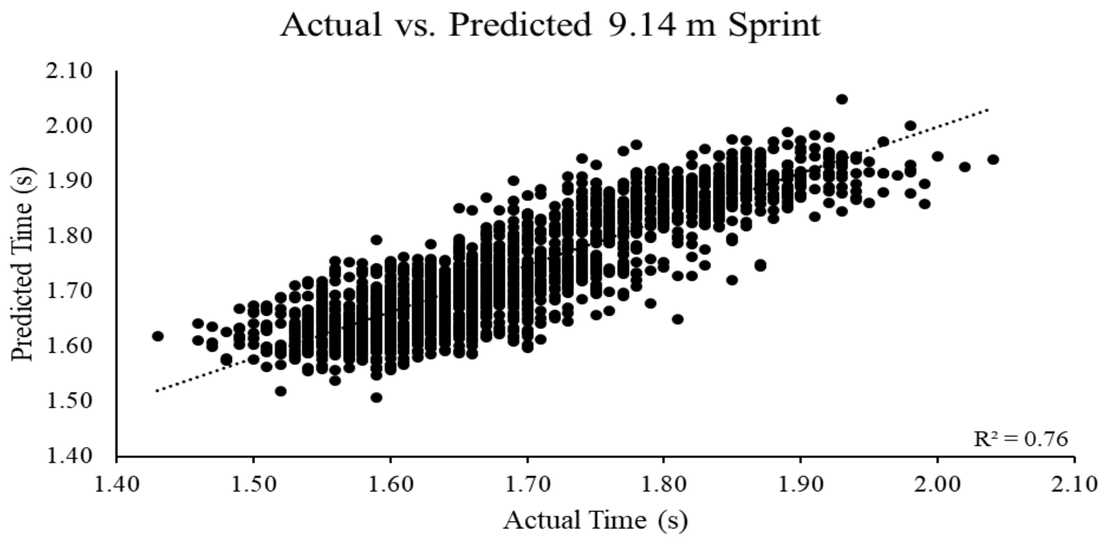

Figure 13. Predicted sprint times utilizing jumping measures and basic anthropometrics utilizing Equation 1.

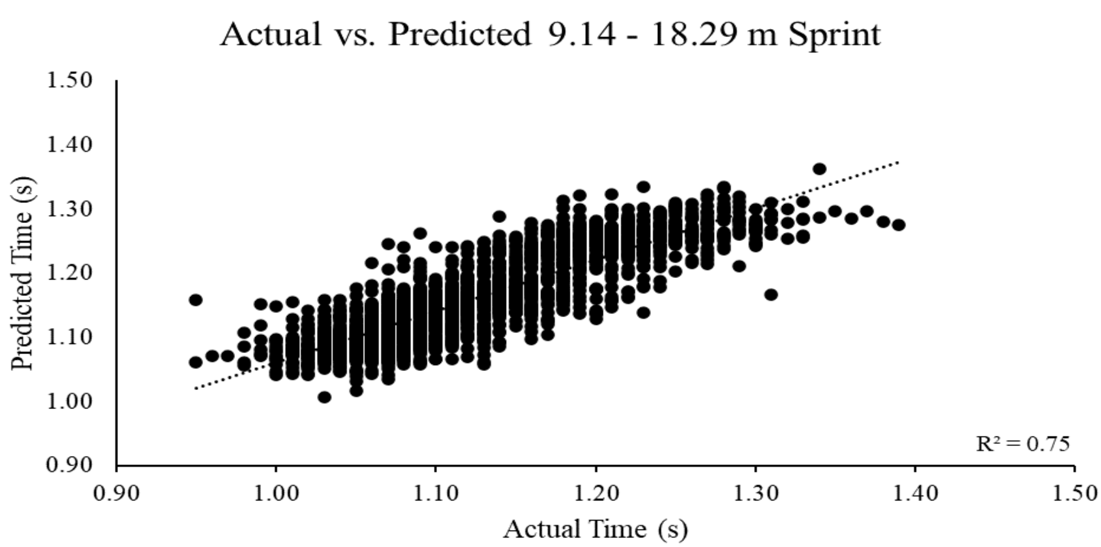

Figure 14. Predicted sprint times utilizing jumping measures and basic anthropometrics utilizing Equation 2.

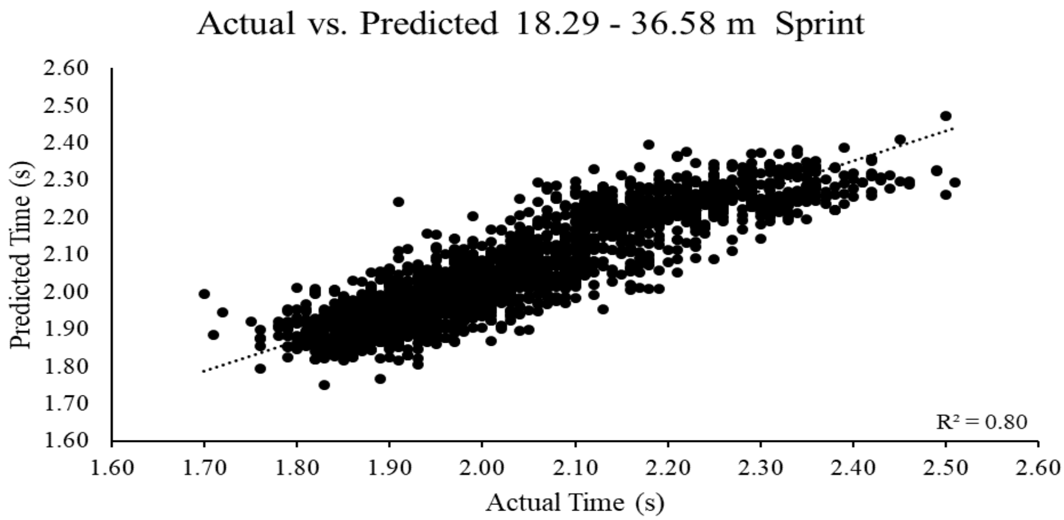

Figure 15. Predicted sprint times utilizing jumping measures and basic anthropometrics utilizing Equation 3.

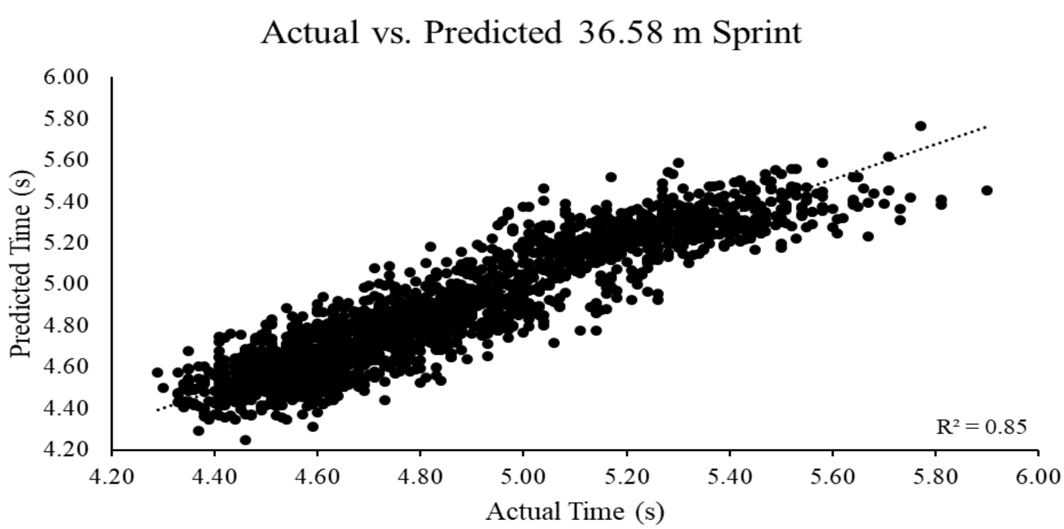

Figure 16. Predicted sprint times utilizing jumping measures and basic anthropometrics utilizing Equation 4.

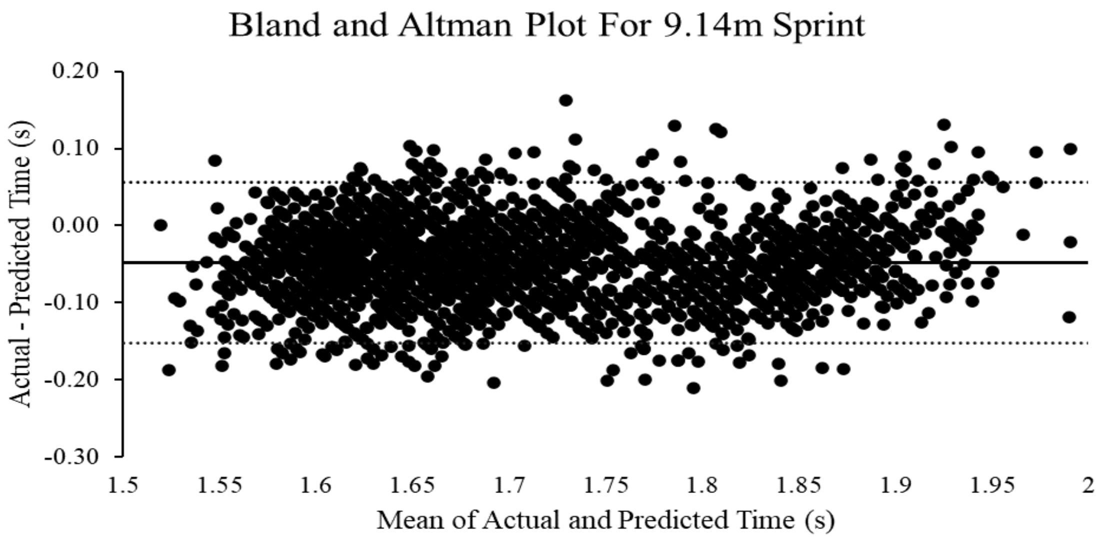

Figure 17. Bland and Altman plot showing the bias (solid line) and limits of agreement (dashed lines) for Equation 1.

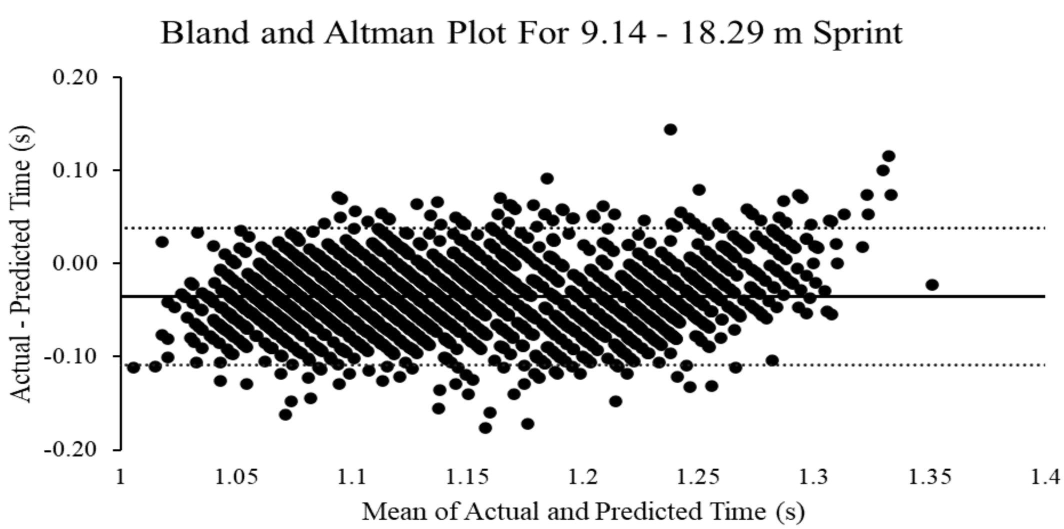

Figure 18. Bland and Altman plot showing the bias (solid line) and limits of agreement (dashed lines) for Equation 2.

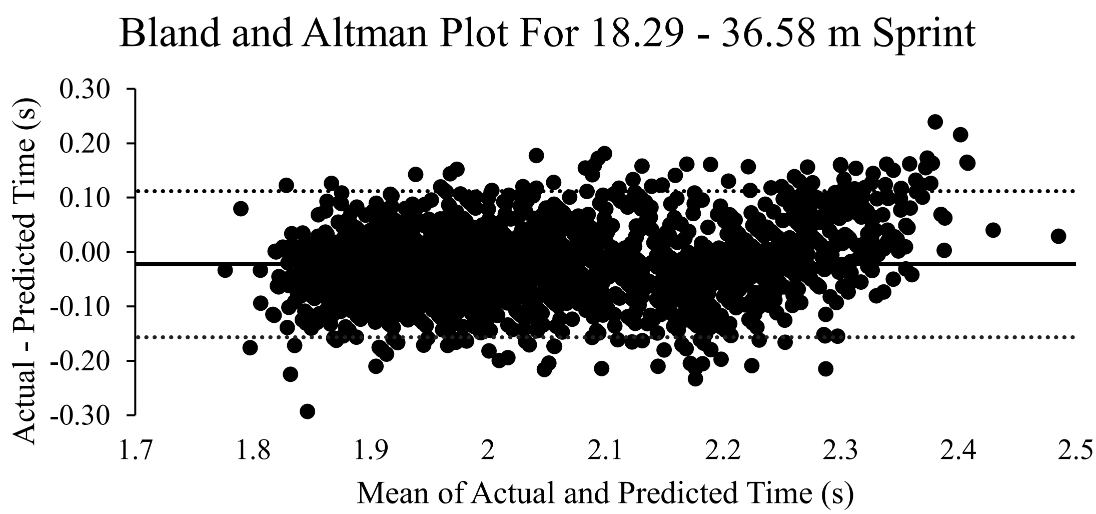

Figure 19. Bland and Altman plot showing the bias (solid line) and limits of agreement (dashed lines) for Equation 3.

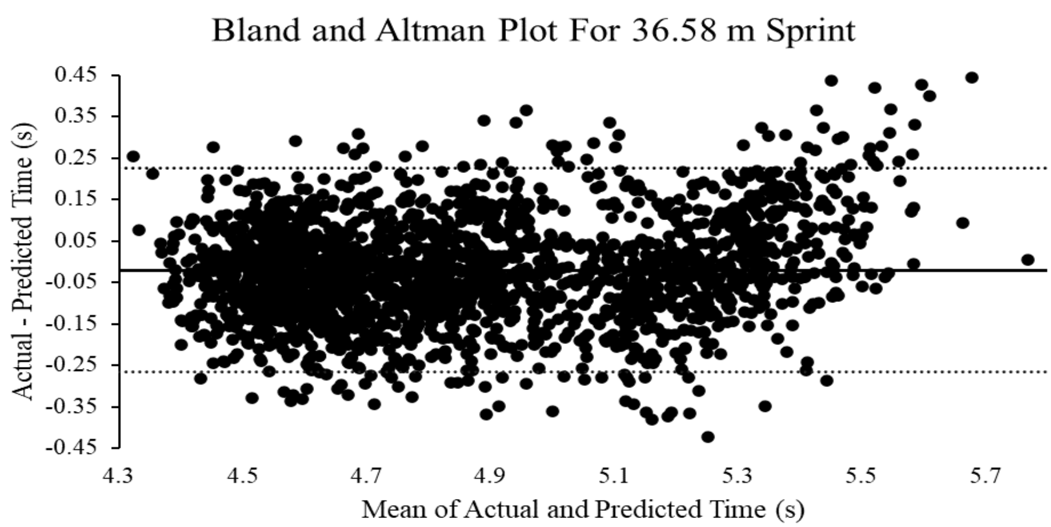

Figure 20. Bland and Altman plot showing the bias (solid line) and limits of agreement (dashed lines) for Equation 4.

6.5 Discussion

This study revealed that there is a relationship between sprint time for 9.14 m, 9.14 -18.29 m, 18.29 - 36.58 m, and 36.58 m sprints and predicted sprint time from VJ, BJ, and basic anthropometrical measurements in elite American Football players. The proposed formulae provide coaches with tools to predict sprint performance from incomplete sets of combine data. Further, these formulae provide coaches with tools to compare an athlete's actual sprint performance against the theoretical time, possibly revealing technical deficiencies or areas of opportunity for training. In addition, the unstandardized beta values in these formulae can be used to show how an improvement in a specific component (i.e., independent variable) will impact sprint time. However, coaches should be cautious with the precision of these models as >5% of the data fell outside of the limits of agreement.

Little research has been conducted to establish predictive validity between the different tests in NFL Combine athletes. A similar analysis to this study was conducted in 2011, however, they only included data from the 2003 and 2008 combines, resulting in a much smaller sample size (n = 443) and failed to test the accuracy of the model (Fairchild et al., 2011). The present study utilized a larger sample (n = 4,141) and a regression analysis aimed to establish predictive validity of BJ, VJ, height and mass for 9.14 m, 9.14 – 18.29 m, 18.29 m – 36.58 m and 36.58 m sprint times. In addition, the present study tests the agreement of the modelled time against the actual time utilizing a test set of data. This study elaborates on the findings from existing literature and goes further to provide equations for the calculation of sprint time from jumping metrics and tests the accuracy of the prediction.

The literature supports our findings that VJ, BJ, height and body mass are closely related to sprint performance in athletes (Fairchild et al., 2011; Köklü et al., 2015; López-Segovia et al., 2011; Merino-Munoz et al., 2021). As expected, increased mass results in slower sprint times in this population of athletes. However, an interesting finding was that increased height also resulted in slower sprint times for the 9.14 -18.29 m segment and 36.58 m sprint. Although increased height likely has a positive impact on sprinting performance through larger contact lengths allowing taller athletes a greater distance/time to produce force, taller athletes in this population are likely increasing their body mass disproportionately, offsetting the advantage the increased contact length provides to maximize their momentum into collisions (26). The relationship between VJ, BJ and sprint time may be due to the importance of the producing mass specific force in the horizontal direction during acceleration, like the broad jump, and vertical mass specific force during maximal velocity, like the vertical jump. Interestingly, the standardized coefficients for the BJ were larger than the VJ for all sprint distances. This difference can possibly be attributed to the fact that the force vector during a BJ has both a vertical and horizontal component like sprinting (7). This means that BJ performance is not only dependent on the athlete's ability to produce mass specific vertical forces which determines flight time during the jump but also the athlete's ability to produce large horizontal forces, which determines their horizontal velocity at take off (7). Possibly a stronger argument supporting the relationship between jumping and sprinting ability is due to both tasks requiring similar underlying physical qualities such as high levels of thigh muscle cross sectional area, optimal body composition and a high percentage of II fibers (Hopwood et al., 2023; Methenitis et al., 2016). In addition, an optimal level of mobility in the hips and ankles likely impacts the landing position of the athlete during the BJ which could be an important factor to sprinting performance, but further research would need to confirm this.

These equations provide coaches with a tool to assess an athlete's sprinting ability against their predicted sprinting ability via jump performance and anthropometrics. As with all predictive equations there is inherently some error, therefore coaches should view the difference between the predicted and actual time as an item that warrants further investigation, with larger differences (outside of the root-mean-square error) warranting greater attention. This allows coaches to identify potential areas of opportunity. For example, if the athlete is running faster than their predicted time coaches may look to examine the athlete's underlying physical constraints (i.e., force expression etc.) and if the athlete is running slower than their predicted time coaches may want to examine the athlete's technical constraints (i.e., direction and timing of force application in the sprint etc.). Some examples of technical aspects which coaches may want to examine include, the position of the center of mass during the stance phase since elite sprinters have greater horizontal orientation of the centre of mass during the initiation of the sprint, allowing them to better direct force in the horizontal direction when compared to well-trained sprinters in a 10 m sprint (Slawinski et al., 2010). Some examples of physical aspects include the absolute and relative cross-sectional area of the psoas major and gluteus maximus muscles, with sprinters having larger areas when compared to non-sprinters (Tottori et al., 2021) and have likely carried out more resistance training (Slawinski et al., 2010). Furthermore, inadequate development of specific musculature may lead to poor performance in the sprinting assessment. Also, the specific muscles required for a vertical jump and broad jump differ, with the vertical jump relying more heavily on muscles about the knee compared to the broad jump (Robertson & Fleming, 1987), and the broad jump requiring the athletes to transition rapidly from a powerful hip extension for takeoff to flexion for the landing and flexibility requirements around the hips and ankles to maximize the landing. Potential imbalances in VJ, BJ, and sprint could possibly indicate a relative area of opportunity in one of these aforementioned areas. As such, it may be prudent to explore the underlying causes of the variation in performance in the NFL Combine movements as a potential explanation for a poor performance in one area. It is plausible that this could again be due to a technical deficiency. Furthermore, the unstandardized beta values in the equations could be used to estimate how much an improvement in a specific component will impact the sprint time. This would be done by multiplying the beta value by the athlete's current value and then doing the same with an improved value and comparing the difference which would signify the potential improvement in seconds.

Although, this study has provided four equations that can be used to predict sprint performance from the predictors with high accuracy there are several limitations. First, the protocols utilized in the NFL Combine are not perfect as the sprint test timer is started with a hand-trigger and a three-point start. Although this may increase the face validity for linemen who start in a three-point stance it reduces the validity of this test for skilled players and potentially the reliability of the test (T. A. Haugen et al., 2012). Furthermore, the VJ and BJ tests both allow for the athlete to perform a countermovement and allows the upper body to contribute to the force production through utilizing an arm swing. Although this possibly makes the VJ and BJ a more global test of upper and lower body force production, coordination and more ecologically valid, these tests fail to isolate the lower body's force producing abilities (e.g., jumping tasks performed akimbo) which may be of interest to practitioners. In addition, the calculation of vertical jump height utilizing a Vertec likely inflates jump height compared to calculation methods utilizing force plates utilizing the impulse momentum method (Ferreira et al., 2010). This is due to the athlete's ability to gain extra height through elevating the reaching arm's shoulder and dropping the opposing shoulder despite the center of mass not travelling higher and discrepancies with how standing reach is measured which may impact the ability to generalize these equations to vertical jump height measured from force plates (Ferreira et al., 2010). Finally, this data set comprises athletes with high levels of performance across the tests utilized, although practitioners should feel confident interpolating results within the range of times utilized in this study, caution should be used when extrapolating the results to populations outside of these performance levels. Therefore, further research should be conducted to validate these equations with more general populations.

6.6 Practical Applications

This study provides four formulae that can be used to predict sprint performance using height, body mass, VJ, and BJ. This will allow practitioners to predict sprint time with incomplete sets of data and to identify athletes that may have possibly underperformed or overperformed in the 36.58 m sprint. Therefore, not every slow or fast athlete is equivalent and those with superior jumping skill may still be draft candidates. Furthermore, practitioners can use these equations when performing a needs analysis to identify an athlete's strengths and weaknesses to improve sprinting performance.

7. Conclusion

7.1 Dissertation: Summary

The assessment and prediction of athletic performance is essential in research and sports science. The following series of studies were designed to address practical challenges faced by a practitioner working with large groups of athletes, with a limited budget and under time constraints. Accordingly, these studies systematically investigated the relationship between jumping performance and athletic tasks, with the aim of improving the accuracy and applicability of athletic assessments ranging from lab to field-based tests. Each study built upon the findings of the previous research, progressing from lab-based assessments to field-based application, and demonstrated how advancements in technology and methodology can enhance athletic evaluation. Collectively, these studies aimed to provide simpler, cost and time efficient approaches to athlete assessment, while illustrating how practitioners can use accessible methods to inform their practice.

In Chapter 2, a prevalent issue in SJ assessments was addressed, where identifying an unweighting phase before the upward propulsive phase is often subjective. Chapter 2 determined a quantitative threshold of unweighting amplitude by categorized SJs based on the amplitude of unweighting relative to bodyweight and conducting an Analysis of Covariance with jump height as the dependent variable and external load as the covariate. The study found a significant difference in jump height across unweighting groups ($F(5,930) = 13.65$, $p < 0.01$). The results indicated that above a threshold of 2% BW for unweighting amplitude jump height was significantly increased compared to the < 1% BW threshold. This is important for practitioners as it provides a standardized threshold for ensuring the validity of SJ assessments and reduces the subjectivity of previous studies utilizing the squat jump. This threshold not only aids in accurate assessment but also paves the way for the automation of detecting valid SJs.

Chapter 3, focused on enhancing the practicality of performance assessments in a field setting. The chapter explored how other jumping metrics can be reliably measured utilizing portable and cost-effective equipment. This study established the predictive validity of utilizing the peak-speed measurements from a LPT to estimate takeoff speed in hex-bar jumps. Peak-speed data was collected from a LPT and compared to the criterion measure (takeoff speed) obtained from force plates. The study demonstrated a high association between peak-speed and takeoff speed ($r = 0.99$, $p < 0.05$), with a mean difference of only 0.18%, indicating minimal bias. Bland-Altman plot analysis further confirmed that there was no systematic bias in the prediction. This finding is significant because it shows that LPTs, which are more portable and less costly than force plates, can accurately estimate takeoff speed. This capability is crucial for field-based assessments where the availability of "gold standard' equipment may be limited due to logistical or financial reasons.

Chapter 4 built on Chapter 3 by introducing a computational model to calculate average force, velocity, and power from hex-bar jumps. While Chapter 3 validated the use of LPTs to calculate takeoff speed, Chapter 4 extended this by validating a three-factor computational model that utilizes takeoff speed in conjunction with hex-bar jumps to derive comprehensive v-FVP. The findings confirmed that the three-factor computational model utilizing a hex-bar jump accurately computes average force, average velocity, and average power with mean biases for force, velocity, and power being 85.38 N, 0.00 $m \cdot s^{-1}$, and 73.36 W, respectively. These findings are important as they demonstrate that a novel exercise can be used in conjunction with a simple computational model to replace expensive force plate measurements. This offers a cost-effective and field-applicable solution for assessing key performance metrics. The ability to calculate these metrics using the hex-bar jump is particularly advantageous for sports where traditional jump tests may be less specific or feasible.

Chapter 5 followed Chapter 4 by focusing on applying the three-factor computational model to sport specific contexts. While Chapter 4 demonstrated the feasibility of a computational model for deriving performance metrics, Chapter 5 applies these insights and explored the relationship between v-FVP metrics and 40 m sprint times in female university rugby athletes. This was done utilizing Pearson correlation coefficients to examine the associations between 40 m time and v-FVP metrics, and a linear mixed model was used to analyze the effect of v-FVP variables on 40 m time, while accounting for individual differences. Significant correlations ($p < 0.01$) were found between 40 m time and several v-FVP metrics. Maximal Mechanical Power (P_{max}, $W \cdot kg^{-1}$) and the Slope of the Force-Velocity Relationship (S_{FV}, $N \cdot s \cdot m^{-1} \cdot kg^{-1}$) were significant predictors of 40 m time in the linear mixed model ($p < 0.01$). The model explained 93% of the variance, with fixed effects accounting for 46.79% of the variance and the remaining variance explained by the random effects (i.e. individual effects). P_{max} showed a strong negative relationship with 40 m time, while S_{FV} had a low positive correlation. This chapter suggests that practitioners should focus on improving and monitoring P_{max} and S_{FV} to enhance sprint performance over 40 m. The study's application of v-FVP metrics offers a refined approach to enhancing sprinting speed by focusing on individual v-FVP metrics, thus bridging the gap between lab-based measurements and sport-specific training applications.

Chapter 6 culminated this series of studies by utilizing even simpler jumping tests, addressing a practical challenges many practitioners face, an inability to utilize lab-based methods. While the previous studies focused on improving measurement techniques and predictive models, Chapter 6 extends these concepts to a large dataset from the NFL Combine to develop predictive models for sprint performance utilizing simple jumping tasks. The study developed regression models to predict sprint times for different segments of the 36.58 m sprint based on vertical jump, broad jump, height, and mass. The models demonstrated accuracy with statistically significant predictions for segmental and overall sprint times; however, caution should be taken due to the precision of the models. Chapter 6's findings are significant because it provides an alternative method for predicting sprint performance when direct testing utilizing lab-based measures is not possible, thus offering practical solutions for evaluating and training athletes.

Collectively, this series of studies collectively advances the field of athletic performance assessment by progressing from the establishment of standardized testing thresholds to the development of portable and practical measurement solutions. Each study builds on the previous one, transitioning from lab-based validations to field-applicable techniques and demonstrating how these advancements can be utilized across various sports contexts.

In summary, this dissertation:

1. Established a quantitative threshold for unweighting that can be utilized for monitoring SJ performance, ensuring the validity of SJs.

2. Determined that peak speed from a LPT can be utilized to calculate takeoff speed, allowing peak speed to be inputted into a three-factor computational model. This allows the use of a linear position transducer which is time efficient to calculate jump height.

3. Confirmed that the three-factor computational model can be used with a hex-bar jump to accurately computes force, velocity, and power allowing practitioners to use of an

alternative exercise to a squat jump in environments where a squat jump may not be less specific or feasible (i.e. injury).

4. Determined that metrics from the v-FVP (P_{max} [W·kg^{-1}] and S_{FV} [N·s·m^{-1}·kg^{-1}]) are significant predictors of 40 m time. This allows practitioners to be targeted in the assessment of athletes for the purposes of improving 40 m time.

5. Determined that sprint times for different segments of the 36.58 m sprint can be predicted from simple jump tests (VJ and BJ) and anthropometrics (height, and weight) and presented four formulae that can be used to predict sprint performance using height, body mass, VJ, and BJ, allowing practitioners to predict sprint time with incomplete sets of data and to identify athletes that may have possibly underperformed or overperformed in the 36.58 m sprint.

7.2 Dissertation: Practical Applications

The preceding series of studies has several practical applications to practitioners working in the field of athletic development:

1. Chapter 2 established that unweighting amplitude >2% of BW led to increased jump heights. Therefore, it is recommended that a threshold for amplitude of unweighting of 2% BW is utilized by practitioners interested in SJ performance. This means that SJs with an unweighting >2% BW should be excluded from analysis due to the impact the unweighting period can have upon jump height. The adoption of a threshold of 2% BW will remove subjectivity from the analysis process and allow practitioners to utilize a

standardized, research supported threshold in algorithms to automatically detect valid SJs. The adoption of this threshold will not only speed up data collection through removing subjectivity but standardize the data collection process.

2. In Chapter 3 it was determined takeoff speed calculated using the impulse-momentum method from force plates can be predicted using peak speed from a LPT during hex-bar jumps. This allows a quicker way to assess jump height where equipment portability (e.g. travelling with teams on the road) and time (e.g. team settings) may be a limiting factor. As an extension, this equation may allow a quicker way to assess mean velocity, power and force using Samozino et al's (2008) three factor model.
3. Another interesting finding of Chapter 3 for practitioners to be aware of when using a LPT, is there is a possibility that precision may be compromised at lower speeds and heavier loads. This possible discrepancy could be due to the inverse relationship between sampling rate and movement speed present in the LPT used in this research. Another possibility for the values outside of the 95% limits of agreement at the slower speeds is due to changes in movement strategy as the load increases. Nonetheless, it is important that practitioners are aware of possible strengths and weaknesses when using different technologies and movements to measure athletic performance.
4. Chapter 4 showed that a simple three-factor computational model utilizing values collected from a hex-bar jump validly allows the calculation of force, velocity and power. This allows a practitioner in the field to easily calculate kinetic and kinematic measures with simple measures such as push off distance, jump height and system mass. Furthermore, this supports the use of a movement that may be more specific to sports requiring a low center of mass, a lower body pulling action, or when squat and

countermovement jumps are contraindicated for the calculation of force-velocity profiles utilizing the three-factor computational model, providing practitioners with options besides the commonly used SJ and CMJ for the purposes of constructing v-FVP.

5. In Chapter 5 it was found that P_{max} and S_{FV}, normalized to body mass from a v-FVP are the most important predictors of 40 m time, while F_0 is redundant. The findings of this study are useful for practitioners seeking to streamline their gym-based assessments for the purpose of improving 40 m sprinting ability. This finding also suggests that it is important for athletes to develop the ability to produce force across a spectrum of loads with a particular emphasis on developing force and speed at higher loads to bias the S_{FV} to be more force dominant.
6. Another finding of practical importance for practitioners is interindividual differences account for a large proportion of the variance in predicting sprint time suggesting that other factors besides v-FVP metrics calculated from a SJ are influencing sprint performance. This could suggest that practitioners may want to include tests that assess other physical qualities that may be important to sprinting performance, such as tests that captures an athlete's ability to utilize the stretch shortening cycle (e.g. DJs or 10-5 Repeated Jump Test) that have been shown to relate to sprint performance (Brady et al., 2024; Robles-Palazón et al., 2024) in their testing batteries.
7. Chapter 6 determined that sprint times for different segments of the 36.58 m sprint can be predicted from simple jump tests (VJ and BJ) and anthropometrics (height, and weight). This study provides four formulae that can be used to predict sprint performance using height, body mass, VJ, and BJ, allowing practitioners to predict sprint time with incomplete sets of data and to identify athletes that may have possibly underperformed or

overperformed in the 36.58 m sprint. This is important for practitioners as not every slow or fast athlete is equivalent and those with superior jumping skill may still be draft candidates. Furthermore, practitioners can use the equations presented in Chapter 6 when performing a needs analysis to identify an athlete's strengths and weaknesses to improve sprinting performance. For example, when examining two athletes from the data set utilized in Chapter 6 (see Table 12), practitioners can individualize their training interventions to better target likely limiting factors.

Table 12. Example Athlete Performance Metrics for Sprint Optimization

Metric	Athlete A (Technique-Dominant)	Athlete B ('Power'-Dominant)
Height (m)	1.88	1.85
Weight (kg)	138.35	95.71
Vertical Jump (m)	0.66	0.74
Broad Jump (m)	2.41	2.82
Actual 36.58 m Sprint Time (s)	4.98	5.15
Predicted 36.58 m Sprint Time (s)	5.34	4.78
Training Recommendation	🏋 Good ability at applying current lower body neuromuscular capabilities in the sprint. Further sprinting improvements likely driven through strength and power training to further develop lower body neuromuscular capabilities.	🏃 Enhanced lower body neuromuscular capabilities. Further sprinting improvements likely driven through increased sprinting and improving sprinting biomechanics to apply neuromuscular capabilities in the specific task.

8. Finally, the formulae presented in Chapter 6 allows practitioners an alternative method for predicting sprint performance when direct testing utilizing lab-based measures is not possible.

7.3 Dissertation: Recommendations for Future Research

The studies within this dissertation have contributed to further our understanding of jump tests and their strengths and limitations when assessing athlete performance. However, questions may remain for practitioners and researchers; recommendations for future research include:

1. Although, this dissertation determined a standardized threshold of unweighting based on the primary outcome of jumping performance (i.e. jump height) further investigations into the impact of unweighting amplitude on secondary measures such as force, power, or average velocity collected from the SJ are warranted, as these measures are often used in research (Jiménez-Reyes et al., 2018, 2019; Jiménez-Reyes, Samozino, Brughelli, et al., 2017; Sleivert & Taingahue, 2004).
2. The study investigating unweighting amplitude utilized female rugby athletes. However, differences in the impact of unweighting on jump height have been found across different sports and genders (Hawkins et al., 2009; Kozinc et al., 2022). Further it is likely that unweighting periods will impact individual athletes differently as shown by observations from the Australian Institute of Sport (J. M. Sheppard & Doyle, 2008). Therefore, future researchers may want to replicate the

findings of Chapter 2 with different sports and genders, in addition to investigating individual differences.

3. In this research we demonstrated that a LPT can predict TS; however, uncertainty remains regarding the LPT's accuracy at slower speeds and heavier loads. This may be due to changes in movement strategy or possibly issues with sampling rate at the heavier loads. Therefore, future research should compare heavier loads (lower speeds) and lighter loads (higher speeds), performing a kinematic analysis using a motion capture system. This would determine if different movement strategies were employed under different conditions (i.e. load).
4. Further, the LPT used in this research Tendo Power Analyzer (v.314, Trenčín, Slovak Republic) is commonly used in athletic settings. However, there are many different models of LPTs and other tools that proport to measure velocity (e.g. accelerometer-based tools) on the market. Therefore, future research should validate the use of PS to predict TS with novel tools, prior to using of the formula presented in this dissertation. Even if a new tool proports to directly calculate TS or by extension jump height, it is recommended that this measure is validated in the research prior to its use in an athlete training setting.
5. This dissertation showed that the three-factor computational (Samozino et al., 2008) utilizing a hex-bar jump has good agreement with the force-pate derived criterion measures, providing a simple way for a practitioner to calculate kinetic and kinematic measures utilizing a ballistic lower body pulling action if jump height, push off distance and system mass are known. However, future research should determine why the slope against identity for power and force is significantly

different than 1 ($p < 0.05$) and tighten the precision of the method at higher forces. These findings may be related to Point 3, with athletes possibly utilizing different movement strategies at heavier loads. Therefore, this future research should be done using a motion capture system and kinematic analysis to determine if movement strategy changes and how to control this in a test setting.

6. Further, there are different tools that can capture the data necessary to use the three-factor computational model. This being the case, determining if force, power and velocity derived in the field using a hex-bar, scale, tape measure, and smartphone or jump mat produces similar results is an essential next step for this line of research.
7. Chapter 5 showed that metrics from a v-FVP can predict 40 m time in a cohort of collegiate level female rugby athletes. However, caution should be taken when extrapolating these findings to other populations (Jiménez-Reyes et al., 2018). Therefore, future research should try to replicate these findings across different sports, levels of athletes and genders to ensure that practitioners are focusing on the correct metrics within their populations.
8. Second, v-FVP can differ depending on the movement tested (Bobbert et al., 2023), therefore future research should use similar methods to Study 4 (Chapter 5) but utilizing other movements such as the CMJ which relies on the use of the slow stretch shortening cycle (Young, 1995). Along with the use of other movements researchers may want to include other jump tests such as the 10-5 repeat jump test or DJs in their models to determine if they account for some of the unexplained variance in the predictions.

9. Chapter 6 showed the ability of simple jump tests and anthropometrics to predict sprint performance. However, the data utilized consisted of athletes with high levels of performance across the tests. Although practitioners should feel confident interpolating results within the range of times utilized in this study, caution should be used when extrapolating the results to populations outside of these performance levels. This means that future research should validate these equations with other populations of athletes or possibly develop new equations specific to different levels of athletes. Furthermore, we propose that these equations can be used to target training interventions to better address the limiting factors in the athlete's sprinting ability. Future research should determine if this approach is more effective than a generalized strength, power and sprinting program.

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