Two-Point Vertical Force-Velocity Profile with Model Predicted Maximal Theoretical Force

by

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Supervisory Committee

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Abstract

Vertical jump performance is a key component of sporting success. In order to improve jump height, athletic assessments using constrained vertical jumps have been created to inform training decisions. The vertical force-velocity (FV) profile is a protocol that involves an athlete performing a series of squat jumps with multiple loads to create an athlete profile that is used to assess lower limb strength and speed performance and provide training recommendations. Yet, some practitioners avoid force-velocity profiling having expressed concerns about athlete safety during heavily loaded jumps, or the time cost of testing. As a simpler, faster and safer assessment, an unloaded squat jump, and a maximal voluntary isometric mid-thigh pull (IMTP) have been used to provide general training recommendations. These basic tasks have yet to provide the array of FV profile metrics or the accuracy of the training recommendations developed from the standard vertical FV profile protocol. Fortunately, due to the similarity of these IMTP and jump task metrics and the standard FV profile it may be possible to predict the same vertical FV metrics and training recommendations using multiple athlete measures, that include IMTP and jump task metrics and predictive modeling. Therefore, the purpose of this paper is to determine if an unloaded squat jump and an IMTP, alongside other athlete variables, can be used to create an athlete vertical FVP and training recommendation comparable to the standard protocol.

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1 Introduction

Physical assessments are highly valued in competitive sport and the results are used to monitor athletic status, determine deficits, and inform training decisions. Practitioners select tests based on relevant characteristics. Assessing athletic abilities with respect to the force-velocity properties of muscle has piqued the interest of many researchers and practitioners for its broad range of applications. The vertical force-velocity (FV) profile is at the forefront of this trend. A force-velocity (FV) profile summarizes an athlete's ability to produce force and velocity in a series of conditions (Jiménez-Reyes, et al., 2017). It has been shown that the slope of an optimal FV profile (S_{FVopt}) can be accurately determined for jumping based on an athlete's maximal power, mass, jump height, leg length, and squat height (Samozino, et al., 2008). Providing individualized training to bring the slope of an athlete's force-velocity (S_{FV}) profile closer to S_{FVopt} results in greater improvements in jump height in a shorter period of time, compared to a standard periodized program (Jiménez-Reyes et al., 2017). In order to optimize an athlete's FV profile, an initial assessment involving a series of weighted and bodyweight jumps must be completed. Based on the push-off distance, jump height, system mass (subject mass + external load) from each load, the S_{FV}, theoretical maximal force (F_0), theoretical maximal velocity (V_0), and theoretical maximal power (Pmax) can be calculated. Using the Pmax and push-off distance an optimal S_{FV} and FV imbalance (FVimb) can be determined to provide a specific training recommendation. Depending on the number of weighted jumps completed, the protocol required to attain a training recommendation can be time-consuming, and the protocol needs to be executed perfectly by both the athlete and practitioner. Further, some practitioners hold safety concerns about athletes jumping with high loads. For these reasons, there has been recent interest in alternative protocols and assessments that offer similar training recommendations (Šarabon, Kozinc & Marković, 2020; Jaric, 2016).

The Dynamic Strength Index (DSI) is a commonly used alternative to the FV profile that assesses force capabilities at multiple velocities and provides a training recommendation. To assess maximal force output, the DSI uses an IMTP. Maximal force expression at a higher velocity is assessed with a bodyweight jump. The FV profile is still considered superior to the DSI because it offers a specific, validated training recommendation (Jiménez-Reyes, Samozino, & Morin, 2019). The peak force expressed in an IMTP is similar to the F_0 as it is an expression of an athlete's maximal force output. Bodyweight jump assessments with and without countermovement are often used to summarize an athlete's lower limb power, and ability to produce force at high velocities. The velocity expressed in a bodyweight jump is much lower than V_0, but it carries a component of velocity that an IMTP does not. These assessments have been previously combined to provide a recommendation of either ballistic or strength training in many sport populations (Sheppard, Chapman, & Taylor, 2011; Comfort, et al; 2018). However, recommendations attained from the FV profile have provided the most consistent improvements in athlete performance (Jiménez-Reyes, Samozino, & Morin, 2019). Šarabon, Kozinc, & Marković (2020) attempted to create a proxy protocol for the FV profile using a maximal voluntary contraction (MVC) isometric squat and a squat jump. The Pmax estimation demonstrated a high level of agreement with the traditional FV protocol, but there was poor agreement for the S_{FV} and intercepts (F_0 and V_0). Šarabon, Kozinc, & Marković used a simple linear model that only included two variables for reference. Thus, it is possible that a model developed with more variables from other relevant assessments could improve the prediction of F_0 and provide FV metrics with high agreement to those provided by the multi-load FV profile.

Therefore, the purpose of this study was to develop a predictive model using common lower limb jump tasks and an IMTP to predict FV variables. This model could have important implications for athletes and practitioners who wish to ascertain FV metrics without using a progressively loaded squat jump protocol.

1.1 Use of Athletic Assessments

Physical assessments are widely used to monitor progress and identify strengths and weaknesses in athletic populations. The use of assessments is considered necessary to safely improve an athlete's performance to the greatest degree possible. Based on the results of the assessments, practitioners can identify deficits and create effective programs that target weaknesses. Deficits are often determined by comparing athlete data to normative data from a specific league, state/province, age group, and/or nation. Follow-up assessments can then be compared to previously collected athlete data and normative data to assess progress. Practitioners choose which assessments to complete based on characteristics of value as determined by a needs analysis that considers the demands of the sport, injuries, training experience, fitness, and skill (NSCA tests and Assessments 2012).

Muscular strength is crucial for sport performance (Suchomel, Nimphius & Stone 2016). Lower body strength can be assessed in a number of ways, but is commonly assessed in a wide range of populations through the use of lower-body maximal voluntary contractions (MVCs) such as the isometric mid-thigh pull (IMTP). The IMTP is a reliable tool to use in many populations including young female athletes (ICC > 0.87, CV < 8%) (Moeskops, et al., 2018). Because IMTP peak force can be assessed using a gradually increasing force output, there is greater opportunity for self-monitoring and coach interference if necessary to correct the position or halt the test if the athlete cannot maintain the appropriate position. These factors make IMTP peak force testing a reasonable strength test for athletes with a low training age. The IMTP peak force measure demonstrates global value as it is correlated with many sport skills (Suchomel, Nimphius & Stone 2016). It has consistently shown moderate to strong correlations with jump performance (Suchomel, Nimphius & Stone 2016). Through the investigation of this relationship, it has been found that the body position during the IMTP is highly similar to that seen during the late propulsion phase of a jump (MacKenzie, et al., 2014).

Jump performance is also a key component for success in many sports (McCluskey, et al. 2010; Arnason, et al., 2004). Significant literature exists to support the key predictors of jump performance (Daugherty, et al., 2021). While rate of force development and peak force output have been investigated for their contributions, concentric power has been highlighted as a significant predictor of jump performance (McCluskey, et al. 2010; González-Badillo & Marques, 2010; Walsh, et al. 2007). Thus, training interventions have focused on increasing peak power output (Mihalik, et al., 2008). In recent years it has been determined that the force-velocity imbalance of an athlete's musculature as determined by FV profiling affects jump height independently from peak power (Samozino, et al., 2012). With this finding, many researchers have focused on monitoring and correcting a FV imbalance.

1.2 FV Properties of Muscle

A muscle's ability to express force decreases as the contraction velocity increases. This force-velocity relationship of muscle has been heavily explored since Hill's initial finding in 1938 (Hill, 1938). Within a single joint movement, this relationship is curvilinear (Wilkie, 1949). This differs from explosive multi-joint movements with moderate loads, where the FV relationship is shown to be exceptionally linear (Farris, Lichtwark, Brown, & Cresswell, 2015; Iglesias-Soler et al., 2019; Jaric, 2016; Sreckovic et al., 2015). Recent investigation has found that the force-velocity relationship responds to resistance training, resulting in more dominant force or velocity properties with strength or speed training, respectively (Samozino, et al., 2012). Further, it has been shown that there is an optimal slope for this force-velocity relationship for explosive multi-joint movements. An optimal FV profile for a vertical jump is one in which body mass provides the optimal load (Samozino, et al., 2012). Training to correct a FV deficit develops the muscular ability to express Pmax in a bodyweight jump. Both the optimal and current slope can be accurately determined through an incrementally loaded test protocol and simple calculations (Samozino, et al., 2012).

1.3 Vertical Force-Velocity Profiling

To optimize an athlete's FV profile, an initial assessment involving a series of weighted and bodyweight jumps must be completed to determine the athlete's current FV profile. Based on athlete jump height, system mass (subject mass + external load), and the total push-off distance, the average force and average velocity produced in each jump may be calculated and recorded (Samozino et al., 2008). Using the points representing average force and average velocity at each load, a linear regression model is applied to determine the linear S_{FV}, theoretical maximal force (F_0) and theoretical maximal velocity (V_0). Theoretical maximal power (Pmax) can also be calculated using the equation outlined by Samozino, et al. (2012). Using an athlete's relative Pmax and push-off distance, an optimal S_{FV} (S_{FVopt}) can be determined with the equations outlined by Samozino, et al. (2012). The FVimb is then calculated using the S_{FV}, S_{FVopt} and the equation outlined by Samozino, et al. and used to determine the training prescription

(2014). There are five categories that guide different forms of training depending on the magnitude and direction of deficit; high or low, and force or velocity deficit (Jiménez-Reyes, Samozino, & Morin, 2019).

Correcting a FV imbalance is an efficient way to increase jump performance. FV imbalances can be independently responsible for as much as a 30% reduction in vertical jump height (Fig.1.1) (Morin & Samozino, 2016; Samozino, et al., 2014). In the example shown in Fig 1.1 athlete A has a high force deficit (FVimb = 49%) while athlete B has a well-balanced FV profile (FVimb = 99%). Even though athlete A has a higher maximal power output, athlete B has a greater squat jump height. This is because an athlete's maximal power output is achieved within a specific FV condition. If, due to a force or velocity deficit, it does not correspond to the condition of a bodyweight vertical jump, then the resulting jump will be lower than if the FV profile was optimal. Once a FV imbalance is identified, an athlete-specific training recommendation can be determined based on five categories of imbalance (Jiménez-Reyes, Samozino, & Morin, 2019). Following the training recommendation will efficiently correct the imbalance and improve vertical jump height without necessarily affecting Pmax (Jiménez-Reyes, Samozino, & Morin, 2019).

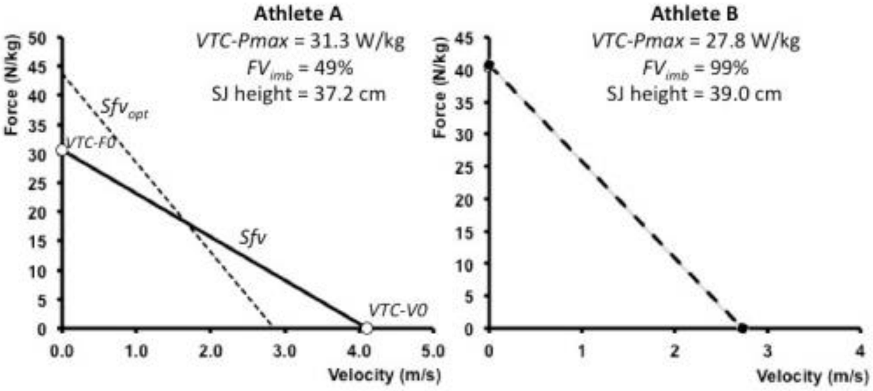

Figure 1-1: The effect of FVimb on jump height (Morin & Samozino, 2016). VTC -Pmax: Theoretical maximal power (Pmax).

Force-velocity profiling metrics generally have acceptable reliability between sessions. The Pmax and F_0 variables typically demonstrate good to excellent reliability, while S_{FV} and V_0 demonstrate moderate to excellent reliability (F_0: CV = 5.1 - 6.7%, ICC = 0.82 - 0.95 ; V_0: CV = 6.0 - 15.4%, ICC = 0.54 - 0.93; S_{FV}: CV = 9.8 - 22.3%, ICC = 0.57 - 0.96; Pmax : CV = 3.8 - 10.36%, ICC = 0.81 - 0.93) (García-Ramos, et al., 2017; Cuk, et al., 2014; Lindberg, et al., 2021). It has been suggested that reliability is improved with increased familiarization with loaded squat jumps, a wide range of loads, and fewer load conditions to control for fatigue (Lindberg, et al., 2021; Jaric, 2016; Picerno, 2017).

1.4 Applications of Vertical Force-Velocity Profiling

Vertical FV assessments are useful for assessing and improving explosive performance in a variety of skills and the potential applications continue to increase. Jump-based vertical FV profiling has clear benefit for jump dependent sports and sports that require vertical acyclic maximal or near-maximal lower-body power output such as soccer, and dance (Marcote-Pequeño, et al., 2019; Escobar Álvarez, et al., 2020). As the popularity of FV profiling has grown, several new applications have appeared in the literature. Of note, there are now applications for assessing upper-body explosive power, correlating vertical FV metrics with sprint performance, predicting 1RM loads and assessing lower-body power endurance. In a similar manner to jump FV profiling, an incremental load protocol has been proposed for the bench press throw, and pull-up exercises to assess upper-body force, velocity and power capabilities across the FV spectrum (Rahmani, et al., 2018; Levernier, et al., 2020). As a power assessment, jump FV profiling also acts as a robust assessment of lower-body power output that is correlated to the performance of other skills such as sprinting. There is a well-documented relationship between sprint performance and jump height (Loturco, et al., 2015). With the development of FV profiling, there has also been investigation into the correlation between jump and sprint FV metrics with large and significant correlations existing between sprint Pmax and jump Pmax (r = 0.75) as well as jump height and time to 20m (r = -0.74) (Marcote-Pequeño, et al., 2019). Further, while sprint performance has been shown to be more closely correlated with horizontal or broad jump performance (r = 0.86-0.90) than vertical jump performance (r = 0.76-0.86), there is a simple alternative calculation for S_{FVopt} that optimizes explosive jump performance horizontally to increase relevance to horizontal movements such as sprinting (Morin & Samozino, 2017). The FV profile has also been investigated for its use in predicting an athlete's 1RM load. The 1 repetition maximum (RM) squat can be considered as a point within the FV relationship (Picerno, et al., 2016). This makes it possible to prescribe loads for a squat exercise based on the FV profile. However, the 1-RM prediction is highly sensitive to small changes in velocity so the validity of the prediction relies on the accuracy of velocity characteristics in the FV profile and decreases with fatigue (Hughes, Peiffer & Scott, 2020). Alternatively to maximal performance, the FV jump assessment has recently been investigated for its relationship with strength endurance during repeated jumps. Rivière, et al. (2020) found that strength-endurance during submaximal squat jumps was highly dependent on the specific condition relative to the athlete's individual force-velocity and power-velocity relationships. While this is a novel application of the vertical FV profile, with further development, it has potential to inform training decisions in a variety of endurance sports. As applications for vertical FV profiling continue to grow, new populations that are unaccustomed to jumping with heavy external loads will create demand for more accessible testing protocols.

1.5 Force-Velocity Profiling and Athlete Safety

Some practitioners have reservations about their athletes completing heavily loaded jumps (Šarabon, Kozinc, & Marković, 2020). Significant literature exists around knee injuries related to landing. Anterior cruciate ligament (ACL) injuries are often highlighted in relation to landing tasks, and the consequences of ACL injury are severe. Only 55% of athletes return to competitive sport, and an ACL tear often results in early posttraumatic knee osteoarthritis (Lopes, et al., 2018; Ardern, et al., 2014). It has been proposed that there are four main risk factors for ACL injury upon landing from a jump: landing with the knee in a valgus position and femur in adduction and internal rotation; landing with the knee extended and with excessive quadriceps activation relative to the hamstrings; landing with poor trunk control; and landing with high leg-to-leg asymmetries (Lopes, et al., 2018). Certain populations are at a higher risk for injury when jumping with heavy loads. In particular, young, female athletes have been identified for demonstrating high-risk lower-body joint mechanics. Given these risk factors, it is reasonable for practitioners who work with athletes displaying significant knee valgus, limb-to-limb asymmetries, and/or poor trunk control to limit jumping activities with high load and thus avoid the traditional FV protocol. Even in populations that have minimal concern related to jumping with high loads, limitations do exist in relation to the traditional FV protocol.

1.6 Force-Velocity Profiling and Time Cost

Practitioners have limited time to develop athlete’s abilities in the gym over the season and within each session. Training an athlete to resolve force or velocity deficits can improve their performance faster than general training programs (Jiménez-Reyes, et al., 2017). However, testing to assess status and progress is time consuming. It is recommended that subjects perform three jumps at each of at least three and up to seven incremental load conditions (Picerno, 2017; Cuk, et al., 2014). For reliability, it has been recommended to allow a two to five minutes rest for a complete recovery between conditions. Depending on the time available and the number of athletes to be tested, this protocol can take a full training session or more to complete. With increasing popularity, there is demand for shorter testing protocols.

1.7 Alternative Protocols

Shorter protocols for the vertical FV profile have been proposed. Because of the linearity of the FV relationship, Jaric (2016) proposed a two-load protocol to ascertain FV metrics. This method has shown comparable reliability and high concurrent validity to an incrementally loaded protocol using five loads (CV < 12.1; ICC > 0.72; r > 0.91) (García-Ramos, Pérez-Castilla & Jaric, 2021). However, the reliability of this protocol relies on the use of two distinct loads. A two-load method using loads that are too close together may result in significant error. García-Ramos, et al. (2021) found coefficients of variation (CV) ranging from 37.5% to 173.9% for FV metrics with all ICCs <0.4 when using a bodyweight trial and 17kg trial. Thus, a valid and reliable two-load method requires the use of a heavy external load. As stated previously, this may pose a risk factor for some populations.

There are alternative assessments to the FV profile which provide insight into athletic abilities at different velocities. The dynamic strength index (DSI) is one such assessment that provides a training recommendation based on a bodyweight jump and an IMTP (Sheppard, Chapman, & Taylor, 2011; Comfort, et al; 2018). The resulting metric is a number that represents the proportion of maximal force (as determined by the peak force during an IMTP) that can be expressed during a bodyweight jump. It has been suggested that athletes with a score of <0.60 are prescribed ballistic training to improve the ability to apply force at speed, and those with a score >0.8 are prescribed strength training to increase available force capacity. The protocol is short and does not involve heavy external loading, but the resulting recommendation is less precise than that provided by the FV profile. Nevertheless, this assessment demonstrates the potential to assess force capacity at multiple velocities using a MVC and a bodyweight jump.

There has been recent interest in devising an alternate FV protocol using bodyweight jumps and MVCs that acts as a proxy to the traditional FV profiling method and provides similar FV metrics (Šarabon, Kozinc, & Marković, 2020). This type of protocol addresses both the athlete safety and time related concerns associated with the traditional FV profile. Šarabon, Kozinc, & Marković (2020) developed a two-point FV protocol using bodyweight jumps and a MVC task as a proxy for F_0. Maximal isometric tests share similarities with the F_0 metric. They aim to describe an athlete's maximal force capabilities with a similar applied direction of force. Šarabon, Kozinc, & Marković's study used an isometric squat which is similar in concept, reliability (ICC > 0.7), and normative peak force values to the IMTP used in the DSI (Brady, Harrison & Comyns, 2020). They determined that an isometric squat test at any of 30°, 60° or 90° knee angles was not equivalent to F_0, but the average of the force from all knee angles had better agreement. Similar to the F_0 metric, maximal isometric tests such as the isometric squat and IMTP aim to describe an athlete's maximal force capabilities with a similar applied direction of force. However, it has not yet been determined whether it is possible to use a predictive equation to determine F_0 through the use of a MVC task.

Jump height and lower body power are key characteristics for success in many sports, and the assessment of these qualities to inform training decisions is highly valued. This is reflected in the increasing popularity of FV profiling and the growing number of applications. However, the concerns that some practitioners hold with the traditional FV profile protocol are significant. There is a lack of research investigating alternative protocols that address these concerns while providing the same value as the traditional FV profile. It is possible that an alternative protocol that is time-efficient and refrains from heavy external loading may be developed to be used as a proxy to the traditional protocol. The aim of the study in chapter 2 is to investigate whether common lower body jump assessments (squat and countermovement jump) and an isometric mid-thigh pull (IMTP) maximal contraction task, along with other athlete specific metrics, could be used in a predictive model to obtain F_0 and calculate vertical FVP metrics that are traditionally obtained from loaded jump protocols. This study is the first to develop a predictive model for F_0 to create a two-point FV profile. This model could have important implications for athletes and practitioners who wish to ascertain FV metrics without using a progressively loaded squat jump protocol.

2 Two-Point Jump Force-Velocity Profile with Model Predicted Maximal Theoretical Force (F_0)[1]

2.1 Abstract

The purpose of this study was to determine if a predictive model including common lower body jump assessments (squat and countermovement jump) and an isometric mid-thigh pull (IMTP) maximal contraction task could be used to calculate vertical FVP metrics that are traditionally obtained from loaded jump protocols. Twenty-two high-level baseball and diving athletes (age: 18.55 years ± 3.70, body mass: 74.38 kg ± 17.53) completed bodyweight countermovement jumps and squat jumps, an IMTP and loaded squat jumps on two force plates. Individual force-velocity metrics were calculated using mean concentric force and velocity values from the incrementally loaded squat jumps. A linear mixed model from the IMTP peak force, countermovement jump (CMJ) height, squat jump (SJ) height, sport, and body mass explained 82% of the variance to predict force at zero velocity (F_0). Using the predicted F_0 and the force and velocity values from the bodyweight SJ, force-velocity metrics were calculated and compared to those calculated from the incrementally loaded squat jumps. The F_0 and predicted F_0 demonstrated a very strong and significant relationship (ICC = 0.88, $p<0.001$). Strong and significant correlations existed between the predicted and actual Pmax and optimal force-velocity slope (ICC = 0.99, $p <0.001$ and ICC = 1.00, $p < 0.001$). Moderate and significant relationships existed between the predicted and actual V_0, force-velocity slope and the relative FV slope (ICC = 0.54, $p < 0.01$; ICC = 0.45, $p<0.05$; ICC = 0.46, $p < 0.05$, respectively). A poor an insignificant relationship existed between the predicted and actual force-velocity imbalance

(ICC = 0.33, $p > 0.05$). These results suggest that force and power metrics can be accurately predicted from a linear model that includes IMTP, SJ, CMJ, body mass and sport. However, velocity, force-velocity slope and force velocity imbalance could not be accurately predicted. This limits the potential to use common jumps and isometric tasks to prescribe training recommendations. Limitations in the tasks as well as the fitting technique used to predict the FV metrics could be investigated to improve the accuracy of all predicted FV metrics.

2.2 Introduction

The vertical force-velocity profile is a lower body assessment that is used to assess strength and/or speed deficits in an athlete's lower body movement and provide specific training recommendations to optimize performance (Samozino, et al., 2012). The recommended vertical force-velocity protocol involves athletes performing three squat jumps at each of three to seven incremental loads with two to five minutes between each loaded trial. The force and velocity data from this protocol is fit to a linear function to calculate metrics such as maximum force at zero velocity (F_0) and maximum velocity at zero force (V_0). Additionally, the slope of an optimal FV profile (S_{FVopt}) can be determined. It has been found that individualized training prescribed to adjust the slope of an athlete's force-velocity profile (S_{FV}) closer to S_{FVopt} results in greater improvements in jump height in a shorter period of time, compared to a standard periodized program (Jiménez-Reyes, Samozino, & Morin, 2019). Therefore, this method of lower body assessment is becoming a valuable standard practice for strength and conditioning practitioners. However, due to the technical proficiency required, as well as the number of jumps and rest periods, this standard force velocity protocol can take a full training session to complete and requires both the athlete and the sport science practitioner to execute the testing and performance perfectly. In order to mitigate the time requirements, a two-point method has been suggested (Jaric, 2016). Additionally, there are potential safety concerns for some populations performing jumps with a heavy load as adding external load to athletes who display altered landing mechanics may increase the likelihood of significant injury, especially in young, female athletes (Lopes, et al., 2018; Hewett, et al., 2005). While this specific lower body force-velocity protocol may be contraindicated for some athletes or not utilized by some practitioners, there are other lower limb assessments that can be used to assess lower body maximum strength and speed. For example, it is common practice to assess athletic abilities at speed through bodyweight jump assessments like a squat jump with and without countermovement. Additionally, to assess maximum force potential, an isometric mid-thigh pull is used. While the squat jump velocity is much slower than a predicted maximum velocity for an athlete from a FV profile, an IMTP force should closely approximate F_0 as it is a maximum effort performed isometrically (at zero velocity). With commonalities between these assessments and the standard vertical force velocity profile there is thought that these tasks can provide common metrics comparable to the metrics output from a standard force velocity profile. For example, Šarabon, et al. (2020) attempted to use a linear relationship between points obtained from a maximal voluntary contraction (MVC) isometric squat and a squat jump. However, they found poor agreement between the predicted FV metrics and ones calculated from a traditional FV profile using loaded squat jumps. While this JUMP-MVC approach was not valid for all FV metrics, Pmax estimation had high to excellent agreement. Further, this was a simple linear model that only included two variables for reference. Thus, it is possible that a model developed with more variables from other lower limb force assessments could improve the prediction of F_0. A linear fit using the predicted F_0 and a bodyweight SJ could then be used to ascertain more accurate FV metrics and support the development of a proxy to a standard FV profile. Therefore, the purpose of this study was to develop a predictive model using common lower limb assessment jump tasks and an IMTP to predict FV variables. This model could have important implications for athletes and practitioners who wish to ascertain FV metrics without using a progressively loaded squat jump protocol.

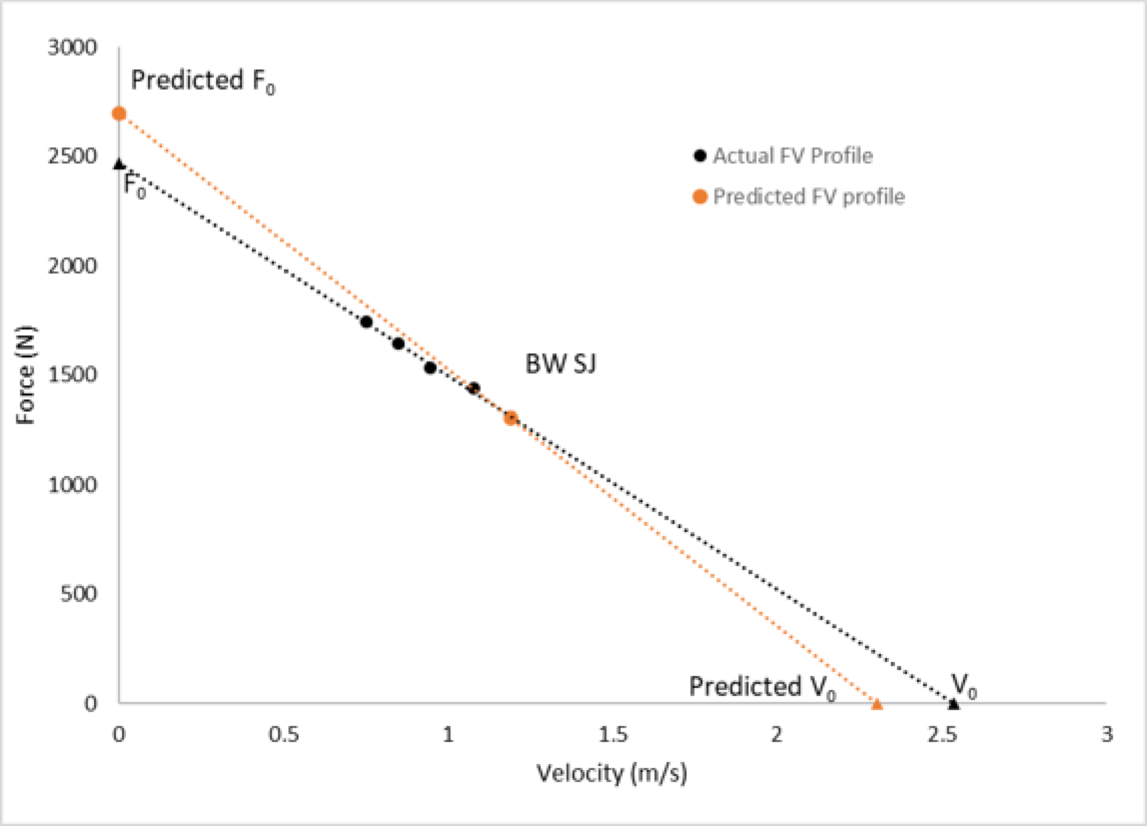

Figure 2-1: Depiction of the Two-Point Predicted Force-Velocity Profile and the Traditional Force-Velocity Profile.

2.3 Methods

2.3.1 Approach to the Problem

A cross-sectional design was used to compare metrics derived from a traditional FV profile to a modeled FV profile calculated from an IMTP, bodyweight jumps, body mass and sport. Subjects attended at least one testing session where they completed an IMTP, a series of incrementally loaded squat jumps (SJs), bodyweight SJs and countermovement jumps (CMJs). For reliability of the FV profile, only test events containing successful squat jumps with at least three loads were retained for analysis. One test event for each athlete was randomly selected to be included in the study. A linear regression model was developed to predict F_0 from IMTP peak force, bodyweight CMJ height, bodyweight SJ height, subject mass and sport. Using the predicted F_0 as well as the average force and average velocity from a bodyweight squat jump, predicted FV profile metrics were calculated.

2.3.2 Subjects

Data was collected from twenty-two athletes (4 females, 18 males) from high-level baseball and diving teams. The baseball athletes were members of a provincial level baseball team. Three diving athletes were on the Canadian national team, four competed at the Open level, and three competed at A or B level. The participants had a mean age of 18.55 ± 3.70 years (females: 21.73 ± 6.11 years, males: 17.85 ± 2.72 years) and a body mass of 74.38 ± 17.53 kg (females: 58.42 ± 6.89 kg, males: 77.93 ± 17.26 kg). All participants had resistance training experience. All participants consented to having data utilized 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.

2.3.3 Procedures

Tests were completed in the same order on the same day. Subjects wore athletic clothing and running shoes. All testing was completed on bilateral force plates (AMTI©, OR6-7, Watertown, MA, USA). Body mass was collected via the force plates prior to jump data collection. Push-off distance was obtained by using the force-time data to calculate the subject displacement between the initial stationary squat position and the fully extended take-off position.

Subjects performed a general warm-up prior to performing three bodyweight squat jumps and countermovement jumps of increasing intensity. Bodyweight jumps were completed first and were performed using a 0.5kg wooden dowel held across the back and shoulders. Participants had three to five minutes rest between load conditions. For all squat jump conditions, an elastic was set at a height of 0.5m from the ground. Participants were instructed to squat down until the back of their legs touched the elastic and pause. The practitioner counted three seconds aloud at which point the participant could jump straight up with maximal effort and no countermovement. Weighted squat jumps were performed using either a 15kg or 20kg barbell held across the back. Subsequent trials with increasing load used a barbell and weightlifting plates. External load was increased incrementally in each trial. Participants performed three jumps at each load. The squat jump test was terminated if participants could not jump higher than 0.10m and technical proficiency could no longer be displayed. After a five-minute rest, participants completed the IMTP trials. A horizontal steel bar was fixed to the ground with a custom rack that allowed adjustment of the height of the bar. The bar height was set for each individual so that the bar was just beneath the hip crease, and the participant’s relative knee angle was approximately 120° as confirmed with a goniometer by the practitioner. Lifting straps were used to reduce the likelihood of grip strength as a limiting factor. Participants were instructed to pull directly upwards while slowly increasing their force output until achieving a maximal pull. The test was stopped when the force levelled off or began to drop. Two submaximal practice trials with 50% and 75% effort were allowed.

2.3.4 Data Analysis

Ground reaction force and time data were collected using bilateral force plates (AMTI©, OR6-7, Watertown, MA, USA) sampling at 1000 Hz. Data was collected using custom Labview software (2015) and filtered with a Double Butterworth filter at 20 Hz. The force plates were zeroed prior to each trial. Jump height was calculated using take-off velocity as determined by the impulse-momentum method (Linthorne, 2001). The average force and average velocity for each squat jump was calculated using the methods outlined by Samozino, et al. (2008). The IMTP peak force was determined as the greatest force reading during the pull.

For the loaded squat jump force velocity (FV) profile a linear regression model was applied to the force and velocity points from all loaded SJs from each participant to determine the slope (S_{FV}) and intercepts (F_0 and V_0) of each subject's FV profile. Other FV metrics were calculated using the methods outlined by Samozino, et al. (Samozino, et al., 2012; Samozino, et al., 2014). To create a predicted F_0, a linear mixed model was developed using IMTP peak force, bodyweight SJ height, bodyweight CMJ height, subject mass, and sport as independent variables. A leave-one-out analysis was used to cross validate the model. The predicted FV profile was developed using the predicted F_0 and the average force and velocity of the bodyweight SJ. A linear fit was applied to attain the V_0 intercept. All other FV metrics were calculated using the methods outlined by Samozino et al. (Samozino, et al., 2012; Samozino, et al., 2014).

All statistical analyses were performed using R (Version 4.1.0; Vienna, Austria, 2021). Descriptive statistics were reported as mean ± standard deviation. The root mean square error and adjusted r^2 were calculated for the F_0 prediction model to assess the error associated with the model and the explained variance in F_0, respectively.

A two-way mixed effects absolute agreement ICC with 95% confidence interval was calculated to assess the agreement between the predicted and actual FV metrics. Bland Altman plots were used to assess bias between actual and predicted FV metrics. Outcomes were considered to be statistically significant at $p < 0.05$.

2.4 Results

Actual and predicted FV metrics, IMTP peak force, and jump height are presented as mean ± standard deviation in Table 2.1. The linear fit of the FV profile was high ($r^2 = 0.97$, range = 0.89 - 1.00). The linear mixed model was able to explain 82% of the variance in F_0 (Equation 1).

$$F_0 \sim -592.7394 + 0.1961\ \text{IMTP} + 17.5243\ \text{Subject Mass} + 5.2762\ \text{SJ Height} - 7.7334\ \text{Sport} + 25.8170\ \text{CMJ Height} \quad \text{(Equation 1)}$$

The model predicted F_0 demonstrated a RMSE of 255.55 N with a range of 1.63 N to 617.47 N. Subject mass was the only significant univariate predictor of F_0 ($p < 0.05$) (Table 2.2).

Table 2-1: Mean and SD of the Predicted and Actual FV metrics, IMTP Peak Force and Jump Height.

	Actual	**Predicted**
F_0 (N)	2349.27 ± 529.15	2355.71 ± 506.24
V_0 (m/s)	2.40 ± 0.30	2.34 ± 0.24
P_{max} (W)	1418.64 ± 408.57	1393.97 ± 400.43
Relative P_{max} (W/kg)	19.13 ± 3.53	18.83 ± 3.56
S_{FV} (N/m/s)	-987.49 ± 226.73	-1006.09 ± 193.13
Relative S_{FV} (N/m/s/kg)	-13.61 ± 2.82	-13.82 ± 2.33
S_{FVopt}	-13.89 ± 1.06	-13.93 ± 1.05

FV_{IMB} (%)	2.11 ± 19.16	0.77 ± 15.53
IMTP Peak Force (N)	3271.74 ± 700.96	
SJ Height (cm)	27.36 ± 5.85	
CMJ Height (cm)	33.19 ± 7.23	

Table 2-2: Significance of Univariate Predictors for Model Predicted F_0

Predictors	**Sig.**
Subject Mass *	$p = 0.0385$ *
Peak Force	$p = 0.1638$
CMJ Height	$p = 0.2363$
SJ Height	$p = 0.8354$
Sport	$p = 0.9697$

*significant to $p < 0.05$

Predicted and actual F_0 had high to excellent agreement (ICC = 0.88, $p<0.001$). A Bland Altman plot suggested that there was no bias between F_0 and predicted F_0 as there were points above and below 0 (Figure 2.1). A numerical summary of the Bland Altman plots can be found in Table 2.3.

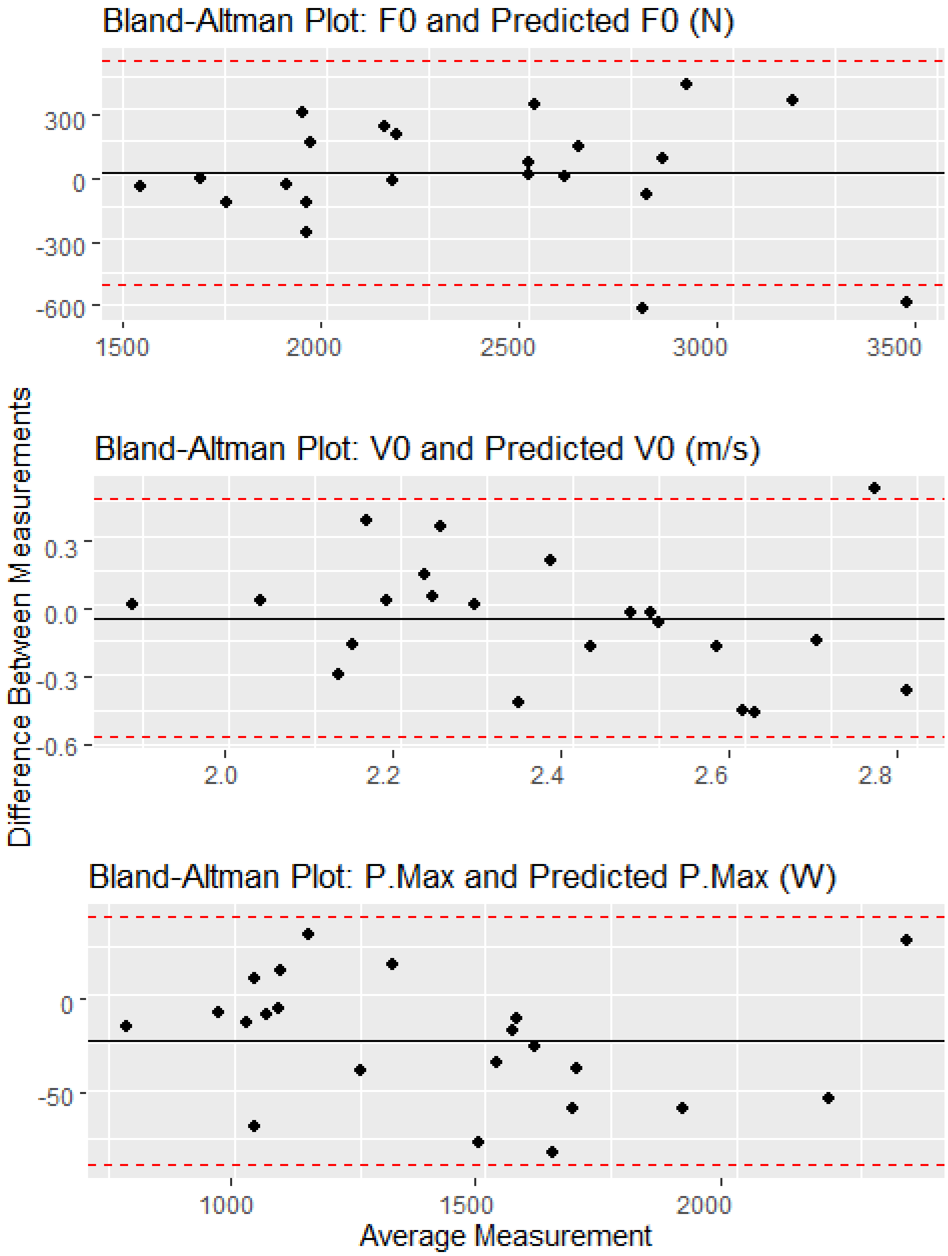

Figure 2-2: Bland-Altman plots for F_0, V_0, and Pmax.

Table 2-3: Summary of Bland Altman Plots for FV Metrics

	Bland Altman Mean Difference	**Bland Altman 95% CI**	**% within 95% CI**
F_0	6.44 N	(-506.07 - 518.94)	92%

V_0	-0.05 m/s	(-0.57 - 0.46)	96%
Pmax	-24.67 W	(-89.16 - 39.82)	100%
Rel Pmax	-0.30 W/kg	(-1.12 - 0.52)	96%
FV slope	-18.60	(-454.19 - 416.99)	92%
Rel FV slope	-0.20	(-5.52 - 5.12)	96%
Optimal FV slope	0.02	(-0.05 - 0.08)	92%
FV_{IMB}	4.88	(-99.41 - 109.16)	96%

The predicted and actual FV metrics demonstrated varying levels of agreement. Predicted Pmax and relative Pmax had excellent agreement with actual values (ICC = 0.99, $p < 0.001$ and ICC = 0.99, $p < 0.001$). Similarly, the predicted and actual optimal FV slope demonstrated excellent agreement (ICC = 1.00, $p < 0.001$). A moderate, significant agreement was demonstrated for predicted and actual V_0 (ICC = 0.54, $p < 0.01$). There was poor agreement displayed for the predicted and FV slope, relative FV slope and FV_{IMB} (Table 2.4). More than half of the FV deficit category assignments did not match the assignment provided by the traditional FV protocol (Table 2.5).

Table 2-4: Interclass Correlation Coefficients and 95% Confidence Interval for Predicted FV Metrics.

	ICC	**95% CI**
F_0	0.88***	(0.73 - 0.95)
V_0	0.54**	(0.17 - 0.78)
Pmax	0.99***	(0.98 - 1.00)
Rel Pmax	0.99***	(0.96 - 1.00)
FV slope	0.45*	(0.04 - 0.73)
Rel FV slope	0.46*	(0.05 - 0.74)
Optimal FV slope	1.00***	(0.99 - 1.00)

FV_{imb}	0.33	(-0.12 - 0.65)

*significance level $p < 0.05$, **significance level $p < 0.01$, ***significance level $p < 0.001$

Table 2-5: Predicted and Actual FVimb Values and Deficit Categories

Athlete	FVimb	Deficit Category	Predicted FVimb	Predicted Deficit Category	Agreement
1	-2.59	Well-Balanced	-20.34	Low Velocity Deficit	no
2	10.45	Low Force Deficit	5.83	Well-Balanced	no
3	26.31	Low Force Deficit	-0.89	Well-Balanced	no
4	13.00	Low Force Deficit	12.19	Low Force Deficit	yes
5	26.88	Low Force Deficit	11.57	Low Force Deficit	yes
6	24.82	Low Force Deficit	4.70	Well-Balanced	no
7	0.85	Well-Balanced	5.25	Well-Balanced	yes
8	-15.99	Low Velocity Deficit	18.47	Low Force Deficit	no
9	-50.24	High Velocity Deficit	-0.42	Well-Balanced	no
10	22.53	Low Force Deficit	-6.15	Well-Balanced	no
11	15.16	Low Force Deficit	14.64	Low Force Deficit	yes
12	-6.56	Well-Balanced	-1.22	Well-Balanced	yes
13	29.81	Low Force Deficit	5.65	Well-Balanced	no
14	13.03	Low Force Deficit	14.19	Low Force Deficit	yes
15	-1.16	Well-Balanced	-13.47	Low Velocity Deficit	no
16	-18.72	Low Velocity Deficit	-42.31	High Velocity Deficit	no
17	-7.70	Well-Balanced	-2.48	Well-Balanced	yes
18	-12.24	Low Velocity Deficit	-10.44	Low Velocity Deficit	yes
19	-8.98	Well-Balanced	18.33	Low Force Deficit	no
20	-14.98	Low Velocity Deficit	-24.96	Low Velocity Deficit	yes
21	0.93	Well-Balanced	12.73	Low Force Deficit	no

22	1.75	Well-Balanced	16.07	Low Force Deficit	no

2.5 Discussion

This is the first study to compare force-velocity metrics derived from a progressively loaded squat jump protocol to the same metrics predicted from a multiple variable model. Ultimately, the metrics of F_0, Pmax, and S_{FVopt} can be accurately predicted from a linear model that includes IMTP, CMJ and SJ, body mass, and sport. This supports similarities between the IMTP and jump task to the progressively loaded squat jump protocol. While some of the metrics were well predicted, SFV, V_0, and FVimb from the linear model showed poor agreement with the standard approach. These differences could be related to slight variations in the predicted F_0 values resulting in large discrepancies in other values due to a linear fit (Fig. 2.2). Inability to accurately determine these metrics limits the use of this predictive model to prescribe training focus. Overall, this investigation supports the use of simple common maximal force and jump tasks to predict maximum force and power but not velocity. This may support comparisons within and between athletes for load prescription.

In this study a linear mixed model that included an IMTP, CMJ, SJ, body mass and sport produced an estimate of F_0 that was in excellent agreement with the standard protocol (ICC = 0.88, $p < 0.001$). Šarabon, et al. (2020) developed a two-point protocol using bodyweight jumps and a maximal effort isometric squat test. However, there was poor agreement, and it was determined that an isometric squat test was not equivalent to F_0 (ICC = 0.305-0.481). Šarabon, et al. used a MVC isometric squat as a proxy for F_0. This suggests that an IMTP alone also may not provide a valid approximation of F_0. In this study, an IMTP was used in conjunction with other variables to predict F_0 which resulted in good agreement for the F_0 metric (ICC = 0.88). Jump tasks, body mass and sport offer important contributions to the estimation of maximal theoretical force. This approach is similar to that used by Brown, et al., (2004) who used multiple regression to predict jump height with 30-second Wingate cycle power test, 1-RM squat, and 1-RM powerclean weightlifting measures which further demonstrates that the inclusion of multiple athlete specific variables may improve the approximation of unknown values based on deterministic relationships between strength and speed in common tasks. The predictive equation to determine F_0, in this study, included body mass as a significant univariate predictor ($p < 0.05$). Lean body mass as well as muscle cross sectional area are highly correlated to strength and jump measures (Dawes et al., 2016; Zaras et al., 2020). While body mass includes fat mass, the sports that were investigated in this study rely somewhat on power to weight ratio and therefore were likely to have a high lean body mass to fat mass ratio (Peart, et al., 2019; Roelofs, et al., 2017). Another interesting finding in this study using athletes from distinct sports is that the equation to determine F_0 was not dependent on sport. It has previously been shown that there are differences in vertical FV profile metrics between sports (Giroux, et al., 2016). Further, Laffaye, et al. (2014) found that there are sport-specific differences in force-time variables during countermovement jumps between sports that rely on jump height and sports that rely on short ground-contact time, such as baseball. Such differences are expected due to different training regimens and sport demands. In this study, differences in the F_0 metric between sports is largely explained by body mass, peak force in an IMTP, and jump height. This is shown by the non-significant contribution of sport to the F_0 prediction model ($p = 0.97$). The variables of IMTP, SJ and CMJ used in the prediction model have different force and velocity requirements which may account for the force-time variations expected between sports. The F_0 metric is determined by assessing a series of jumps, but neither SJ height nor CMJ height provided a significant contribution to the model for predicting F_0 ($p = 0.84$, $p = 0.24$). Including jump heights in this model allowed for some consideration of the velocity generating capabilities of the athlete. While the actual F_0 metric was determined through the use of squat jumps, the CMJ is typically associated with greater velocities than the SJ (Jiménez-Reyes, et al., 2014). This may explain why CMJ height provided greater predictive value to the model.

The IMTP peak force is a conceptually and physically similar measure to F_0. The IMTP peak force is frequently used as a measure to assess maximal force capabilities (Suchomel, Nimphius & Stone 2016). It is a task that attempts to assess maximal force output at zero velocity. Further, the body position required for the IMTP is similar to the body position seen during the propulsion phase of a jump (MacKenzie, et al., 2014). Because human muscle displays a force-length relationship, this similarity may be important for relevance to the F_0 measure (Gordon, Huxley, & Julian, 1966). Šarabon, et al. (2020) measured the peak force in an isometric squat task at three different knee-angles and found higher and lower forces than the predicted F_0. Only the mean of the values from squats at different knee angles resulted in a comparable value to F_0. This could suggest that the theoretical F_0 may relate to the force-length relationship of muscle and lower limb joint angles and therefore require greater investigations to determine an optimal task and body position to produce values that replicate F_0. However, it is important to note that the F_0 as determined from the FV profile is a theoretical representation of average concentric maximal force modelled from the average concentric force and velocity of loaded jumps. Due to the process of this modelling, F_0 may be different from, and likely lower than absolute maximal force. This study provides support for the difference between maximal force and F_0 as the IMTP peak force measure was greater than F_0 for all participants (Table 2.6).

Table 2-6: Predicted and Actual Maximal Force Measures for Each Participant

Athlete ID	Peak Force (N)	Predicted F_0 (N)	F_0 (N)
1	3237.74	1888.56	2018.34
2	3523.00	2583.23	2594.79
3	2736.35	1814.97	2086.80
4	3904.29	2682.49	2560.77
5	2059.74	1515.85	1569.01
6	3802.84	2149.65	2180.32
7	3367.86	2524.95	2471.10
8	2329.33	2079.48	1801.63
9	3426.67	2497.07	2498.70
10	2849.37	2029.80	1888.95
11	4696.42	3315.57	2977.87
12	2838.97	1875.54	1926.40
13	4214.41	3135.93	3720.68
14	2047.63	1689.37	1820.92
15	3571.48	2472.00	3089.47
16	3305.65	2254.53	2033.46
17	4137.14	2738.73	2836.87
18	3677.35	2673.22	2356.22
19	3349.48	2862.18	2789.16
20	2982.57	2266.25	2081.57
21	2318.13	1684.11	1702.93
22	3601.88	3092.06	2677.98

In this study, the model predicted F_0 was used in combination with a bodyweight SJ and push-off distance to calculate predicted FV metrics. The variables of Pmax and the S_{FVopt} were able to be calculated with high agreement to the actual values (ICC = 0.99, ICC = 1.00, respectively). Due to the linear model and fixed point of the bodyweight SJ, differences in F_0 had an inverse relationship with V_0. Because of this effect, the predicted Pmax calculated using V_0 and F_0 was robust. Pmax was then utilized in the calculation of the S_{FVopt}. As a result of the high level of agreement between predicted and actual Pmax, the S_{FVopt} also displayed a high level of agreement. Overall, the agreement demonstrated between the predicted and actual F_0, Pmax and S_{FVopt} supports important similarities between the MVC IMTP and jump task to the progressively loaded squat jump protocol. While some FV metrics demonstrated strong agreement, others had poor agreement with the actual values. The predicted V_0 was extrapolated from distant points; predicted F_0 and a bodyweight SJ. Due to the relatively low velocity of a SJ, equating to a large distance from V_0, small errors in F_0 resulted in large errors in V_0 and thus demonstrated moderate agreement with the actual metric (Fig.2.2). This may suggest that points closer to the force intercept have smaller error than points distal to F_0 on the predicted FV profile. This could be useful for prescribing loads within resistance training exercises. It has previously been shown that an athlete’s 1RM squat exists within the FV relationship, but cannot be reliably predicted due to variations in velocity within the FV profile that are highly affected by fatigue (Picerno, et al., 2016; Hughes, Peiffer & Scott, 2020). Future research could investigate whether the protocol used in this study is suitable to determine resistance training load prescription for loads close to F_0 where error is low and mainly affected by the accuracy of the F_0 prediction.

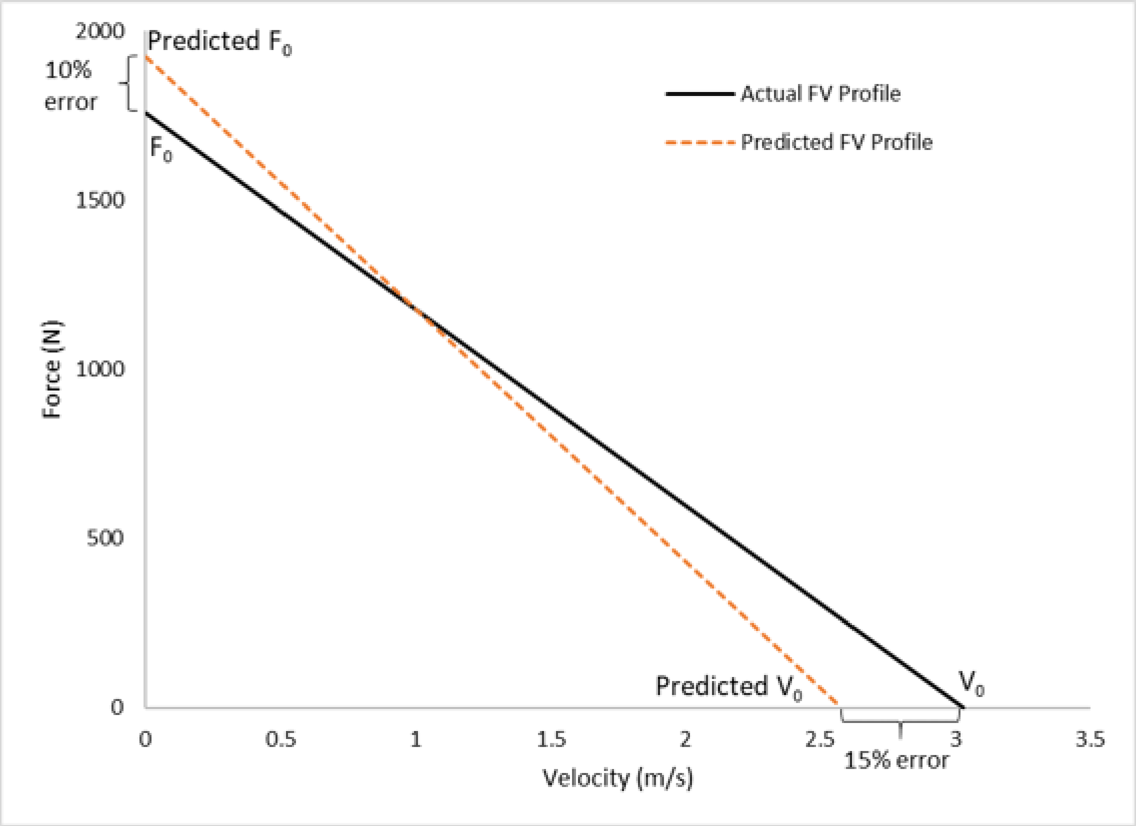

Figure 2-3: The effect of errors in F_0 on V_0.

Šarabon et al. found that due to the discrepancy in the predicted F_0, the predicted FV metrics calculated also demonstrated poor agreement (V_0: ICC = 0.09 - 0.44, S_{FV}: ICC = 0.13 – 0.33). In this study, the V_0 had moderate agreement (ICC = 0.54), but similar to Šarabon, et al. the error associated with the predicted V_0 contributed to the error in dependent metrics. The agreement for S_{FV} was poor, despite the good and moderate agreement in predicted F_0 and V_0 (ICC = 0.45). The slope of the predicted FV profile was significantly impacted by errors in F_0 and the inherited error associated with the linear fit of V_0. It is worth noting that the V_0 and S_{FV} metrics typically have lower between-session reliability than F_0 and Pmax (García-Ramos, et al., 2017). The inherent variability may have affected the prediction of the variables related to V_0. This study did not assess the reliability of the FV metrics, so assumptions related to variability of metrics cannot be made. The S_{FV} and S_{FVopt} was used to calculate FVimb. The FVimb provides a concrete training prescription. Therefore, it is the most important outcome of the FV profile. With the model utilized in this study, the S_{FV} is not accurate enough to appropriately compare to the S_{FVopt}, resulting in poor agreement between the actual and predicted FVimb. The actual and predicted FVimb and resulting deficit categories as described by Jiménez-Reyes, et al. (2019) are displayed in Table 2.5. When using five discrete categories, 41% of the training recommendations provided by the protocol proposed in this study matched the training recommendation provided by the loaded jump protocol.

Future research could address the error in V_0, S_{FV}, and FVimb by replacing the SJ with a point closer to V_0 or increasing the accuracy of predicted F_0. The accuracy of F_0 may be improved by including additional variables in the model such as leg length which has some effect on muscle cross sectional area and push-off distance (Burton, et al., 2012). The accuracy of S_{FV} and V_0 could be improved more directly by using an unweighted jump in the predicted FV profile rather than a bodyweight jump due to its increased proximity to V_0. Finally, while the focus of this study was predicting F_0, future research may look at predicting the S_{FV} instead.

Bibliography

Ardern, C. L., Taylor, N. F., Feller, J. A., & Webster, K. E. (2014). Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: An updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. British Journal of Sports Medicine, 48(21). https://doi.org/10.1136/bjsports-2013-093398

Arnason, A., Sigurdsson, S. B., Gudmundsson, A., Holme, I., Engebretsen, L., & Bahr, R. (2004). Physical Fitness, Injuries, and Team Performance in Soccer. Medicine and Science in Sports and Exercise, 36(2), 278–285. https://doi.org/10.1249/01.MSS.0000113478.92945.CA

Brady, C. J., Harrison, A. J., & Comyns, T. M. (2020). A review of the reliability of biomechanical variables produced during the isometric mid-thigh pull and isometric squat and the reporting of normative data. Sports Biomechanics, 19(1), 1–25. https://doi.org/10.1080/14763141.2018.1452968

Brown, L. , Whitehurst, M. , Findley, B. , Comeau, M. , Noffal, G. & (2004). Power Regression Formula to Predict Vertical Jump in Div. I Female Volleyball Players. *Medicine & Science in Sports & Exercise*, *36* (5), S206.

Burton, R. F., Nevill, A. M., Stewart, A. D., Daniell, N., & Olds, T. (2012). A negative relationship between leg length and leg cross-sectional areas in adults. American Journal of Human Biology, 24(4), 562–564. https://doi.org/10.1002/ajhb.22258

Comfort, P., Thomas, C., Dos'Santos, T., Jones, P. A., Suchomel, T. J., & McMahon, J. J. (2018). Comparison of methods of calculating dynamic strength index. *International*

Journal of Sports Physiology and Performance, *13*(3), 320–325. https://doi.org/10.1123/ijspp.2017-0255

Cuk, I., Markovic, M., Nedeljkovic, A., Ugarkovic, D., Kukolj, M., & Jaric, S. (2014). Force-velocity relationship of leg extensors obtained from loaded and unloaded vertical jumps. European Journal of Applied Physiology, 114(8), 1703–1714. https://doi.org/10.1007/s00421-014-2901-2

Daugherty, H. J., Weiss, L. W., Paquette, M. R., Powell, D. W., & Allison, L. E. (2021). Potential Predictors of Vertical Jump Performance : Lower Extremity Dimensions and Alignment , Relative Body Fat , and Kinetic Variables. 24.

Escobar Álvarez, J. A., Reyes, P. J., Pérez Sousa, M. Á., Conceição, F., & Fuentes García, J. P. (2020). Analysis of the Force-Velocity Profile in Female Ballet Dancers. Journal of Dance Medicine & Science : Official Publication of the International Association for Dance Medicine & Science, 24(2), 59–65. https://doi.org/10.12678/1089-313X.24.2.59

García-Ramos, A., Feriche, B., Pérez-Castilla, A., Padial, P., & Jaric, S. (2017). Assessment of leg muscles mechanical capacities: Which jump, loading, and variable type provide the most reliable outcomes? European Journal of Sport Science, 17(6), 690–698. https://doi.org/10.1080/17461391.2017.1304999

García-Ramos, A., Pérez-Castilla, A., & Jaric, S. (2021). Optimisation of applied loads when using the two-point method for assessing the force-velocity relationship during vertical jumps. Sports Biomechanics, 20(3), 274–289. https://doi.org/10.1080/14763141.2018.1545044

González-Badillo, J. J., & Marques, M. C. (2010). Relationship between kinematic factors and countermovement jump height in trained track and field athletes. Journal of Strength and Conditioning Research, 24(12), 3443–3447. https://doi.org/10.1519/JSC.0b013e3181bac37d

Gordon, A. M., Huxley, A. F., & Julian, F. J. (1966). The variation in isometric tension with sarcomere length in vertebrate muscle fibres. The Journal of Physiology, 184(1), 170–192. https://doi.org/10.1113/jphysiol.1966.sp007909

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., McLean, S. G., Van Den Bogert, A. J., Paterno, M. V., & Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *American Journal of Sports Medicine*, *33*(4), 492–501. https://doi.org/10.1177/0363546504269591

Hill, A. V. (1938). The heat of shortening and the dynamic constants of muscle. Proceedings of the Royal Society of London. Series B - Biological Sciences, 126(843), 136–195. https://doi.org/10.1098/rspb.1938.0050

Hughes, L. J., Peiffer, J. J., & Scott, B. R. (2020). Load–velocity relationship 1RM predictions: A comparison of Smith machine and free-weight exercise. Journal of Sports Sciences, 38(22), 2562–2568. https://doi.org/10.1080/02640414.2020.1794235

Jaric, S. (2016). Two-Load Method for Distinguishing Between Muscle Force, Velocity, and Power-Producing Capacities. Sports Medicine, 46(11), 1585–1589. https://doi.org/10.1007/s40279-016-0531-z

Jiménez-Reyes, P., Samozino, P., Brughelli, M., & Morin, J. B. (2017). Effectiveness of an individualized training based on force-velocity profiling during jumping. Frontiers in Physiology, 7(JAN), 1–13. https://doi.org/10.3389/fphys.2016.00677

Jiménez-Reyes, P., Samozino, P., Cuadrado-Peñafiel, V., Conceição, F., González-Badillo, J. J., & Morin, J. B. (2014). Effect of countermovement on power–force–velocity profile. European Journal of Applied Physiology, 114(11), 2281–2288. https://doi.org/10.1007/s00421-014-2947-1

Jiménez-Reyes, P., Samozino, P., & Morin, J. B. (2019). Optimized training for jumping performance using the force-velocity imbalance: Individual adaptation kinetics. PLoS ONE, 14(5). https://doi.org/10.1371/journal.pone.0216681

Levernier, G., Samozino, P., & Laffaye, G. (2020). Force-velocity-power profile in high-elite boulder, lead, and speed climber competitors. International Journal of Sports Physiology and Performance, 15(7), 1012–1018. https://doi.org/10.1123/ijspp.2019-0437

Lindberg, K., Solberg, P., Bjørnsen, T., Helland, C., Rønnestad, B., Frank, M. T., Haugen, T., Østerås, S., Kristoffersen, M., Midttun, M., Sæland, F., & Paulsen, G. (2021). Force-velocity profiling in athletes: Reliability and agreement across methods. PLoS ONE, 16(2 February), 1–20. https://doi.org/10.1371/journal.pone.0245791

Lopes, T. J. A., Simic, M., Myer, G. D., Ford, K. R., Hewett, T. E., & Pappas, E. (2018). The Effects of Injury Prevention Programs on the Biomechanics of Landing Tasks: A Systematic Review With Meta-analysis. American Journal of Sports Medicine, 46(6), 1492–1499. https://doi.org/10.1177/0363546517716930

Loturco, I., D’Angelo, R. A., Fernandes, V., Gil, S., Kobal, R., Cal Abad, C. C., Kitamura, K., & Nakamura, F. Y. (2015). Relationship between sprint ability and loaded/unloaded jump tests in elite sprinters. Journal of Strength and Conditioning Research, 29(3), 758–764. https://doi.org/10.1519/JSC.0000000000000660

MacKenzie, S. J., Lavers, R. J., & Wallace, B. B. (2014). A biomechanical comparison of the vertical jump, power clean, and jump squat. Journal of Sports Sciences, 32(16), 1576–1585. https://doi.org/10.1080/02640414.2014.908320

Marcote-Pequeño, R., García-Ramos, A., Cuadrado-Peñafiel, V., González-Hernández, J. M., Gómez, M. Á., & Jiménez-Reyes, P. (2019). Association between the force–velocity profile and performance variables obtained in jumping and sprinting in elite female soccer players. International Journal of Sports Physiology and Performance, 14(2), 209–215. https://doi.org/10.1123/ijspp.2018-0233

McCluskey, L., Lynskey, S., Leung, C. K., Woodhouse, D., Briffa, K., & Hopper, D. (2010). Throwing velocity and jump height in female water polo players: Performance predictors. Journal of Science and Medicine in Sport, 13(2), 236–240. https://doi.org/10.1016/j.jsams.2009.02.008

Mihalik, J. P., Libby, J. J., Battaglini, C. L., & Mcmurray, R. G. (2008). Comparing short-term complex and compound training programs on vertical jump height and power output. Journal of Strength and Conditioning Research, 22(1), 47–53. https://doi.org/10.1519/JSC.0b013e31815eee9e

Moeskops, S., Oliver, J. L., Read, P. J., Cronin, J. B., Myer, G. D., Haff, G. G., & Lloyd, R. S. (2018). Within- and between-session reliability of the isometric midthigh pull in young female athletes. Journal of Strength and Conditioning Research, 32(7), 1892–1901. https://doi.org/10.1519/JSC.0000000000002566

Morin, J. B., & Samozino, P. (2016). Interpreting power-force-velocity profiles for individualized and specific training. International Journal of Sports Physiology and Performance, 11(2), 267–272. https://doi.org/10.1123/ijspp.2015-0638

Morin, J. B., & Samozino, P. (2017). JUMP FVP profile spreadsheet.

Picerno, P. (2017). Good practice rules for the assessment of the force-velocity relationship in isoinertial resistance exercises. Asian Journal of Sports Medicine, 8(3). https://doi.org/10.5812/asjsm.15590

Picerno, P., Iannetta, D., Comotto, S., Donati, M., Pecoraro, F., Zok, M., Tollis, G., Figura, M., Varalda, C., Di Muzio, D., Patrizio, F., & Piacentini, M. F. (2016). 1RM prediction: a novel methodology based on the force–velocity and load–velocity relationships. European Journal of Applied Physiology, 116(10), 2035–2043. https://doi.org/10.1007/s00421-016-3457-0

Rahmani, A., Samozino, P., Morin, J. B., & Morel, B. (2018). A simple method for assessing upper-limb force–velocity profile in bench press. International Journal of Sports Physiology and Performance, 13(2), 200–207. https://doi.org/10.1123/ijspp.2016-0814

Samozino, P., Edouard, P., Sangnier, S., Brughelli, M., Gimenez, P., & Morin, J. B. (2014). Force-velocity profile: Imbalance determination and effect on lower limb ballistic performance. International Journal of Sports Medicine, 35(6), 505–510. https://doi.org/10.1055/s-0033-1354382

Samozino, P., Morin, J. B., Hintzy, F., & Belli, A. (2008). A simple method for measuring force, velocity and power output during squat jump. Journal of Biomechanics, 41(14), 2940–2945. https://doi.org/10.1016/j.jbiomech.2008.07.028

Samozino, P., Rejc, E., Di Prampero, P. E., Belli, A., & Morin, J. B. (2012). Optimal force-velocity profile in ballistic movements-Altius: Citius or Fortius? Medicine and Science in Sports and Exercise, 44(2), 313–322. https://doi.org/10.1249/MSS.0b013e31822d757a

Šarabon, N., Kozinc, Ž., & Marković, G. (2020). Force–velocity profile during vertical jump cannot be assessed using only bodyweight jump and isometric maximal voluntary contraction tasks. *Scientific Reports*, *10*(1), 1–12. https://doi.org/10.1038/s41598-020-76262-4

Sheppard, J. M., Chapman, D., & Taylor, K.-L. (2011). An evaluation of a strength qualities assessment method for the lower body. *J. Aust. Strength Cond*, *19*(2), 4–10.

Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The Importance of Muscular Strength in Athletic Performance. Sports Medicine, 46(10), 1419–1449. https://doi.org/10.1007/s40279-016-0486-0

Walsh, M. S., Böhm, H., Butterfield, M. M., & Santhosam, J. (2007). Gender Bias in the effects of arms and countermovement on jumping performance. Journal of Strength and Conditioning Research, 21(2), 362–366. https://doi.org/10.1519/R-19825.1

Wilkie, D. R. (1949). The relation between force and velocity in human muscle. The Journal of Physiology, 110(3–4), 249–280.