Predicting Barbell Takeoff Speed from Peak Speed in the Bench Press Throw using a Linear Position Transducer

by

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Abstract

Key Words: Bench press throw, force-velocity profiling, power, performance testing

In order to determine if the takeoff speed of a barbell in a bench press throw may be predicted from the peak speed as measured by a linear position transducer, 10 participants with at least 1 year of resistance training experience performed multiple sets of the bench press throw, at increasing loads, on a vertical Smith machine. Predictive validity was assessed by comparing the estimated takeoff speed, to the measured takeoff speed from a linear position transducer. The relationship between peak and takeoff speed was $0.2589e^{0.897(PS)}$, and the correlation was statistically significant ($R^2=0.961$, $p < 0.05$). A Bland-Altman plot revealed the 95% limit of agreement ranged from $0.262\ m\cdot s^{-1}$ to $0.175\ m\cdot s^{-1}$, with a mean difference of $0.043\ m\cdot s^{-1}$ (2.92%), and points above and below zero, suggesting no systematic bias exists. This study demonstrates that takeoff speed of a barbell may be predicted from its peak speed in a barbell bench press throw using a linear position transducer. Therefore, practitioners may use peak speed to estimate takeoff speed more quickly in field testing, when the accessibility and availability of equipment necessary to measure takeoff speed may be a limiting factor.

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Acknowledgements

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Chapter 1. Introduction and Literature Review

Athletic testing is an important part of a high-performance sports program, used for workload monitoring, assessment of a program's efficacy, injury rehabilitation, and more (McGuigan & Clubb, 2022). Tests for athletic performance may include assessments across the spectrum of physical abilities such as: cardiovascular fitness, agility, and musculoskeletal tests which characterize the strength, power, and velocity of the athlete. In sport, these tests are often used within a barrage of tests as an indicator of an athlete's playing ability (Gabbett et al., 2007); although, physical performance tests may not perfectly distinguish between successful and unsuccessful athletes. While it is important to address all facets of athletic performance, this review focuses specifically on tests that measure force, velocity, and power for the purposes of the research project.

Power in the context of this project refers to power generated by the athlete, measured as an absolute in Watts (W) or relative to the athlete as Watts/kilogram of bodyweight (W/kg) (van der Kruk et al., 2018). Power may be defined as the rate of work (or energy generated/transferred) per unit of time. The importance of power in sports is well-established, as the ability to generate maximal power while performing complex motor skills, such as sport-specific tasks like running, jumping, and throwing, is associated with performance in these tasks (Baker, 2001; Cormie et al., 2011; Hawley et al., 1992).

According to van der Kruk *et al.* (2018), mechanical power in humans is the sum of: Joint power (the power generated about the joints by the human); kinetic power (the rate of change of kinetic energy); environmental power (the mechanical power from external applied forces); frictional power (the loss of power from frictional forces) and gravitational power (the rate of change of the gravitational energy). Thus, it must be stated that the mechanical power output of given muscular power test is not exactly the power generated by a single muscle, rather the expression of the involved segments of the musculoskeletal system to generate a power output (Suchomel et al., 2016). Similarly, external mechanical power measured during a squat jump has been found to represent the coordinated effort of the lower body, rather than a single muscle (Moir et al., 2012). Tests of muscular power may give an estimation of the athlete's abilities but may not be interpreted as an exact reflection of an individual muscle, and an individual muscle/joint approach may not be useful in sport as most movements are dynamic multi-joint and multi-muscle movements (Cormie et al., 2011; Suchomel et al., 2016). Therefore, in a practical setting most power testing is broken into upper and lower body tests, estimating the external power output of the athletes from large groups of muscles that produce actions rather than single muscles alone.

Power is also the product of force (F, in Newtons (N)) and velocity (v, in m/s) (Minetti, 2002). Understanding the relationships between force, velocity and power may aid practitioners in achieving better athletic performance. Two popular tests among practitioners to calculate lower body power are the countermovement jump and the squat jump (Klavora, 2000). Each test has unique formulae for peak (greatest power achieved in the test) or mean (mean power throughout the concentric phase) power, typically calculated from jump height and body mass (Sayers et al., 1999). While these tests are useful for estimating the mean or peak power generated by the limbs in a simple manner, there exists another mathematical relationship to describe power relying on physics which is described later in this chapter.

The relationship between force and velocity in human skeletal muscle originates in the early 20th century, where A. V. Hill observed a similar relationship between force and velocity of shortening in frog muscle; the more force the muscle needs to generate to shorten, the velocity at which it may shorten decreases (Hill, 1922). It was later observed in elbow flexor muscles (Dern et al., 1947), and human sartorius muscle (Wilkie, 1949) that, as the velocity of shortening in human muscle increases, the force generation ability of the muscle decreases, or inversely, the heavier the load under which the muscle must shorten, the slower it may do so—in simpler terms, “light weights can be lifted more quickly than heavy ones”, and vice-versa (Abbott & Wilkie, 1952). It is important to note that this specific relationship applies to concentric movements alone, or those movements wherein the muscle is shortening while contracting; the relationship between force and velocity in eccentric or isometric movements, where the muscle is contracting but lengthening or unchanged in length, respectively, are beyond the scope of this review (Winter & Fowler, 2009). The relationship between force and concentric shortening velocity in human skeletal muscle has been reproduced in individual muscles over the years, confirming the hyperbolic relationship of the curve (Alcazar et al., 2019). However, multi-joint movements appear to have a quasi-linear force-velocity relationship rather than hyperbolic due to the segmental dynamics, i.e., relative segments involving moment arms and torque rather than a single shortening muscle along a plane of movement (Alcazar et al., 2019; Bobbert, 2012).

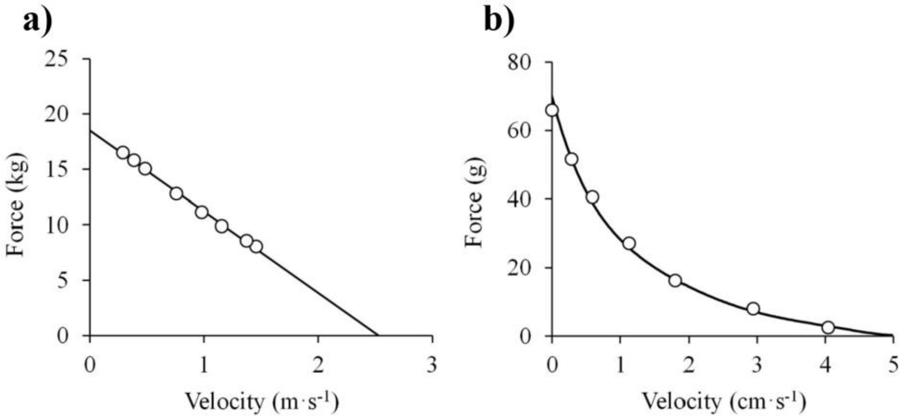


Fig. 1.1: a) Quasilinear force-velocity relationship in a concentric multi-joint movement and b) Hyperbolic force-velocity relationship in a concentric single-muscle contraction. Adapted from Alcazar et. al. (2019).

Force and velocity are important for practitioners working in performance sport, as athletes with similar performance (power, in Watts) on a jump test from the listed methods may have relied more heavily on force or velocity to achieve these performances (Samozino et al., 2012). Using knowledge of the force-velocity curve, practitioners may then target the variable they wish to manipulate for the athlete to improve performance—in traditional power testing using the other methods of calculation, these insights are lost. Therefore, a new method was introduced in recent years to determine these variables in the vertical plane with a squat jump, and horizontal plane with a sprint, titled "force-velocity profiling" (Samozino et al., 2012, 2016). This review will focus exclusively on vertical force-velocity profiling.

Force-velocity profiling is specific to performance in ballistic movements, or those which do not involve a distinct braking phase during the concentric phase of the movement (Frost et al., 2008; Lake et al., 2012). In other words, ballistic movements are those which involve a projectile, and during the concentric phase of these movements there may be a point at which velocity of the body in motion slows, however does not reverse the direction of travel during movement (Lake et al., 2012). Rather, the body in motion continues its path to become a projectile at the end of the propulsion phase. One example of this is the squat exercise versus the squat jump; during the non-ballistic squat, the athlete begins the concentric phase at the bottom, or deepest position of the squat, then accelerates upwards during the concentric portion, slowing for a longer deceleration phase at the movement at the top of the movement to then reverse and return to the starting position for another repetition. Conversely, in the squat jump, from the bottom of the squat the athlete accelerates with minimal deceleration prior to jumping. The same is true for the non-ballistic bench press and the ballistic bench press throw (Frost et al., 2008; Rahmani et al., 2017), where the barbell is slowed and returned to the starting position in the bench press but becomes a projectile in the bench press throw. Force-velocity profiling has been achieved for both the lower and upper body using the ballistic squat jump and bench press throw, the former defining the origination of this technique.

Force-velocity profiling with a computational model was first introduced as Samozino et al. (2008) established that traditional tests of power in athletic performance fail to provide insight the forces and velocities of the movement, whose product is power. Therefore, testing was established to tease out these variables using similar movements to power testing by applying biomechanical principles to the squat jump. The countermovement jump and squat jump are both valid and reliable tests for lower limb power (Bobbert et al., 1996; Klavora, 2000), but a key difference separates the two; the countermovement jump involves a "dip", or the downward countermovement prior to the concentric phase of the movement in which the athlete accelerates upwards, where the squat jump involves a pause at the bottom of the movement. The countermovement stretches the muscle that will shorten in the concentric phase, and it has been established that by stretching the muscle prior to shortening (given little latency between the lengthening and shortening of the muscle), performance on the subsequent task is enhanced due to the utilization of stored elastic energy from the stretch of the muscle and tendon in preload, the muscle-tendon interaction, residual force enhancement, reduction of muscle slack, and the stretch-shortening cycle (SSC), which results in greater force production at the beginning of the concentric period (Alcazar et al., 2019b; Bobbert et al., 1996; van Hooren & Zolotarjova, 2017). By pausing at the bottom of the squat for the squat jump, this elastic energy dissipates and the resultant force, velocity and power production is a result of the propulsive concentric phase alone (Bobbert et al., 1996). The results of the squat jump are also more reliable, as technique can be better controlled than in the countermovement jump (Sayers et al., 1999). To address the question of the force and velocity capabilities of the lower body's explosive concentric capacities, without the influence of confounding mechanics of the countermovement jump, the squat jump was therefore chosen (Samozino et al., 2008). The squat jump also better allows a practitioner to control the push-off distance, or the depth to which the athlete squats before jumping, which is known to influence performance due to factors including the differences in a muscle's ability to produce force at different lengths (Arnold et al., 2013). The computational method involves a series of squat jumps at increasing loads, from the same squat depth to address specific points on the force velocity relationship (light loads at greater velocities, increasing to heavier loads moved at slower velocities). The average force ($\bar{F}$) and velocity ($\bar{v}$) during the concentric phase of the movement at each load are then plotted, and the slope of the relationship between force and velocity at each load is the "profile". This profile is determined by calculating the linear relationship between the plotted points, including the intercepts. These intercepts are assigned the variable F_0, or the theoretical maximal force production at zero velocity, and v_0, or the theoretical maximal velocity at zero force production. The slope (S_{fv}) is computed as:

$$S_{fv} = -F_0/v_0$$

This technique to develop the squat jump force-velocity profile was originally performed using the gold standard force plates, where the average ground reaction force over the pushoff phase was measured and represents $\bar{F}$, while acceleration over the pushoff phase is integrated to calculate instantaneous velocity over pushoff, representing $\bar{v}$ (Samozino et al., 2008). A three-factor computational method was later validated against the outputs from the gold standard tests that allows practitioners to perform the squat jump protocol with a few key measured variables including jump height, each external load, and anthropometric measures (Samozino et al., 2008). This computational method was developed to make force-velocity profiling more accessible to practitioners who may be limited on time and financial resources, rendering it possible to test many athletes quickly and with common equipment found in the daily training environment. It appears that there is an optimal slope for each athlete, dependent on the relationship between $\bar{F}$ and $\bar{v}$, that results in the greatest performance on the jump (Samozino et al., 2008). Ultimately, the goal with these outputs for practitioners is to train the "deficient" side of the force-velocity relationship and approach this optimal profile (García-Ramos et al., 2016; Jiménez-Reyes et al., 2018; Samozino et al., 2008, 2012); however, this review focuses on the exclusively on the methodology and key variables of force-velocity profiling, and training considerations are beyond its scope.

When analyzing ballistic movements like the vertical jump or bench press throw, Newton's laws of motion may be applied, such as the fundamental principle of dynamics which dictates that the acceleration, and resultant velocity of a body during the concentric push-off phase in the ballistic movement depends on the force applied to the body (Samozino et al., 2010). The velocity of takeoff (v_{to}) is also function of maximal power, or P_{max} (Samozino et al., 2012). Height of the body in motion, h, may also be calculated from the velocity of takeoff, using the following equation:

$$h = \frac{v^2{}_{to}}{2g}$$

This principle allows for the computational model that was introduced to retrieve v_{to} from h, i.e., jump height in the case of the squat jump, or peak barbell displacement in the case of the bench press throw. Then, the total external mechanical work (W_t) can be calculated from the height of push off (h_{po}), or the distance covered by the body in motion over the concentric push off phase, and known variables m (the mass of the moving body) and acceleration due to gravity (g) in the following:

$$W_t = \frac{1}{2} m v^2{}_{to} + m g h_{po}$$

$\bar{F}$ may be calculated after finding W_t:

$$\bar{F} = \frac{W_t}{m h_{po}}$$

And substituting the equation for W_t in the above gives:

$$\bar{F} = \frac{v^2{}_{to}}{2h_{po}} + g$$

This relationship is the result of the laws of movement dynamics on an accelerating body and allows the calculation of $\bar{F}$ and v_{to} from a few key variables rather than more cost and time prohibitive methods such as force plates (Samozino et al., 2010). Perhaps most importantly, it is known that during a ballistic movement with a null starting velocity, such as the squat jump, $\bar{v}$; can be calculated from v_{to}:

$$\bar{v} = \frac{v_{to}}{2}$$

which is achievable from the computational method, rather than averaging velocity outputs across the push-off phase as in the force plate or linear position transducer methods (Samozino et al., 2008).

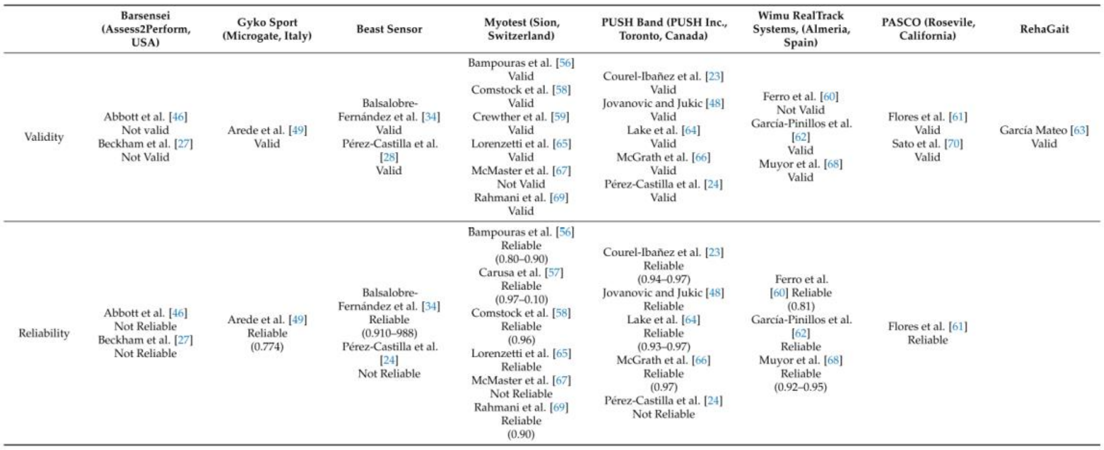
The bench press throw (BPT) has been shown to have acceptable reliability over multiple sessions in collecting mean propulsive velocity, peak velocity, and peak power (Alemany et al., 2005; García-Ramos et al., 2018). Therefore, this test can provide reliable variables for the application of force-velocity profiling to the upper body, for which research is less prevalent than for the lower body. Like the squat jump test, the force, velocity, and power output of the bench press throw exercise were originally determined utilizing force plates, and the optical encoder of a linear position transducer to determine the moment of takeoff (Rahmani et al., 2009; Sreckovic et al., 2015; Young et al., 2015). However, more recently the computational principles above were applied to develop a simple method using only the maximal height achieved by the barbell during the bench press throw, the height of push-off (how far the barbell travelled before being released from the hands as a projectile), and the external load (Rahmani et al., 2017). The bench press throw force-velocity profile has been achieved by having participants perform multiple trials of the bench press throw across multiple loads, corresponding to increasing percentages of body mass (Rahmani et al., 2017), or a percentage of previously tested 1-repetition max (McMaster et al., 2016). Due to the linear nature of the force-velocity relationship in the bench press throw, the use of absolute loads is acceptable, as theoretically the load will fall along the same quasi-linear slope for the individual profile given an acceptable number of trials, regardless of its relativity to the participants mass or 1-repetition max (García-Ramos et al., 2016; Samozino et al., 2012). The greater range of loads across the relationship, the more accurate the linear relationship, however exact measures of individual %RM may not be necessary for these reasons.

One key aspect of all bench press throw force-velocity profiling studies is the use of the guided barbell (Smith) machine. To obtain *h*, the protocol is typically performed on a perfectly vertical Smith machine with a measurement tool placed on the guide rails, and the computational method is corrected for friction between the guide rails and support arms of the barbell (Rahmani et al., 2017). This poses several potential problems for practitioners wishing to obtain profiles for their athletes; a) Smith machines are a specialized piece of equipment, and fewer are often present in the daily training environment than free-weight setups; b) the Smith machine may be less familiar to athletes than a traditional free weight bench press, and c) the mass of an unloaded Smith machine barbell is often still heavier than a free weight barbell due to the additional mass of the safety hooks, bearings and sleeve that slides on the guide rails. These points become problematic in terms of feasibility in that a) time or equipment constraints may render testing illogical for large groups, b) athletes may experience unfamiliarity effects on their performance in the test, and due to the force-velocity relationship, c) we may miss the velocities at lighter loads and compromise accuracy of the profile or disqualify less strong or powerful athletes from testing who cannot complete multiple loads starting at the mass of the barbell with the attached safety hooks and sleeves. These limitations further contribute to the need for this research; it is known that the peak velocity in bench press throw is achieved prior to the moment of takeoff, and prior to the moment at which the barbell reaches its greatest height in the bench press. It may then be feasible to use the results of this study to justify the use of peak velocity in an explosive free-weight barbell bench press to obtain a theoretical takeoff velocity for use in the computational model. A potential limitation to this theory that exists are differences in the kinetics and kinematics of the bench press throw versus the bench press exercise, particularly on the Smith machine. The bench press throw is performed with a perfectly linear path of the barbell, while the bench press with free weights follows pattern where the barbell deviates from perfectly vertical after leaving the start position, and this path may change with increasing load on the barbell (Król & Gołás, 2017). The perfectly linear path of the movements performed on the Smith machine result in vertical forces, while the varying path of the free weights may result in horizontal and vertical forces. Linear position transducers have been validated for assessing peak velocity, (Davis et al., 2022) yet future research should explore the forces present during these movements and validate the force-velocity profile developed with the bench press to assess any variations due to the difference in barbell path under increasing load.

Although the computational method using projectile height has been validated, there is potential for error in obtaining height itself due to the use of measurement tools. Obtaining v_{to} via other methods, rather than calculating it from throw height, may be possible, however also introduces error due to the tools available:

First, video analysis software offers researchers and practitioners the opportunity to pull kinematic variables from video of movements, for example acceleration, velocity, and displacement of the barbell in the bench press throw. The user inputs a known-dimension reference value (for example, a meter stick in the frame of the video that the user identifies as a known length), then the software computes variables from the video by comparing the reference's pixels to the input value, and then other objects in the frame and using the camera's time stamps/frame rate as its time dimension. In theory, it may also allow researchers in the case of ballistic actions to determine the moment of takeoff, then pull the velocity at that time point as v_{to}. Performed correctly, video can be a powerful tool for kinematic analyses and interpretation (Beichner, 1996). However, it is also vulnerable to unreliable/invalid results, mostly due to user error or inconsistencies in protocol (Martin et al., 2020). Common issues in video analysis include a) camera settings such as frame rate, which is the sampling frequency of the video, and if too low may miss captures of key moments such as takeoff and b) reference object misplacement due to parallax, as a given object's size on video is relative to its distance from the camera (Stephens et al., 2019). For example, if the reference object is placed far behind the object of interest in the camera view, but its reference length is input as a given length, the software will assign the given length as an incorrect number of pixels in relation to the actual size of the reference. Finally, the camera angle relative to the object of interest may affect its perception of acceleration and relative dimensions (Martin et al., 2020). Errors in analysis may also occur if the protocol's criteria for target variables such as "moment of takeoff" to obtain v_{to} are vague or unclear. Therefore, the measures themselves that may come from video analysis may be inaccurate, and user error may also result in inconsistencies in identifying the moment of takeoff to identify v_{to}, when the protocol to do so is poorly defined. Finally, the time required for video analysis is significant, and makes obtaining results from large groups frequently difficult for practitioners.

Inertial measurement units, or IMU's, have also become popular as a tool from which researchers and practitioners may obtain kinematic variables. IMU's measure acceleration in different planes of motion, which may be integrated to obtain the velocity of the object and integrated again to obtain displacement in these planes (Kok et al., 2017). Integration in this context is the calculation of the area beneath the curve of a given variable-time curve, for example the area under the acceleration-time curve is the velocity. Performing an integration involves calculating the area between two data points, and the summation of all the areas gives the total area under the curve. From a theoretical standpoint, this poses an initial problem with calculated velocity and displacement, as each integration introduces error due to the imperfect estimation of these area between data points (Marinov et al., 2014). This error may be improved by a higher sampling frequency (more datapoints means less interpolation between each to establish the area for a given sampling duration), however is still imperfect. Also, determining the starting point for the movement at the point at which the integration begins is imperfect, due to human error in selecting the point, while noise in the acceleration signal may render feature detection for mathematical determination of this point inaccurate. Therefore, obtaining velocities and displacements by integrating the raw acceleration signal of an IMU may prove both cumbersome and inaccurate for practitioners. There are many commercial IMU's available on the market today that allow more feasible analysis, due to the proprietary software available, so that the practitioner themselves is not conducting the integration. These devices offer a solution in terms of time and upskilling constraints for practitioners, however, have varying validity and reliability when it comes to barbell velocity and displacement. One study involved a systematic review on 8 commercially available IMU's across 22 studies, assessing their validity and reliability in velocity outputs from multiple barbell movements including the back squat, bench press, hip thrust, bench throw, prone bench pull, countermovement jump, power snatch, clean, jerk, and hexagonal bar deadlift (Clemente et al., 2021). The results are interpreted from the review below:



	Barsensei (Assess2Perform, USA)	**Gyko Sport (Microgate, Italy)**	**Beast Sensor**	**Myotest (Sion, Switzerland)**	**PUSH Band (PUSH Inc., Toronto, Canada)**	**Wimu RealTrack Systems, (Almeria, Spain)**	**PASCO (Rosevile, California)**	**RehaGait**
Validity	Abbott et al. [46] Not valid Beckham et al. [27] Not Valid	Arede et al. [49] Valid	Balsalobre-Fernández et al. [34] Valid Pérez-Castilla et al. [28] Valid	Bampouras et al. [56] Valid Comstock et al. [58] Valid Crewther et al. [59] Valid Lorenzetti et al. [65] Valid McMaster et al. [67] Not Valid Rahmani et al. [69] Valid	Courel-Ibañez et al. [23] Valid Jovanovic and Jukic [48] Valid Lake et al. [64] Valid McGrath et al. [66] Valid Pérez-Castilla et al. [24] Valid	Ferro et al. [60] Not Valid García-Pinillos et al. [62] Valid Muyor et al. [68] Valid	Flores et al. [61] Valid Sato et al. [70] Valid	García Mateo [63] Valid
Reliability	Abbott et al. [46] Not Reliable Beckham et al. [27] Not Reliable	Arede et al. [49] Reliable (0.774)	Balsalobre-Fernández et al. [34] Reliable (0.910–988) Pérez-Castilla et al. [24] Not Reliable	Bampouras et al. [56] Reliable (0.80–0.90) Carusa et al. [57] Reliable (0.97–0.10) Comstock et al. [58] Reliable (0.96) Lorenzetti et al. [65] Reliable McMaster et al. [67] Not Reliable Rahmani et al. [69] Reliable (0.90)	Courel-Ibañez et al. [23] Reliable (0.94–0.97) Jovanovic and Jukic [48] Reliable Lake et al. [64] Reliable (0.93–0.97) McGrath et al. [66] Reliable (0.97) Pérez-Castilla et al. [24] Not Reliable	Ferro et al. [60] Reliable (0.81) García-Pinillos et al. [62] Reliable Muyor et al. [68] Reliable (0.92–0.95)	Flores et al. [61] Reliable	

Fig. 1.2: Summary of systematic review on 8 commercially available IMUs Interpreted from Clemente et al. (2021).

From this review it was determined that one sensor, the Barsensei, was neither valid nor reliable in determining barbell velocity in these movements. The Gyko sport, Beast Sensor, and PASCO IMU's were valid and reliable for barbell velocity in all the reports. The Myotest, PUSH band, and Wimu RealTrack were valid and reliable in most tests, while the Rehagait was valid but not reliable in determining barbell velocity. This review shows inconsistencies in the validity and reliability of IMU's, rendering the selection of an appropriate IMU difficult for practitioners. Displacement (and therefore the height of the projectile) has yet to be widely validated in IMU's. Linear position transducers, while valid in providing measures of acceleration and peak velocity, may also overestimate displacement of the barbell and need recalibration after reach repetition to obtain mean velocity, therefore making it difficult to obtain these values (h and $\bar{v}$) for the computational method from these tools (O'Donnell et al., 2018; Wadhi et al., 2018).

We have established that v_{to} is an important component of the three-factor model of developing the force-velocity profile, due to its relationship with $\bar{v}$ over the concentric push off phase. We also know that obtaining v_{to} requires a projectile in a ballistic action, such as the bench press throw. However, if it were possible to predict v_{to}, perhaps an accurate profile may be developed in a way that solves the possible issues with upper body force-velocity profiling listed above— eliminating the need for the bench press throw on a Smith machine and calculating v_{to} in another manner that doesn't require barbell height/the identification of a moment of takeoff. We may be able to do so, given key principles of the mechanics of ballistic and non-ballistic movements. First, in a maximal effort bench press, peak velocity (v_{peak}) occurs prior to the braking phase during the concentric portion of the movement (Król et al., 2010). Second, it has been shown that a linear mixed model may be applied to predict takeoff velocity from peak speed in a hexagonal bar jump (Agar-Newman et al., 2020a, 2020b). Therefore, we propose that we may be able to predict v_{to} from peak velocity in the bench press throw by applying a linear mixed model. We may then validate this method by comparing it to the v_{to} output from the Tendo Sports Machines linear position transducer at the moment of takeoff, which provides advantages over other methods as the Tendo is compact, comparatively less expensive than force plates, and easy to use with large groups (Garnacho-Castaño et al., 2014). This may then, in the future, allow practitioners to a) predict a theoretical v_{to} from v_{peak} in a maximal effort free weight bench press throw, eliminating the need for the Smith machine, or b) allow v_{to} to be calculated from v_{peak} in the bench press throw on the Smith machine yet avoid issues with determining a moment of takeoff/barbell height to obtain this value. Ultimately, this research may lay the foundation for the development of a more accessible method of creating the upper-body force velocity profile for practitioners. Though the terminology in this chapter remained consistent with the literature describing these variables for clarity purposes, v_{to} and v_{peak} will henceforth be referred to as "Takeoff speed" and 'Peak speed", respectively. This is due to the reporting of these variables in the scalar unit "speed" in the present study, rather than the vector unit "velocity" in the background literature.

Chapter 2: Predicting Barbell Takeoff Speed from Peak Speed in the Bench Press Throw using a Linear Position Transducer

Introduction

Force-velocity profiling has emerged as a popular tool for characterizing an athlete's physical capabilities and has been useful for developing training interventions to improve performance of ballistic actions (Morin & Samozino, 2016a). To be an effective force velocity assessment, important measurements of the ballistic task at various loads are required. A simple three factor model to calculate mean force, velocity and power from a squat jump using push off distance, system mass and flight time (Samozino et al. 2016). This model has been successfully applied to lower body tasks to simplify the process of collecting a force velocity assessment. While a predominant amount of research has focused on the refinement and application of lower body vertical force velocity techniques (Samozino et al., 2008, 2016), recently an upper body assessment using a bench throw on a Smith machine has been developed and validated (Rahmani et al., 2017). This bench throw vertical force-velocity protocol provides unique opportunities for upper body assessment, however there are technical considerations that may limit its broad application. First, the requirement of a Smith machine limits accessibility as this equipment may not be readily available. Additionally, many Smith machines have a high fixed load (the load of the barbell plus accessories) that may make it difficult to measure ballistic action at low loads and high velocities. Further, the specific measurement of the height of the projectile (height of the thrown weight) achieved to use in the 3-factor model requires important consideration. In the specific protocol developed by Rahmani et al. 2017, they used an ingenious method to determine the height of the projectile by measuring the displacement of a ring on the Smith machine guide that would rise with the barbell and maintain its highest height achieved (Rahmani et al. 2017). While this approach was suitable for the validation study, manual measurement of height in this manner is difficult to standardize, may introduce human error and can be time consuming during testing sessions. Other measurement tools such as video, inertial measurement units (IMU's) and linear position transducers may also be limited as the ability to readily determine the displacement, and the time of bar release requires high resolution tools and comprehensive analysis. To simplify the collection of important kinematic values for input in the 3-factor model during a hex bar jump, Agar-Newman et. al. (2020) predicted takeoff speed (TOS) using peak speed from a Linear Position Transducer (LPT), as peak speed is commonly outputted from various commercially available LPTs. They found a strong relationship ($R^2 = 0.98$), minimal error and developed an equation that could be used to transform the native measurement output of peak speed from an LPT into TOS that could be input into the force velocity 3 factor model. This finding enables a simple and effective way of collecting relevant measures using an LTP which reduces the time for manual measurement making this method applicable for practitioners working in the field. Using this same method of predicting the relationship between peak speed and take-off speed in the ballistic bench throw task may provide a unique way of making this protocol and other potential upper body force-velocity protocols more accessible.

Therefore, the purpose of this study was to determine the relationship between PS and TOS during a bench throw task using an LPT. We hypothesize that in the bench press throw, TOS may be predicted from PS. This finding may eliminate the need for a measurement of barbell displacement with the Smith machine setup, and allow practitioners to use PS obtained via more common LPT technology.

Methods

Experimental Approach to the Problem

Subjects

178 throws from were collected from 10 healthy male participants (mean age 27.03 ± 5.26 years, mean body mass 88.41 ± 13.24 kg), with a minimum of 1 year of resistance training experience,

at the Canadian Sport Institute Pacific High Performance Gym. Subjects refrained from high-intensity physical activity for 24 hours prior to testing. All subjects gave their informed consent to partake in this study and ethical approval was obtained from the University of Victoria Human Research Ethics Board and complied with the principles outlined in the Declaration of Helsinki.

Procedures

All data were recorded by University of Victoria strength and conditioning coaches, overseen by a National Strength and Conditioning Association (NSCA) Certified Strength and Conditioning Specialist. A vertical Smith machine was outfitted with a Tendo Unit LPT (Tendo Sports Machines UK LTD, London, UK). Participants arrived at the facility and birthdate and bodyweight were collected prior to warmup. Participants performed a 5-minute standardized general dynamic warmup, followed by a specific warmup of 5 repetitions of the bench press throw with the unloaded barbell only (22kg). During the specific warmup, participants assumed a supine position on the bench with hips and knees flexed to 90 degrees and ankles crossed for comfort. An overhand grip width was selected with the barbell at sternum level and forearms perpendicular to the ground (as comfort allowed), which was marked on the barbell for each participant and remained consistent for each trial at each load (Figure 2.1).

Fig 2.1: Participant assuming an overhand grip with legs raised and crossed, with markers placed at the inside border of the 1st knuckle to ensure consistency in grip width between trials.

Following a 5-minute rest period after the specific warmup, participants performed 3 trials at each load with minimum of 3 minutes of rest between each load, starting with the unloaded barbell minus its collars (22kg), the barbell minus its collars + 5kg (27kg), the unloaded barbell with its collars (31kg), followed by 5kg increments until either a) the subject could no longer throw the barbell, or b) the subject voluntarily stopped the protocol. Participants performed a minimum of 4 loads for the analysis and a maximum of 9 loads. It has been demonstrated that when performing the bench press throw at loads approaching 1RM, the ability to create a projectile with the barbell is compromised and force production is decreased, and this may not be "substantial throw" (Moir et al., 2017). Therefore, greater loads at which participants failed to throw the barbell in a manner that created a distinct flight phase, determined by a plateau in acceleration as calculated from the LPT velocity, were excluded from this analysis.

TOS was determined for all repetitions of a bench press throw at increasing loads by calculating the intercept of the acceleration during the concentric phase with the acceleration in flight (Figure 2). Acceleration during the flight phase of the barbell is constant, as only gravity is acting on the barbell(Fontana et al., 2020) and the constant force due to friction between the Smith machine support bars and the mechanism holding the barbell along its track (Rahmani et al., 2017). The flight phase was therefore determined as the point following the concentric phase of the movement, in which acceleration was constant. The intercept between this constant acceleration and the acceleration during the concentric phase refers to the first moment the barbell changes from being accelerated by the athlete to entering its flight phase, and this point was deemed the moment of takeoff of the barbell. The velocity at this moment represents TOS (indicated by the gray circle in Figure 2), which was then used to develop the exponential model against PS.

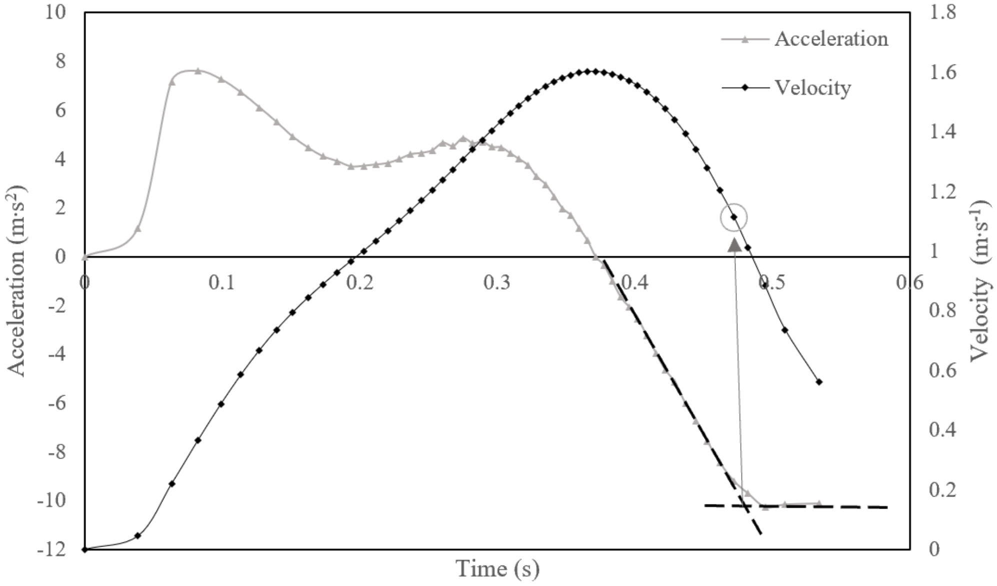


Fig. 2.2: Moment of takeoff as the intercept between negative acceleration of barbell during concentric phase of bench press throw and flight phase, as determined by having little variance (difference between points < 0.3 m·s-1), and corresponding velocity.

Statistical Analyses

Statistical analyses were performed in R (Version 1.4.1103; Vienna, Austria). The relationship between TOS and PS was assessed with an exponential model. The plot of the residuals displayed a random scatter of points, and the normality assumption was appropriate for TOS. A Shapiro-Wilk test of normality determined that predicted speeds (in both the test and training sets) were not normally distributed and appear to be skewed towards the slower velocities (W = 0.954, p = 1.291e-05). Trials were then split into a training set (n = 62) and a test set (n=116) of throws, with at least one throw per load per participant in each of training and test sets. The relationship between TOS and PS from the training set was used to establish the mathematical model applied on the test set. The exponential model ($R^2 = 0.951$) was applied to PS in the test set to obtain an estimated TOS for each test set throw, which was then compared to its corresponding measured TOS. Agreement between measured TOS and estimated TOS in the test set were compared to determine if the exponential model developed by the training set accurately predicts TOS of the barbell in a bench press throw from PS. Within-session reliability of LPT measured PS was assessed by Two-Way Mixed Model Intraclass Correlation with Absolute Agreement (ICC = 0.974 (95% CI 0.957-0.984), *SEM* of = 0.3 $m \cdot s^{-1}$), with the filter set to 0.35 m as per the LPT manufacturer guidelines. Correlation and Bland-Altman analysis was used to assess the level of agreement between measured and estimated TOS. A range of agreement was defined as mean bias ± 2*SD* with 95% of values within the limits (Giavarina, 2015).

Results

The exponential model of PS and TOS had an R^2 of 0.951 (Figure 2.3) with a Residual Standard Error of 0.138 $m \cdot s^{-1}$ on 61 degrees of freedom.

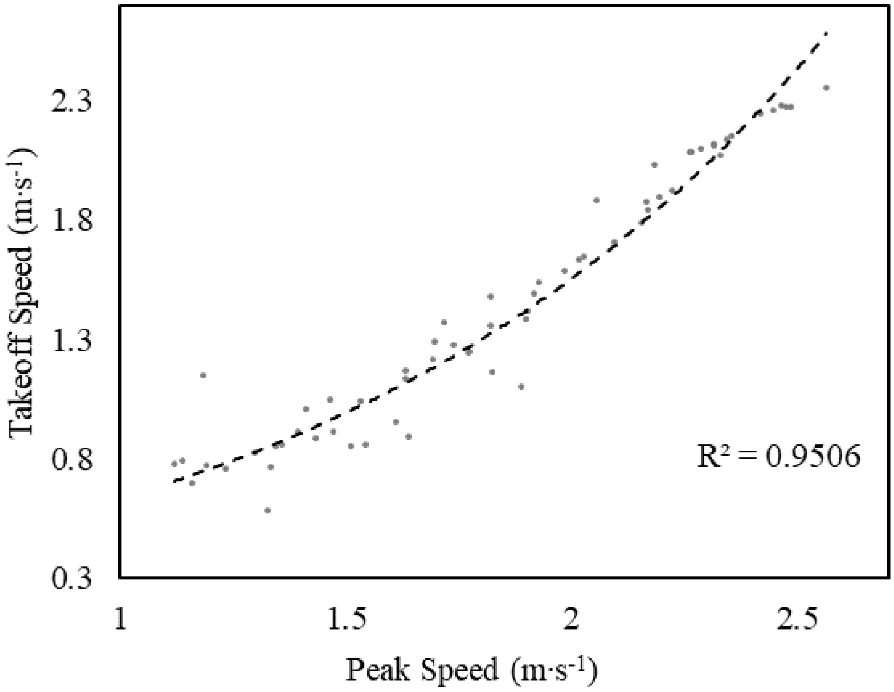


Fig. 2.3: Peak speed and Takeoff Speed in the training set, fit with an exponential model.

The exponential model determined that the relationship between TOS and PS was:

$$TOS = 0.2589e^{0.897(PS)}$$

This formula was then applied to the test set to obtain an estimated TOS, and there was a statistically significant correlation between measured and estimated TOS and ($R^2 = 0.961$) (Figure 2.4).

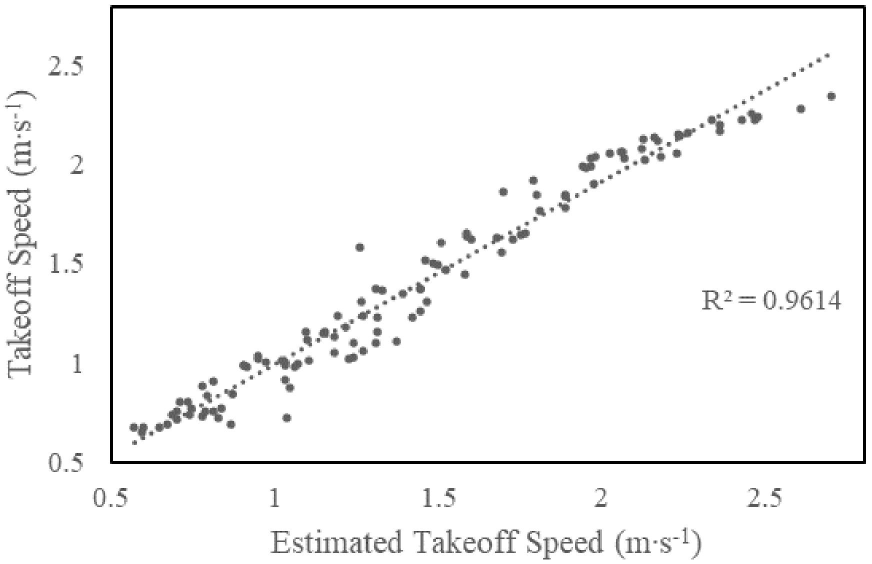


Fig. 2.4: Regression plot of estimated vs. measured TOS from the test set (n=117, R2=0.9614)

Bland-Altman analysis (Figure 2.5) indicated that the 95% limits of agreement ranged from 0.262 m·s^{-1} to 0.175 m·s^{-1}, with a mean difference of 0.043 m·s^{-1} (2.92%), and points above and below zero, suggesting no systematic bias exists between each metric. This range is within the range of ± 5% of takeoff speed, defined a priori as acceptable.

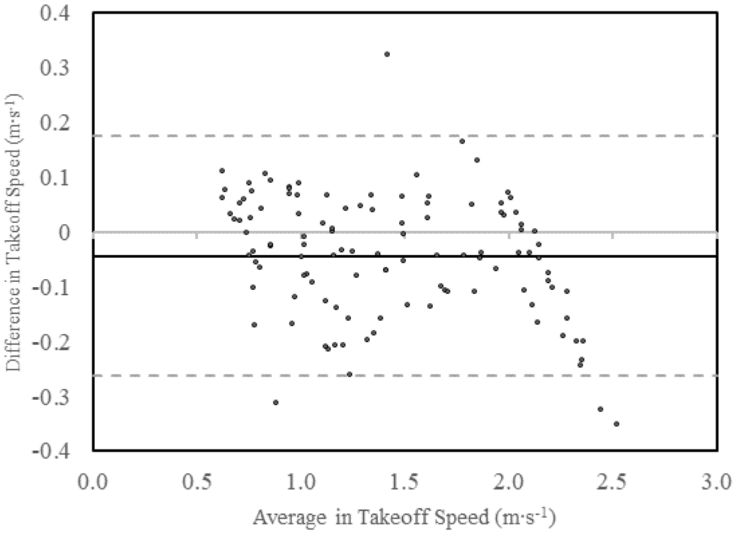


Fig. 2.5: Bland-Altman analysis of measured and estimated TOS from the test set

Discussion

This study demonstrated that TOS can be predicted from PS during a bench throw task across a range of speeds using an LPT. The relationship between PS and TOS was found to be exponential as opposed to previously reported linear relationships between PS and TOS for the lower limbs. This difference may be related to the specific task dynamics. Overall, these findings support the use of a common LPT PS output and a predictive equation, determined from this study, to calculate TOS and develop upper body FV profiles. This finding may improve the accessibility of upper body force-velocity profile assessment across different tasks.

To the authors' knowledge, this is the first study to predict barbell TOS from LPT-measured PS in an upper body ballistic task. Agar-Newman et al. (2020) first successfully applied a similar model to TOS from PS in the hexagonal bar jump, supporting the use of the LPT and the hexagonal bar for the three-factor model in lower body force-velocity profiling (Samozino et al., 2008). This study may allow practitioners to use this common LPT output to easily predict the takeoff velocity of the barbell in a bench press throw with little equipment or analysis time, rendering the task of testing large groups more accessible. The benefit of using a LPT transducer native output of PS improves efficiency of testing large cohorts without complex data collection or analysis. The strong relationship with minimal error enables practitioners' confidence in using this method. Additionally, the strong relationship between PS and TOS supports the potential to use different upper body tasks potentially without releasing the weight. As the PS precedes the TOS in projectile motion PS may still be reached without releasing the weight. While this would need to be experimentally determined, it is possible that an explosive bench press action without releasing the bar may be a suitable, and more accessible and safer alternative to a Smith machine bench throw. That is, athletes could perform an explosive bench throw technique and obtain PS during different loads and then predict a TOS to input into a 3-factor model. Additionally, the TOS predicted from the LPT may then be used to calculate other necessary variables, such as impulse-momentum. This supports the use of PS as measured by an LPT as an easily obtained variable to use in the three-component model of the upper-body force-velocity profile (Rahmani et al., 2017).

An interesting finding, and not similar to previous PS-TOS relationships, was the exponential relationship between PS and TOS in the present study. While Agar-Newman et al. (2020) found a linear relationship between PS and TOS in a hex-bar jump lower body task, there was a strong exponential relationship in this upper body bench-throw. This could be related to inherent differences between the tasks as there are notable differences between the upper body bench throw task and squat jump. First, while the system mass in both is a sum of the exercise equipment and body segments during the concentric phase, this entire mass becomes the projectile in the squat task but only the equipment becomes the projectile in the bench throw when the athlete lets the weight go. This may impact the strategy utilized when throwing vs jumping to decelerate the limbs, especially across different loads. Second, the exponential relationship, which exhibits a lower rate of change in TOS vs PS at slower velocities (and therefore heavier loads) may be explained by the technique of the bench press throw. It is known that there are distinct phases in bench press and bench press throw, including a peak speed, a "sticking region" where the velocity of the barbell plateaus and may drop before increasing again, then decreases further to the end of the concentric phase (van den Tillaar & Saeterbakken, 2012). The phases of the bench press are longer at heavier loads due to the force-velocity relationship, where the load is accelerated more slowly, and it may be that the longer deceleration phase following the PS allows the barbell to decelerate for longer before takeoff compared to lighter loads. These technical considerations may explain the exponential relationship between PS and TOS, however further research is warranted to support these claims in the bench press throw, as most work in these distinct phases has been done in the traditional, non-ballistic bench press. Also interesting is that while Agar Newman *et al.* (2020) found a strong linear relationship between

PS and TOS in the hex-bar jump, in examination of their Bland-Altman assessment, they noted some discrepancies in precision of predicted speeds in the low range. This finding could suggest a slight non-linear relationship between TOS and PS in the hex-bar task as well. They concluded that this could be related to a measurement technology issue or potentially a different movement strategy at higher loads. It has been demonstrated that when performing the bench press throw at loads approaching 1RM, the ability to create a projectile with the barbell is compromised, and this may not be a “substantial projection” of the barbell (Moir et al., 2017). This supports further exploring the nonlinear relationship in future research, where a greater range of loads may be permitted if constraints imposed by the bench press throw in this study were eliminated; i) further adjusting the initial load of the barbell to be lighter, which may allow more low-load, high-velocity throws for some participants, and ii) further familiarization with the movement that may allow greater high-load, low-velocity throws for others.

The outcome of this study supports the potential to facilitate the development and measurement of more upper body FVP tasks. Past research has focused on power-load/load-velocity profiles, and mean/peak velocity variables for bench press throw/bench press (García-Ramos et al., 2016; Iturricastillo et al., 2019; Moir et al., 2017), however the present study introduces force-velocity principles that may be applicable to both of these exercises as well as other explosive upper body tasks such as throws or pushes is other planes of movement, specific to sport demands (for example, volleyball hitting, baseball pitching, etc). While the ability to develop and measure upper body force-velocity tasks has been limited by measurement technologies, the present finding of a simple way to determine TOS from PS combined with the 3-factor model of Samozino et al. (2016b) and Rahmani et al. (2017) creates the fundamental approach that may be used in many upper body tasks.

Practical Applications

The practical applications of this project include the use of the linear mixed model to predict barbell TOS from a linear position transducer in the bench press throw, a method which is less equipment- and time-intensive than other methods.

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