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# Investigating Force-Velocity Profile Alterations and Methodology after Traditional Resistance Training

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Investigating Force-Velocity Profile Alterations and Methodology after Traditional Resistance Training

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# ABSTRACT

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The purposes of this dissertation were to examine the agreement the agreement between double integration using the trapezoidal method and measurements for push-off distance to create force-velocity profiles, examine the change in push-off distance between loading conditions when force-velocity profiling, and to observe the alterations in mechanical outputs of force-velocity profiles after 15-weeks of off-season training. The major findings are as followed. Using double integration with the trapezoidal method may be a reliable way to estimate push-off distance, despite a small systematic bias. This bias should have negligible effects on push-off distance and therefore not alter or effect calculations in a meaningful way. Therefore, using double integration for push-off distance estimation may provide the ability to retrospectively create force-velocity profiles. The analysis of change in push-off distance at each loading condition suggests that there is 5-10% change in push-off distance between conditions. The significant changes in push-off distance occurred between the bodyweight condition and 20 kg as well as bodyweight and 40 kg loading conditions. The observed mechanical output alterations after training did not yield any significant changes in mechanical outputs. However, based on the observed output changes in conjunction with the previous training, force-velocity profiling may be primarily indicative of acute training styles.

DEDICATION

This work is dedicated to my family. Through all my travels and adversity, you have remained with me as an anchor to keep me grounded. You have consistently kept faith in me, even when I all but quit. The ability to produce this work, is only because of you and how far we've come as a family.

In addition to my family, this work is dedicated to the memory of Tommy Mingle and Mike Odre. I can only hope that if you saw me now, you'd be proud of me and I live to be half the men you were.

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# Chapter 1. Introduction

Jumping is a fundamental athletic movement found in the performance and monitoring of many sports. In Sports Science and Strength and Conditioning, assessing the athlete's jumping ability is used as a field test to indirectly measure performance indicators and athlete readiness and preparation. There are two predominant forms of jumps in Sports Science and Strength and Conditioning, the countermovement jump (CMJ) and the static jump (SJ) (Markovic et al., 2004). Unlike other assessment methods for performance, vertical jump testing (both CMJ and SJ) requires minimal risk and familiarization (Moir et al., 2004), provides reliable information (Arteaga et al., 2000; Moir et al., 2005; Moir et al., 2008), and has been directly tied to athletic activities (Brughelli et al., 2008; Cronin & Hansen, 2005; Peterson et al., 2006). Additionally, vertical jump assessments have been linked to strength and power measures such as peak force, jump height, and peak power (Kraska et al., 2009; Stone et al., 2003a). Because of the relative ease of vertical jump testing as well as the performance indicators provided through the assessment make this a highly practical assessment method for practitioners in a laboratory or field setting.

The countermovement jump begins in a standing position and the jumper initiates the jump with a pre-jump countermovement, the rapid lowering of the center of mass, immediately followed by a propulsive upward acceleration. The static jump begins in a partial squat position, which is held for a short period of time before the propulsive upward acceleration. Unlike the CMJ, which generally has higher jump height, theoretically due to the stretching of the series elastic components and muscle active states (Bobbert & Casius, 2005; Ettema et al., 1992; Herzog et al., 2003) through pre-stretching, the SJ negates the pre-stretch enhancement of the stretch shortening cycle by holding the partial squat position (Turner & Jeffreys, 2010). The squat jump, in particular, is correlated with speed (Wisloff et al., 2004), lower limb explosive characteristics (Markovic et al., 2004), used for fatigue monitoring (Sams et al., 2018), as well as potential sport position and fitness identification (Furlong et al., 2021; Sporis et al., 2009; Wing, Turner, & Bishop, 2014), and force- velocity profiling (Samozino et al., 2008; Samozino et al., 2012; Wisloff et al., 2004). Therefore, the squat jump may provide valuable information that transcends jump height and may be utilized for a variety of variables indicative of performance.

Recently, practitioners have found increased utility through creating and monitoring an athlete's force- velocity profile via loaded squat jumps. Traditional research has highlighted the role of maximal power output of the lower limbs and its role on jump performance (Stone et al., 2003a; Stone et al., 2003b), however, more recent research has identified mechanical force and velocity characteristics as a contributor to performance, establishing force- velocity profiling as an assessment method to assess the athletes' maximal capabilities (Jimenez-Reyes et al., 2017; Jimenez-Reyes et al., 2019; Morin et al., 2018; Yamauchi & Ishii, 2007). The established force-velocity profile is then compared to the theoretical optimal profile for key variables like force-velocity imbalance ($FV_{IMB}$), slope ($S_{FV}$), max power ($P_{Max}$), max force ($F_0$), and max velocity ($V_0$) (Escobar Alvarez et al., 2020a; Jimenez-Reyes et al., 2017; Morin et al., 2018). Consequently, the force-velocity profile is used to drive training prescription in a manner that would aid in correcting the force- velocity profile towards the theoretical optimal and diminish any imbalance found.

Although the utility of force-velocity profiling is promising for individualized training that will enhance jump performance via jump height, observing the changes in mechanical outputs could further enhance the understanding and applicability that force-velocity profiling would have throughout the training process or through retrospective creation. However, very little information is available regarding the retrospective creation of force-velocity profiles, as well as force-velocity profile mechanical output alterations following multiple stages of training.

**Dissertation Purposes**

1. To examine the efficacy of double integration using the trapezoidal method for estimating push-off distance.
2. To determine the change in push-off distance at each loading condition used in the creation of force-velocity profiling.
3. To observe the alterations in force-velocity profile alterations following a 15-week offseason resistance training program.

**Operational Definitions**

1. Force-velocity imbalance ($FV_{imb}$): Individual imbalance between force and velocity capabilities that is present.
2. $F_0$: Theoretical force production capabilities of the lower limbs at near maximal conditions.
3. $V_0$: Theoretical lower limb force production at nearly maximal velocities.
4. $P_{max}$: Lower limb power production capabilities.
5. $S_{FV}$: Orientation of lower limb force producing capabilities, trend towards force or velocity.
6. $S_{FVopt}$: Optimal balance between force and velocity capabilities that maximize jump performance.

7. Initial height: Measurement from greater trochanter to ground during a squat with internal knee angle of 90 degrees.
8. Lower limb length: Measurement from greater trochanter to edge of toes while ankle is plantarflexed.
9. Push-off distance: Anthropometric measurement of initial height subtracted from lower limb length.
10. Push-off phase: Concentric portion of jump that is initiated from a static position and ends at the completion of the push-off distance.

## Chapter 2. Comprehensive Review of the Literature

Jumping is a fundamental athletic movement found in a variety of sports. In strength and conditioning and sports science, jumping serves as both a training tool as well as an assessment method for performance indicators and athlete readiness. Practitioners can confidently incorporate vertical jumps in training and testing due to the lack of familiarization required (Moir et al., 2004), reliability (Moir et al., 2009), and efficacy (Markovic, 2007; Stojanovic et al., 2016). Previous research on vertical jumps has reported relationships between vertical jump performance and key performance indicators such as rate of force development (RFD) and peak force (PF) (Alemdaroglu, 2012; McLellan et al., 2011), as well as other sporting movements such as sprinting (Furlong et al., 2021) and change of direction ability (Scanlan et al., 2021). Assessments utilizing vertical jumps can also be used to identify training parameters to maximize performance as well as effectively inform training. By utilizing a series of loaded static jumps, an athlete's power-load curve can be created and used to identify an intensity range at which peak power is maximized during training (Baker et al., 2001; Driss et al., 2001; Cormie et al., 2008).

Due to the usefulness and practicality of vertical jump assessments, recent advancements in technology and analytical techniques have allowed practitioners to implement a variety of assessment methods to monitor and understand training adaptations and needs. One such method is the use of a new and practical field-based method, force-velocity profiling (Samozino et al., 2008). Although there is currently an expanding field of research on the effectiveness of training interventions from the use of force-velocity profiling (Escobar Alvarez et al., 2020a; Jimenez-Reyes et al., 2017; Lindberg et al., 2021; Lindberg et al., 2022), there is a scarcity of research on its utility in athlete monitoring. Therefore, the purpose of this literature is to explore 1) the utility and rationale for vertical jump as an assessment method for lower body explosiveness, 2) establish the importance of force-velocity characteristics on performance, 3) review the use of vertical force-velocity profiling.

**Jump Assessment**

Vertical jump testing for muscular performance was originally introduced in 1921 as the Sargent test (Sargent, 1921). Since its inception, two predominant forms of vertical jump testing have been employed, the countermovement jump and static jump. The two jumping methods have become common for both practitioners (Taylor et al., 2012) and researchers (Klavora, 2000) to implement in their respective domains due to their familiarity and reliability (Cormack et al., 2008; Moir et al., 2004).

One potential reason outside of relative ease, is the strong relationships established throughout sports science research between vertical jump performance in both the countermovement jump and static jump, and the athletic performance indicators. For example, performance in the countermovement jump has been linked to sprint performance (Berthoin et al., 2001; Bret et al., 2002; Peterson et al., 2006), change of direction ability (Brughelli et al., 2008; Peterson et al., 2006), peak power (Gajewski et al., 2018; Philpott et al., 2020), and peak force (Markstrom & Olsson, 2013; Souza et al., 2020). Similarly, static jump performance has been associated with strength levels (Haff et al., 1997; Stone et al., 2003a), explosiveness (Carlock et al., 2004; Haff et al., 1997; Haff et al., 2005), sprint performance (Baker & Nance, 1999; Harris et al., 2011), and fatigue levels (Gee et al., 2011; Raastad & Hallen, 2000). Consequently, implementing jump assessment protocols provide an indirect method of assessing potential athletic performance.

Vertical jump assessments have also become common methods of talent identification. Researchers have also explored the relationship between sport specific capabilities such as sport cycling (Stone et al., 2004) and Olympic weightlifting (Carlock et al., 2004; Vizcaya et al., 2009). Fry et al. (2006) examined performance variables potentially capable of classifying elite and non-elite Olympic weightlifters, vertical jump was a significant factor in the discriminant analysis, allowing for potential talent identification based on vertical jump performance. Additionally, Teramoto and colleagues (2016) investigated and supported utilizing vertical jumps as a method of identifying position specific (running back and wide receivers) performance for National Football Players. Further research on elite level hockey players (Burr et al., 2007; Burr et al., 2008; Janot et al., 2009), soccer (Mujika et al., 2009; Wik et al., 2018), and table tennis (Picabea et al., 2021).

Athlete monitoring programs also frequently employ vertical jump assessments to assess neuromuscular function, fatigue, and provide evidence for training outcomes. As a monitoring technique, vertical jump assessments have been used to track athlete fitness throughout training and competition (Andersson et al., 2008; Cormack et al., 2008; Claudino et al., 2017; Gonzalez et al., 2012; Gonzalez-Rave et al., 2011; de Hoyo et al., 2016; Hughes et al., 2019; Ishida et al., 2021), track effects and recovery from bouts of sport related activities (Coutts et al., 2007; Jakobsen et al., 2012; McLean et al., 2010; Thorlund et al., 2009), and for high level individual athletes in competition (Malone et al., 2015; Marco-Contreras et al., 2021; Thorlund et al., 2009). By utilizing vertical jumps as an assessment method, practitioners and researchers can garner information directly related to the state of the athlete or team being tested.

**Jump Types**

One of the enticing features of jump testing for ballistic performance is the versatility of the testing methodology through the manipulation of jump types. Despite there being many different types of jumps for assessments, there are two jump types that are the most popular: static jump (SJ) and countermovement jump (CMJ) (Markovic & Jaric, 2004; McMaster et al., 2014; Taylor et al., 2012). The static jump is initiated from a semi-squat position, which is held prior to push-off to remove a countermovement and therefore is strictly a concentric movement. The countermovement jump is initiated from an upright standing position, with a rapid eccentric (descent) to lower the center of mass immediately prior to the push-off/concentric phase of the jump. Because the countermovement jump begins with the rapid lowering of the center of mass prior to push-off, it includes the stretch-shortening cycle, which is generally believed to enhance the jump performance and the associated performance indicators (McGuigan et al., 2006; Kozinc et al., 2021). Additionally, the stretch shortening cycle has generally been accepted as a reason for a greater jump height in the CMJ compared to the jump height in the SJ.

Because the CMJ contains both eccentric and concentric muscle actions while the SJ contains is strictly concentric, there are specific applications for each test. Because the CMJ utilizes the stretch-shortening cycle, it is commonly believed to test the ability to use the stretch-shortening cycle (Koznic et al., 2021). However, this belief has been disputed due to the lack of clarity regarding the underlying mechanisms involved in this performance enhancing effect (Van Hooren & Zolotararjova, 2017). In place of this potential rationale, Maarten and colleagues (1996) offer the belief that the CMJ has greater muscle stimulation from the central nervous system due to the muscle active state allowing for greater muscle activation and faster removal of muscle or tendon slack. Whereas the static jump requires the muscle and tendon slack to be taken up prior to the initiation of the movement (Van Hooren & Bosch, 2016). The relatively low levels of muscle slack in the CMJ allows for greater force production leading to the push-off phase, while the SJ requires force production being built up throughout the push-off phase (Koznic et al., 2021).

Practically, this difference is exhibited in the utility of the two jump types. Because the SJ is a concentric only movement that removes the potential effects of stretch shortening cycle of active muscle state enhancements, it can be used to identify the effects of the eccentric phase may have and thus identify training needs (Koznic et al., 2021; Van Hooren & Zolotarjova, 2017). Although there is no clear definition of what this difference reflects, decreases in the difference as a result of increasing SJ performance may reflect increases in muscle tendon stiffness and increased rate of force development (Chelly et al., 2010; Foure et al., 2010; Koznic et al., 2021). Static jump performance can also provide specific measurements because it is a concentric only movement that requires a rapid rate of force development during push-off (Fukashiro & Komi, 1987; Zushi et al., 2018). Because of this, practitioners are able to accurately measure and account for concentric rate of force development in the SJ, while the force developed during the push-off of a CMJ is dependent upon the force at the end of the braking phase and the rate at which this force is developed will be dependent on a series of confounding factors like the stretch shortening cycle (Cheraghi et al., 2017; McMahon et al., 2018; Wilson et al., 1995). The ability to directly measure concentric rate of force development can help provide necessary insight into the force-velocity capabilities of the musculoskeletal system.

**Power Output**

Power is defined as the rate of doing work and is considered by many practitioners and researchers to be an influential component to sporting performance due to the myriad of explosive tasks that regularly occur in sport. When comparing sprinters to endurance athletes, Harrison and colleagues (2004) noted a discrepancy in power testing performance, with sprinters performing significantly better than endurance athletes in jump testing, due to a greater leg stiffness and greater utilization of power. Thus, highlighting the importance of power development and utilization for sprinters and high-speed runners. This conclusion has been supported throughout research, where sprint performance is influenced by and strongly associated with peak power output (Haugen et al., 2019; Loturco et al., 2015; Smirniotou et al., 2008; Triplett et al., 2012). Similarly, research has found power output to be closely associated with jumping (Castagna & Castellini, 2013; Cronin & Sleivert, 2005; Philpott et al., 2020), combat sport attack and defense success (Athayde et al., 2017; Zaggelidis et al., 2012), and sport specific performance (Castagna & Castellini, 2013; Donahue et al., 2018). Consequently, a great deal of research has been completed to understand how training can help optimize maximal power output and measure it.

Despite power output being a well-known indicator of sport performance, directly measuring power output can be difficult for practitioners in the field, resulting in a variety of indirect measurement techniques. The Lewis formula was proposed as a way of estimating power output from the jump and reach test (Fox et al., 1989). Upon further analysis, Harman et al. (1991) determined this method of measurement was ineffective and discontinued and sought to develop alternative equations that could create a more accurate estimation of power. Although there are multiple equations that have been developed and used to estimate the measurement of power, the most prolific assessment method is through the utilization of vertical jumps.

## Loaded Jump Assessment for Power Output

When implementing vertical jump assessments, there are a variety of constraints and methodologies that can be used to provide insight into different and varying metrics related to performance. One such method is through applying a constraint of an external load. Much of the research utilizing loaded jumps has been focused on metrics such as power output to inform effective training interventions (Baker et al., 2001; Cormie et al., 2007; Feeney et al., 2016; Hilmersson et al., 2015; Mundy et al., 2016; Stone et al., 2003a). The use of loaded jumps is primarily on the underlying force-velocity relationship that exists, which underpins the calculation of power output (Darmiento et al., 2012). As the external load increases, the movement velocity decreases with a subsequent increase in muscular force. A trade-off identified and discussed by Samozino and colleagues (2012), where the maximum movement velocity of vertical jumps and the strength of the lower limbs was inversely related when maximizing power output and supported by examination of the maximum dynamic output hypothesis (Pazin et al., 2012). Therefore, training for maximizing power output and identifying the load at which optimal power output is developed will be dependent on each individual's underlying force-velocity relationship and will require individualized examination across a range of loading parameters (McBride et al., 1999; Driss et al., 2001; Pazin et al., 2012).

Currently, the range for maximizing power output during loaded jumps is between 0-59% of the subjects one repetition max (1RM) squat (Pazin et al., 2012). Stone and colleagues (2003) used both static and countermovement jumps with loading conditions between 10-100% of the subjects back squat 1RM. While power outputs were highest at 10% of the subjects one repetition max in weaker subjects, stronger subjects had peak power outputs at approximately 40% of their one repetition max (Stone et al., 2003a). In a similar fashion, using power trained athletes, the results of Baker et al. (2001) determined the range 48-63% of 1RM back squat is optimal for maximizing power output. However, when maximizing power with comparatively weak athletes, the loading condition where peak power is expressed is closer to 0% of 1RM back squat, or bodyweight without an external load (Nuzzo et al., 2010). Based on the discrepancies in loading conditions that maximize power, it is therefore clear that the accuracy of power as a metric through loaded jumps depends on the use of individualized optimal loading.

**Jump Height**

In addition to impacting the loading parameter at which maximal power production is found, absolute strength levels can also be tied to metrics closely associated to power production, such as jump height. For example, Kraska et al. (2009) confirmed previous relationships established between strength levels, power production and jumping performance in both unloaded and loaded jumps. Additionally, subjects with greater strength characteristics not only had a greater jump height, but also smaller decrements in jump height between loading conditions (Kraska et al., 2009). The relationship between jump height and muscular strength has also been found through the examination of 1RM back squat and static jumps (Haun et al., 2017). Haun and colleagues (2017) examined the relationship between both relative and absolute squat strength and jump height from static jumps. Despite both strength measures being associated, relative squat strength had the greatest associations with jump heights in unloaded and loaded conditions (Haun et al., 2017).

To help explain this disparity due to strength levels research by Stone et al. (2003b), where stronger individuals are able to express power more effectively than weaker individuals relative to their 1RM in loaded jump tasks, thus leading to a lower jump height. Further support for this explanation can be found when examining the relationship between jump height and peak power. Harman and colleagues (1990) found predictive capabilities due to the highly positive association between jump height and peak power. Other researchers have also found a similar relationship between peak power output and jump height, allowing jump height to be used as a proxy or indicator for power output (Markovic & Jaric, 2007a; Komi & Bosco, 1978).

However, recent literature has called into question the utility of using jump height as a measurement associated with power due to variables that potentially confound this relationship (Morin et al., 2018). One variable that may confound this relationship is the loading parameter used for the testing. As previously identified, there is a discrepancy in which loading condition optimizes power output for jumps, as loading will directly influence the velocity of the movement, thus affecting the power output of the movement (through laws of motion). The maximum dynamic output hypothesis, as proposed by Jaric and Markovic (2009), proposes that the optimal load for individuals that are not strength-power athletes, is their body weight without external loading. Although this has been supported through multiple sources (Jaric & Markovic, 2013; Suzovic et al., 2013), when including strength trained athletes to test the hypothesis, the results were unable to conclusively support the maximum dynamic hypothesis (Pazin et al., 2012). In combination with previously cited literature that incorporates strength-power athletes, power output during vertical jump assessments will be most closely associated with appropriate loading conditions.

Body size is another variable that may confound the relationship between jump height and peak power, while having limited impact on test performance (Morin et al., 2018). For example, Jaric and Markovic (2004) examined the impact of body size on a full testing battery of rapid movements, strength tests with external loading, and strength tests with bodyweight. The results of this study showed absolute performance in rapid movement tests (ie, countermovement jump, static jump, standing long jump, 20-m sprint) were not confounded by body size. However, when examining the relationship between body size, jump height, and muscle power through the static jump, countermovement jump, and hop test, mean muscle power is scaled geometrically with body size (Markovic & Jaric, 2005). Further support was found by Markovic and Jaric (2007), where the results indicate that muscle strength and power are partly separate locomotor abilities from jump height. Only after normalization of muscle power, body size, and jump height, were these variables closely related (Markovic & Jaric, 2007b). This relationship is further confounded without the incorporation of countermovement depth (push-off distance) based on the subject's anthropometric data. Markovic et al. (2014) examined the effects of both push-off distance and body mass on muscle power. Although the coefficient of determination for predicting jump height from muscle power were 0.41 and 0.48, from the countermovement jump and static jump, respectively, when controlling for body mass, the coefficient of determination increased to 0.63 (countermovement jump) and 0.68 (static jump). Further, power performance was negatively impacted by increasing push-off distance (Markovic et al., 2014).

**Push-Off Distance**

Being that power output is a key metric related to performance, researchers have attempted to quantify and identify the independent variables that determine peak power and create predictive equations as a result. One previous method was to incorporate jump height and body mass into the Lewis formula, to calculate peak or average power (Fox et al., 1989). However, the Lewis formula calculates the average power from gravity on the body as it falls to the ground from the apex of the jump until landing. As a result, Harman et al. (1991) created a linear model from forceplates to calculate peak power (Eq. 1).

Eq. 1: $PMax(W) = (61.9 \cdot Jump\ Height\ (cm)) + ((36.0 \cdot Body\ Mass\ (kg)) + 1{,}822$

This linear regression represents one of multiple linear regressions that were created in an effort to calculate peak power from related variables (Canavan & Vescovi, 2004; Johnson & Bahamonde, 1996; Sayers et al., 1999). However, these equations are linear and do not incorporate push-off distance and do not fully explain the variance in power outputs. As a result, Gajewski and colleagues (2018) created a nonlinear model that incorporated push-off distance, which helped accurately predict peak power outputs for each jump condition tested ($R^2$=0.895, 0.911, and 0.979).

Although push-off distance plays a role in confounding the relationship between jump height and power output has been outlined in predictive equations, the degree to which push-off distance confounds power output has discrepancies based on external load and movement effort (Markovic & Jaric, 2007b; Markovic et al., 2011; Salles et al., 2004; Vanrenterghem et al., 2004). Simulation and modeling studies initially proposed the relationship between push-off distance and jump performance through a “control that works” strategy (Van Soest et al., 1994). The “control that works” strategy proposed that the subjects jumping under varying conditions might use one or the same muscle stimulation pattern under for a range of initial postures (at the start of the push-off phase), and rely on stabilizing properties of the musculoskeletal system for successful jump performance (Van Soest et al., 1994). This proposal was disputed in further simulation studies that determined jump strategy will be altered and determined based on the jump condition itself and jump height will change as a result of this jump strategy alteration (Bobbert et al., 2008). Based on both experimental and modeling studies, jump strategy will effectively be altered based on jump condition.

Further, the degree to which this relationship is confounded is still largely unknown due to the differences in methodologies and reporting found in these studies. To address this ambiguity, Mandic and colleagues (2015) observed the effect of varying the push-off distance on jump height as well as the associated force and power metrics due to the varying depth. The results of the study indicate that greater push-off distances led to a greater jump height, yet yielded decreases in ground reaction forces and maximal power (Mandic et al., 2015). The preferred (self-selected) push-off distance was also constantly below the depth that would optimize jump performance (Mandic et al., 2015). Similar results were found in elite basketball players and sedentary individuals when comparing self-selected push-off distance to a push-off distance that was calculated to lead to the greatest jump height (optimal push-off distance) (Mandic et al., 2016). When using the self-selected push-off distance, jump heights were 5-11 cm less than the optimal push-off distance, with similar effects on both force and power output (Mandic et al., 2016). Consequently, not only will push-off distance change as a result of jump strategy for changing conditions, but also impacts and potentially confounds the relationship between jump height, force and power output.

## Vertical Force-Velocity Profiling

As a result of the confounding variables for jump height to indicate power output, Samozino and colleagues (2008) proposed a simple, field based, testing methodology that incorporates push-off distance, body mass, loading condition, and jump height from a series of unloaded and loaded static jumps. The resulting jump height, body mass, system mass, and push off distance are then used to calculate maximal force at null velocity ($F_0$), maximal extension velocity at null force ($V_0$), maximal power output of the lower limbs ($P_{max}$), the slope of the resulting force-velocity relationship ($S_{FV}$), and the slope of the theoretically optimal force-velocity relationship ($S_{FVopt}$), and the imbalance between the slope of the actual force-velocity profile and the optimal force-velocity profile ($FV_{imb}$) (Samozino et al., 2008; Samozino et al., 2012). Using these calculated values, this method's primary purpose is to test each athlete's actual force-velocity and power-velocity relationships, determine the optimal force-velocity relationship, and calculate the difference between the actual and optimal force-velocity relationship to better inform the training process for each athlete (Samozino et al., 2008).

The approach to force-velocity profiling is based on the power-force-velocity relationship that exists due to the maximal mechanical capabilities of the individual's neuromuscular system (Morin & Samozino, 2016). Force-velocity profiling consists of testing the force-velocity relationship of the lower limbs through a series of both unloaded and loaded static jumps (Samozino et al., 2008). Along with the resulting jump height (from flight time) at each loading condition, push-off distance (which is assumed constant throughout each loading condition) and system mass are then used to create a linear regression that represents the force-velocity relationship of the individual through Samozino et al. 's (2008) validated equation. The calculated linear regression is the “actual” force-velocity curve. The same information (resulting jump height, push-off distance, and system mass) is also used to create a theoretically “optimal” representation of the individual’s force-velocity relationship through the mechanical outputs supplied by the force-velocity profile (Samozino et al., 2008; Samozino et al., 2012; Morin et al., 2018). The combination of actual and optimal force-velocity curves is then used as the force-velocity profile, and the slopes of each are compared for further analysis and training intervention (Samozino et al., 2012).

Both theoretically and experimentally shown, there is an individualized optimal force-velocity profile that maximizes jumping ability and is the optimal balance between force and velocity (Jimenez-Reyes et al., 2014; Samozino et al., 2008; Samozino et al., 2012; Samozino et al., 2013; Samozino et al., 2014). The optimal force-velocity profile is represented by the percent imbalance calculated from the relative difference between the actual force-velocity slope (SFV) and the theoretically optimal force-velocity curve slope ($SFV_{opt}$) (Samozino et al., 2014). This percent imbalance also represents the magnitude and direction of the unfavorable balance, either force dominant of velocity dominant, that exists within the individual, position, and sport, and the respective deficit (Escobar Alvarez et al., 2020b; Giroux et al., 2016; Jimenez-Reyes et al., 2014; Jimenez-Reyes et al., 2019; Marcotte-Pequeno et al., 2019; Samozino et al., 2014). Interestingly, force-velocity profiles have also been shown to be sensitive to targeted training on the force-velocity spectrum (Jimenez-Reyes et al., 2017; Samozino et al., 2014). Therefore, force deficits are reduced by training dedicated to the force side of the force-velocity spectrum, and velocity deficits are reduced by training dedicated to the increasing force production at higher velocities (Samozino et al., 2012).

Identification of deficits through imbalance determination is a key factor in determining training intervention, however, enhancing $P_{max}$ is also a primary concern for force-velocity profiling (Samozino et al., 2018). Because the measurement of power output is directly associated to sport performance and jump height, but may be confounded, force-velocity profiling is used to identify the load at which peak power output occurs (Cronin & Sleivert, 2005; Castagna & Castellini, 2013; Donahue et al., 2018; Haugen et al., 2019; Loturco et al., 2015; Philpott et al., 2020; Smirniotou et al., 2008; Samozino et al., 2008; Triplett et al., 2012). This is then used to help enhance jump performance and training through its enhancement.

Because of this, Jimenez-Reyes (2017) proposed training to enhance vertical jumps should be based on reducing $FV_{imb}$ shifting the profile towards theoretically optimal as well as enhancing $P_{max}$, and coined it "optimized" training. This was individualized training based specifically on the respective deficit the force-velocity profile showed, to enhance jump performance (Jimenez-Reyes et al., 2017). Interestingly, when examining the efficacy of programming specific to force-velocity profile deficit compared to traditional resistance training, jump performance was enhanced by reducing $FV_{imb}$ alone, as well as by the reduction of $FV_{imb}$ and $P_{max}$ (Escobar Alvarez et al., 2020b; Jimenez-Reyes et al., 2017). Further exploration into the efficacy of "optimized" training revealed $FV_{imb}$ reductions accounted for 48.2% of the explained variance in static jump height changes, while $P_{max}$ accounted for 37.7% of the explained variance in static jump height changes (Jimenez-Reyes et al., 2019). Individualized training based on force-velocity profiles also exhibited greater efficiency and stability of improvements through lower levels of variability compared to traditional training styles

(Jimenez-Reyes et al., 2017). Because of these benefits, creating individualized training based on force-velocity profiles is reported to provide clear performance enhancements compared to traditional and non-individualized training programs. Therefore, the primary utility of force-velocity profiling is to drive training interventions to further optimize the force-velocity profile.

**Conclusion**

In sport science, vertical jumping is a commonly used assessment method to assess lower extremity explosiveness. Practitioners use vertical jump assessments and metrics such as power output due to their direct association with sport performance and explosive movements commonly found in sports. Although power output is strongly related to these sporting movements, monitoring techniques associated with power and testing methods to accurately calculate power output may fall short due to the confounding variables such as push-off distance and optimal loading. As a result, force-velocity profiling has been proposed as an accurate way of assessing power output, as well as a tool to drive performance enhancing training for an athlete. Therefore, the purpose of this dissertation is to 1) examine the efficacy of integrating force-time data to calculate push-off distance, a necessary variable to create force velocity profiles, 2) determine the change in push-off distance at each loading condition used in the creation of force-velocity profiling, and 3) observe the alterations in force-velocity profile mechanical outputs following a 15-week offseason resistance training program.

# Chapter 3. Agreement of Double Integration Method for Push-Off Distance Estimation from Static Jumps

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**Abstract**

The purpose of this study was to investigate the agreement between estimating push-off distance through double integration using the trapezoidal method and hand measurement. The unloaded condition for a static jump from thirty-three NCAA baseball players was used for analysis. Following jump collection, force-time data was filtered and double integrated using the trapezoidal method to estimate push-off distance. Agreement between methods was assessed using Bland-Altman plots and Pearson's Correlation. Systematic bias was assessed using Paired *t*-tests and direction of systematic bias was assessed using Bland-Altman Plots. The results indicate using double integration to estimate push-off distance is an acceptable replacement for collecting push-off distance using anthropometric measurement techniques.

**Keywords:** Double Integration, Force plates, Push-off distance

## Introduction

Sport scientists and researchers commonly use vertical jumps as an assessment method and monitoring tool for lower body explosiveness. The data provided potentially give insights into various athletic attributes such as speed (Wing et al., 2020), fatigue/readiness (Sams et al., 2018), lower limb explosive strength (Wisloff et al., 2004), talent identification (Sporis et al., 2009), and force- velocity characteristics (Markovic et al., 2004). Historically, these tests were limited to a lab-based protocol. However, with the increase in technological availability and utility of testing equipment, these types of tests can now be completed in a field-based setting using contact mats (Pueo et al., 2017), phone apps (Balsalobore-Fernandez et al., 2015), linear position transducers (McMaster et al., 2020), and force platforms (Buckthorpe et al., 2012). This increased technological availability has led to subsequent increases in the examination and formulation of methods to determine indicators such as jump height, that positively correlate to kinetic and kinematic variables such as power.

Mechanical power has been identified as a key trainable quality in athletes that strongly influences athletic performance and success in both general and sport specific tasks (Gabbett et al., 2011; Gordon et al., 2009; Haugen et al., 2019). However, the current standard of power assessment calculations has fallen under scrutiny due to the impact of structural and biomechanical variables on peak power that may confound the relationship between peak power and jump height. Although often neglected during analyses, body mass has been shown to have a positive increase on power values during a jump, while simultaneously having little impact on jump performance established through jump height (Markovic & Jaric, 2004; Jaric, 2003). As a method to account for body mass’s impact on peak power, controlling for body mass or allometric scaling can be used to normalize the variables and provide a more accurate representation of the athlete's power (Harman et al., 1991; Markovic et al., 2014). In addition to body mass confounding this relationship, countermovement or squat depth may also have a negative effect on the calculation of power (Markovic et al., 2013). This may be due to decreased ground reaction forces produced by the leg extensors as depth increases, which puts the leg extensors in a position of lower leverage (Gavrilovic et al., 1981; Hunter & Marshall, 2002). Although jump performance as exhibited through jump height may not be impacted by the decreased leverage from an increased depth, peak power may be negatively impacted (Morin et al., 2018). Thus, the key performance indicator and training variable, power, may not be adequately represented.

As a result of the potential impact of biomechanical variables such as countermovement/squat depth on power calculations, it becomes critically important to understand its importance and incorporate push-off distance, or the total extension distance of the lower limbs during the push-off phase (Morin et al., 2018). Without incorporating push-off distance into the interpretation and analysis, the results may be misleading and favor the athlete with a smaller push-off distance. However, the measurement of push-off distance generally requires measurements prior to the collection of jump data, rendering previously collected data biased and misleading when interpreting peak power. To address this concern, double integration using the trapezoidal rule to estimate push-off distance can be used, however few investigators have examined this method and its agreement with measured push-off distance in the static jump and therefore its utility in practice. Therefore, the purpose of this study was to assess the agreement between measured push-off distance and push-off distance estimated through double integration of force plate data using the trapezoidal rule.

## Methods

### *Participants*

Thirty-three NCAA Division I baseball players (mean height:1.83 m ± 0.078, mean body mass: 85.45 kg ± 10.89) participated in this study. All participants were undergoing a block periodized resistance training plan and a weekly monitoring program with jump testing. All athletes were medically cleared to participate and had the risks and benefits explained prior to signing an institutionally approved consent form. This study was approved by the Institutional Review Board at East Tennessee State University.

### *Study Design*

Hydration, body mass, body composition, and anthropometric data was collected prior to the first testing session. Hydration was collected and analyzed using urine specific gravity, acceptable hydration was deemed any value ≤ 1.020. Body mass and body composition was assessed using bioelectrical impedance (seca, mBCA 515). Push-off distance was measured by measuring and subtracting initial height from lower limb length. Initial height was measured as the distance from the greater trochanter to the ground with an internal knee angle of 90º, while the lower limb length was measured as the distance from the greater trochanter to the toe while the ankle is fully plantarflexed (Samozino et al., 2008). Three measurements for push-off distance were collected by the same collector and averaged. All jump testing was conducted on dual AMTI force plates collecting at 1000 Hz and analyzed (Vald Performance, Brisbane, Queensland, Australia).

Immediately following anthropometric data collection, athletes performed a standardized warm-up of 25 jumping jacks, mid-thigh pulls (1x5 at 0 kg and 3x5 at 60 kg) and two bodyweight warm-up static jumps. During the warm-up, athletes had their internal knee angle measured to 90º and standardized across all trials as their starting position. The barbell for loaded conditions and polyvinyl chloride pipe (PVC) was placed across the trapezius muscles for each trial. After the warm-up, each athlete completed two trials at each of the 5 loading conditions (0-80kg) with 2 minutes rest between trials and 5 minutes rest between conditions (Jimenez-Reyes et al., 2017; Morin & Samozino, 2016). For each static jump, athletes had strict instructions regarding their starting positions, and starting position was held for 2- 5 seconds prior to the jump (Jimenez-Reyes et al., 2017). Athletes were verbally instructed to jump and land back on the force platforms. Any jump with a countermovement was discarded and the trial repeated.

### *Data Processing and Analysis*

After the jump collection was completed, data from the first unloaded jump condition was downloaded and processed using Microsoft Excel (Microsoft Office, 2019). The vertical ground reaction force for both force plates was smoothed using a fourth order, 40 Hz, low pass Butterworth filter (Harry et al., 2020; Markovic et al., 2014). Initiation of the movement was identified using a 50 N threshold (Perez-Castilla et al., 2019), and final position was identified when the force platform registered zero force. The force data were then summated to find total vertical ground reaction force. Instantaneous acceleration was calculated by dividing the vertical ground reaction force by the mass of the athlete multiplied by the change in time (0.001 sec). Instantaneous velocity was calculated by adding the product of instantaneous acceleration to the previously calculated velocity using Eq. 1.

Equation 1: $V1 = V0 + (((a1 + a2) * (t2 - t1))/2)$

Position was then calculated by using the trapezoidal rule and integrating velocity data through Eq. 2.

$$\text{Equation 2: } P2 = P1(((v2 + v3) * (t3 + t2))/2)$$

Push-off length was calculated by subtracting position at take-off from the previously established starting position of the first unloaded jump.

### *Statistical Analysis*

Three measured trials of push-off distance were collected by the same rater and averaged. Reliability of measured push-off distance was assessed through standard error of measurement and a 2-way mixed effects, single measurement intraclass correlation coefficient (ICC) with absolute agreement. Agreement between the integrated and measured push-off distances were examined through Bland-Altman Plots and Pearson's Correlation. Systematic bias was assessed through Paired *t*-tests and direction of systematic bias was assessed through Bland-Altman Plots. Alpha level was set to $p<0.05$. Correlation coefficient was qualitatively interpreted through previously established criteria: trivial (< *0.1*), small (*0.1-0.3*), moderate (*0.3-0.05*), large (*0.5-0.7*), very large (*0.7-0.9*), nearly perfect (*0.9-1*), perfect (*1*) (Hopkins et al., 2009). All statistical analyses were performed using IBM's Statistical Package for Social Sciences (IBM SPSS for Windows, Version 27, SPSS Inc., Chicago IL).

## Results

Standard error of the measurement for the three trials was *0.005* m (*95% CL:* ± *0.011 m)* and showed a high degree of reliability (ICC: 0.992; *95% CI: 0.986 - 0.996)* (Weir, 2005). There was a statistically significant relationship between the integration method for push-off distance and the measured push-off distance (*r = 0.924*; *95% CI: 0.849 - 0.963*). The relationship between the integration method for push-off distance and the measured push-off distance was nearly perfect. The Paired *t*-test found significant differences (*p*= 0.0044; *95% CI*: -0.0216 to -0.0036 m) between the integrated push-off distances and the measured push-off distance, indicating systematic bias. Bland-Altman Plot (Figure 1) showed a mean bias of -0.0126 m between the integrated and measured push-off distances.

**Figure 1.1**

***Bland-Altman Plot with Agreement Lines***

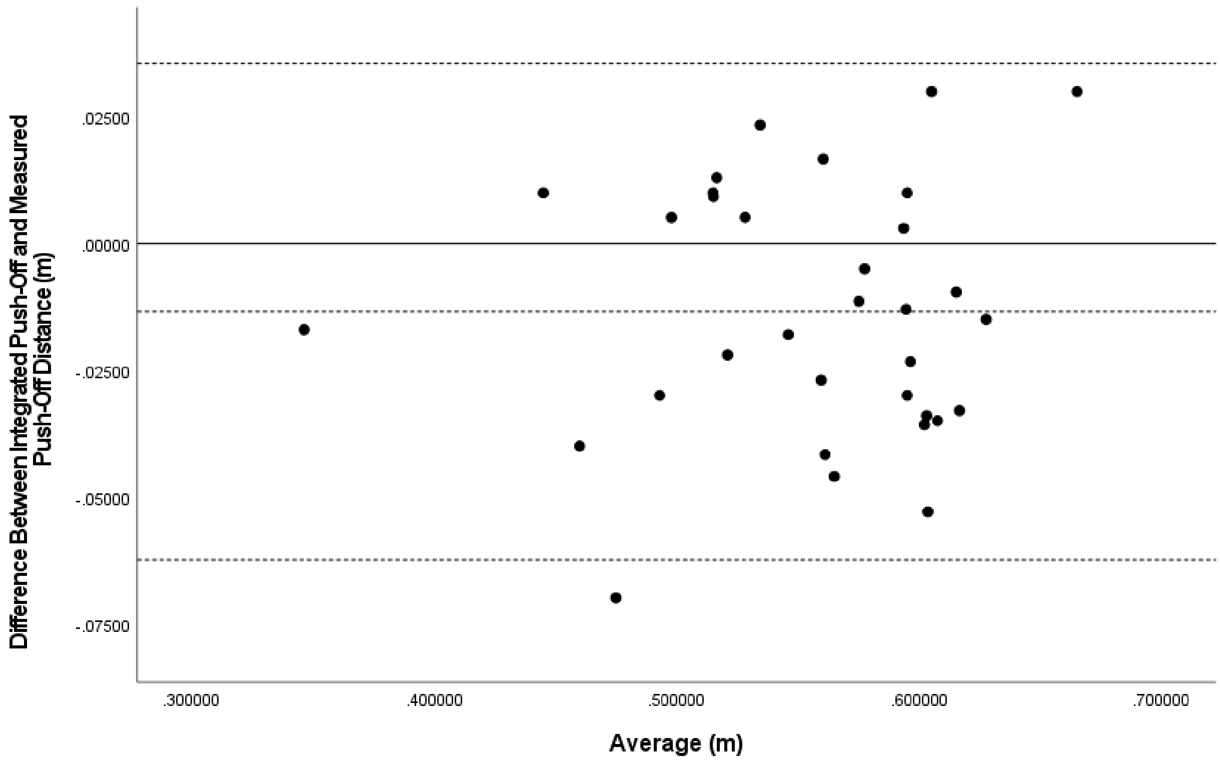


*Figure 1: Bland Altman Plot establishing the agreement between double integration using the trapezoidal method and measured push-off distance. Mean difference was -0.0126, upper limit of agreement at 95% confidence interval was 0.0362, lower limit of agreement at 95% confidence interval was -0.0615.*

## Discussion

The purpose of this present study is to investigate the agreement between the current method of attaining push-off distance and the use of double integrating data collected from force plates. Although the use of double integrating using the trapezoidal rule is not a novel concept, this is the first study to examine its direct utility compared to anthropometric measurements during the static jump. Estimating push-off distance with double integration can be especially important for the creation of force-velocity profiles. When creating a force-velocity profile, three measurements are necessary: body mass, push-off distance, and jump height (Samozino et al., 2008). Both power and force calculations employed in force-velocity profiling directly rely on having a measurement for push-off distance (Samozino et al., 2008). The calculated systemic bias and the associated limits of agreement suggest that practitioners are likely to observe a difference of as much as 0.011 m between prior measurement and double integration. The effect of a difference of such magnitude should be investigated in each specific setting to choose the method that is most appropriate for monitoring purposes.

Previous literature has found questionable results when implementing a method double integrating force- time data for countermovement jumps and static jumps due to potential integration drift, and velocity calculation errors. These errors potentially lead to poor reliability of countermovement depth and push-off time (Carroll et al., 2019; Lindberg et al., 2021). However, due to the nature of static jumps being a more stable measure and the methodology, it is possible that integration drift caused by deviations in baseline weight did not occur, which remains consistent with reliability measures when integration drift is carefully avoided (Mandic et al., 2015). Further, unlike the previous literature which did not utilize a conservative threshold for jump initiation, the integration process in this study used for the analysis utilized a 50 N threshold, which has acceptable reliability for integration compared to less conservative thresholds (10 N, 1% System Weight, 20 N) (Perez-Castilla et al., 2019). The use of a conservative threshold may be necessary for reliable measures as seen in this study.

There is one limitation for the study worth noting that should be addressed in future research. First, although the 50 N threshold provides acceptable reliability for unloaded static jumps, using a threshold of 5 standard deviations of system weight minus 30 ms may provide better reliability (Perez-Castilla et al., 2019). The enhanced reliability may be due to more force signal being retained for analysis (Perez-Castilla et al., 2019). Future research should focus on implementing a tertiary method of estimating push-off distance through motion capture and videography or the use of other technology and establish the agreement between push-off loading conditions as well as other methods.

In conclusion, the use of double integration for push-off distance provides a potential manner of assessing push-off without collecting anthropometric data prior to testing or the creation of force-velocity profiles. This would aid in the development of research by allowing practitioners to take previously collected data, and retrospectively create force-velocity profiles for analysis. Although the results of this study found an underestimation of push-off distance, the impact of this underestimation should be investigated in each practical setting. Practitioners should ensure they are utilizing a conservative movement threshold as well as ensuring each trial's weighing phase is inspected prior to integration, as this may impact the resulting data.

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## Chapter 4. Alterations in Push-Off Distance Between Jump Conditions When Force-Velocity Profiling

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**Abstract:**

The purpose of this study was to assess the change in push-off distance between conditions used when creating force-velocity profiles with unloaded and loaded static jumps. Using double integration with the trapezoidal method, push-off distance was estimated for five jump conditions (0 kg, 20 kg, 40 kg, 60 kg, 80 kg). Following a Shapiro-Wilkes test for normality, alterations in push-off distance were assessed using a one-way repeated measures ANOVA with Holm-Bonferroni post hoc corrections for multiple comparisons. Magnitude of effect was qualitatively assessed using Cohen's d, and overall deviation of push-off distance for every individual was investigated using percent change. The results of the study indicate significant differences between push-off distance at bodyweight and push-off distance at 20 kg and 40 kg, respectively. Based on the results, practitioners should consider measuring push-off distance in a loaded condition or apply strict methodologies to eliminate variation throughout loading conditions.

**Keywords:** Force-velocity profile, Push-off distance, Double Integration

## Introduction

Jumping ability is one of the most common and fundamental aspects of sport and performance training due to its direct application to sport as well as its utility for monitoring and assessing lower body power capabilities. The ability to produce power is dependent on the neuromuscular system to produce high levels of force that can be applied efficiently during a high velocity muscle contraction and is considered to be a performance indicator in many sporting endeavors (Cormie et al., 2011; Cronin & Hansen, 2005; Cronin & Sleivert, 2005). Because of their relation to power, the assessment of force and velocity capabilities becomes increasingly important for practitioners. However, accurate evaluation of force and velocity capabilities are often limited to lab-based equipment such as ergometers (Arsac et al., 1996), linear position transducers (Garcia-Ramos et al, 2015), force plates (Harman et al., 1991; Raymond et al., 2018), or motion analysis systems (Martinez-Cava et al., 2020). As a result, there has been an increasing need for simple, field-based methods that do not require the use of historically lab-based equipment.

One such method is the assessment of vertical force-velocity profiles, a method of quantifying force and velocity characteristics that was designed to be used by practitioners in the field with limited access to lab-based equipment (Samozino et al., 2008). Through the collection of system mass, push-off distance, and jump height (static jumps measured at a series of loading conditions), mechanical outputs are used to create a linear regression that represents the individual's force and velocity relationship as well as a linear regression that represents the theoretically optimal relationship (Morin and Samozino, 2016; Samozino et al., 2008; Samozino et al., 2013). The difference between the slopes of the linear regression and the theoretically optimal regression are compared to determine the force-velocity imbalance ($FV_{imb}$), and then used to drive training that enhances mechanical outputs and purportedly diminish $FV_{imb}$ (Alvarez et al., 2020; Jimenez-Reyes et al., 2017; Samozino et al., 2013).

The current method of force-velocity profiling assumes push-off distance that is measured in an unloaded position and remains constant for every loading condition in the calculation of jump height (Jimenez-Reyes et al., 2017; Samozino et al., 2008). Because of this presupposition, any deviations in push-off distance during a loaded jump may provide a source of error in mechanical output values when creating a force-velocity profile. This error could influence the results of the testing protocol and ultimately the training recommendations derived from it. Therefore, the purpose of this study was to examine the alterations in push-off distance for static jumps at different loading conditions.

## Methods

### *Participants*

Data from 28 athletes (n=28, age 20.07±1.41 years, height 1.82±0.07 m, body mass 84.83±10.73 kg) were included in this study. All athletes were competitive at the National Collegiate Athletic Association (NCAA) Division I level in the sport of Baseball. All athlete data were previously collected as part of an ongoing athlete monitoring program. All data included were approved by the East Tennessee State University Institutional Review Board.

### *Study Design*

Hydration, body mass, body composition, and anthropometric data was collected prior to the first testing session. Hydration was collected and analyzed using urine specific gravity, acceptable hydration was deemed any value ≤ 1.020, and testing commenced only when acceptable hydration was reached. Body mass and body composition was assessed using bioelectrical impedance (seca, mBCA 515). Push-off distance was calculated by measuring and subtracting initial height from lower limb length. Initial height was measured as the distance from the greater trochanter to the ground with an internal knee angle of 90º, while the lower limb length was measured as the distance from the greater trochanter to the toe while the ankle is fully plantarflexed (Samozino et al., 2008). Three measurements for push-off distance were collected by the same collector and averaged. All jump testing was conducted on dual AMTI force plates collecting at 1000 Hz and analyzed (Vald Performance, Brisbane, Queensland, Australia).

Immediately following anthropometric data collection, athletes performed a standardized warm-up of 25 jumping jacks, mid-thigh pulls (1x5 at 0 kg and 3x5 at 60 kg) and two bodyweight warm-up static jumps. During the warm-up, athletes had their internal knee angle measured to 90º and standardized across all trials as their starting position. The barbell for loaded conditions and polyvinyl chloride pipe (PVC) was placed across the trapezius muscles for each trial. After the warm-up, each athlete completed two trials at each of the 5 loading conditions (0 kg, 20 kg, 40 kg, 60 kg, 80kg) with 2 minutes rest between trials and 5 minutes rest between conditions (Jimenez-Reyes et al., 2017; Morin & Samozino, 2016). For each static jump, athletes had strict instructions regarding their starting positions, and starting position was held for 2- 5 seconds prior to the jump (Jimenez-Reyes et al., 2017). Athletes were verbally instructed to jump and land back on the force platforms. Any jump with a countermovement was discarded and the trial repeated.

### *Data Processing and Analysis*

After the jump collection was completed, data from the first unloaded jump condition was downloaded and processed using Microsoft Excel (Microsoft Office, 2019). The vertical ground reaction force for both force plates was smoothed using a fourth order, 40 Hz, low pass Butterworth filter (Harry et al, 2020; Markovic et al., 2014). Initiation of the movement was identified using a 50 N threshold (Perez-Castilla et al., 2019), and final position was identified when the force platform registered zero force. The force data were then summated to find total vertical ground reaction force. Push-off distance was calculated for the first jump at each loading condition by subtracting position at take-off from the starting position that was established based on internal knee angle.

### *Statistical Analysis*

Individual alterations in push-off distance across five loading conditions were examined through a one-way repeated measure ANOVA following a Shapiro- Wilk test for normality. A Holm- Bonferroni post hoc correction was used to assess significant F- ratios and used to account for multiple comparisons. Alpha level was set as $p<0.05$. Cohen's *d* was used to assess magnitude of effect. Magnitude of effect was qualitatively interpreted through previously established criteria: trivial (*0.0- 0.2*), small (*0.2-0.6*), moderate (*0.6-0.1.2*), large (*1.2-2.0*), very large (*2.0-4.0*), nearly perfect (≤*4.0*), perfect (∞) (Hopkins et al., 2009). Percent change was calculated to determine the overall deviation in push-off distance between loading conditions and bodyweight condition for all athletes. All statistical analyses were performed using JASP (JASP Team, Version 0.16, Microsoft Windows).

**Results**

The results of the one-way repeated measure ANOVA showed there was a statistically significant main effect of loading condition on push-off distance ($F(4,108)=4.706$, $p=0.002$, $\eta^2_p=0.148$). Bonferroni post hoc tests (Table 1) showed statistically significant differences and medium effect sizes between bodyweight push-off distance and two loading conditions (20 kg and 40 kg).

**Table 1**

***Alterations of Push-Off Distance***

| | | | 95% CI for Mean Difference | | | | |
|---|---|---|---|---|---|---|---|
| | | Mean Difference (m) | Lower | Upper | Cohen's d | $p_{bonf}$ | Effect Size |
| **BW** | **20 kg** | 0.039 | 0.007 | 0.072 | 0.694 | 0.01 | Moderate |
| | **40 kg** | 0.039 | 0.003 | 0.067 | 0.632 | 0.024 | Moderate |
| | **60 kg** | 0.034 | -0.0009 | 0.069 | 0.561 | 0.062 | Small |
| | **80 kg** | 0.026 | -0.009 | 0.061 | 0.426 | 0.325 | Small |
| **20 kg** | **40 kg** | -0.004 | -0.027 | 0.018 | 0.108 | 1 | Trivial |
| | **60 kg** | -0.005 | -0.037 | 0.027 | 0.09 | 1 | Trivial |
| | **80 kg** | -0.013 | -0.046 | 0.02 | 0.231 | 1 | Small |
| **40 kg** | **60 kg** | -0.00008 | -0.032 | 0.03 | 0.015 | 1 | Trivial |
| | **80 kg** | -0.009 | -0.035 | 0.017 | 0.199 | 1 | Trivial |
| **60 kg** | **80 kg** | -0.008 | -0.4 | 0.024 | 0.147 | 1 | Trivial |

*Holm-Bonferroni corrected p-value ($p_{bonf}$)*

Although not statistically significant, in reference to the bodyweight push-off distance, the 60 kg condition and the 80 kg produced a small effect size. Table 2 contains the group average for percent change for each loaded condition relative to the body weight condition.

**Table 2.**

***Descriptive Statistics for Change in Push-Off Distance Per Condition***

| | Loading Condition | | | | |
|---|---|---|---|---|---|
| | **BW** | **20 kg** | **40 kg** | **60 kg** | **80 kg** |
| **Mean (m)** | 0.556 | 0.517 | 0.521 | 0.522 | 0.531 |
| **Std. Deviation (m)** | 0.053 | 0.05 | 0.048 | 0.045 | 0.055 |
| **Avg Percent Change ± Standard Deviation** | | -6.2 ± 9.9% | -5.5 ± 9.4% | -4.9 ± 11.2% | -3.52 ± 10.9% |
| **Mean Percent Change LL** | | -14.1 | -13.0 | -13.9 | -12.2 |
| **Mean Percent Change UL** | | 1.7 | 2.0 | 4.1 | 5.2 |

*Percent change is calculated relative to the bodyweight condition.*

## Discussion

The aim of this study was to assess the changes in push-off distance at each loading condition for static jumps used during force-velocity profiling, relative to the measured push-off distance collected prior to jump trials. The results of this study indicate that the loading condition for the jump trial has an effect on push-off distance with statistically significant differences in the 20 kg ($p$=0.01, %Δ: -6.2 ± 9.9%) and 40 kg ($p$=0.024, %Δ: -5.5 ± 9.4%) conditions.

When utilizing force-velocity profiling, jump height is calculated through the use of flight time, and kept constant throughout Samozino and colleagues (2008) “simple” method (Jimenez-Reyes et al., 2017; Samozino et al., 2008). However, the results of this study indicate that the push-off distance during a 20 kg and 40 kg loaded jump is likely to vary by as much as 0.07 m, even when depth is monitored. Our mean percent changes for the 20 and 40 kg conditions (Table 2) are consistent with the findings of Lindberg et al. (2021) and the 5-10% variation found in push-off distance across trials and loading conditions. The larger variation in push-off distance when using free weights may be due to alterations in athlete jump strategy across the loading conditions that occur to optimize jump height, despite maintaining an initial internal knee angle of 90º (Bobbert & Knoek van Soest, 2001; Williams et al., 2018), while a smith machine may provide more control over center of mass displacement leading to less variation.

Although the results provide further evidence of variation in push-off distance across at least 20 kg and 40 kg loading conditions, there are four limitations that should be noted. The first limitation is that it is not clear how influential the change in push-off distance is on the actual calculations of force-velocity profiles. Future research should incorporate the average change in push-off distance into force-velocity profiles to examine the effect. The second limitation is the use of free weights instead of smith machines. Although free weights provide a more practical testing methodology, it also makes the standardization of center of mass using knee angle comparably more difficult to a smith machine and may lead to increased variation. Future research on push-off distance alterations should focus on implementing both the smith machine and free weights. A third limitation is the use of standardized loading instead of relative loading. For the athletes with lower levels of relative muscular strength, their trials were completed at a higher intensity compared to athletes with higher levels of muscular strength, which may introduce a source of variance in movement strategy (Kim et al., 2021). In the future, researchers should consider using conditions based on relative strength and consider assessing push-off distance variance at relative strength levels. However, it should be noted that loads encountered in real-life situations including sports, are not relative loads but absolute in nature, this this study provided a measure of ecological validity. The fourth limitation is the absence of video analysis or motion capture for assessing push-off distance changes in conjunction with assessing jump strategy alterations that may occur throughout each condition. This would provide much needed context and insight for the variance seen when using free weights compared to smith machines.

In conclusion, push-off distance collected and measured using Samozino and colleagues (2008) methodology is not constant throughout all trials and loading conditions. Practitioners that implement force-velocity profiling and subsequently measure push-off distance should exercise caution when using push-off distance that was collected only in an unloaded condition. Attention should also be given to reducing variation of push-off distance through the use of practice trials and strict depth monitoring protocols.

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# Chapter 5. Alterations in Force-Velocity Profile in a 15-week Off-season Resistance Training Program

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**Abstract**

The purpose of this study was to retrospectively observe the change in force-velocity profile mechanical outputs ($F_0$, $V_0$, $F_{0\text{-Rel}}$, $P_{max}$, and $FV_{IMB}$) following 15-weeks of off-season resistance training in NCAA baseball players. Twenty-one NCAA Division I athletes engaged in a series of five unloaded and loaded static jumps immediately before and following a 15-week off-season training program. Testing data was retrospectively used to create force-velocity profiles and a paired samples *t*-test with a Bonferroni correction to adjust for multiple comparisons was used to assess changes. Cohen's d was used to qualitatively assess mechanical output changes. The results indicate moderate, but non-statistically significant changes in $V_0$ and $P_{max}$, while $FV_{imb}$, $F_0$, and $F_{0\text{-Rel}}$, incurred small non-statistically significant changes. Based on the results, the changes in mechanical outputs potentially reflect the training completed immediately prior to the testing, and not chronic training adaptations.

**Keywords:** Force-velocity Profile, Force-velocity imbalance, Loaded Jumps

## Introduction

Ballistic movements, such as jumping, have historically been used as a method of training and assessment due to the strong, direct relationship shared with numerous sporting movements. Sporting movements such as change of direction (Brughelli, et al., 2012; Nimphius, et al., 2010; Pereira, et al., 2018), sprinting (Delecluse, et al., 1995; Coutts et al., 2004; Nimphius, et al., 2010; Rimmer & Sleivert, 2000), and jumping (Nuzzo, et al., 2008; Rousanoglou, et al., 2008), require the athlete to generate high movement velocities in short time periods, and directly depend on the force-velocity (FV) characteristics and power-producing capabilities of the athlete's lower limbs. As a result of this increased interest in human muscular FV characteristics, Samozino et al. (2008) proposed FV profiling as a means of assessing an individual's potential to generate muscular force and movement velocity and to track these characteristics across the FV spectrum (Samozino & Morin, 2008; Samozino, et al., 2010). Samozino et al (2008) propose that FV profiling may provide insight into an individual's propensity for muscular power production and provide direction for the programming considerations of future sport training.

FV profiling has been suggested as an assessment for muscular power, in part, due to recent scrutiny directed towards the relationship between external power and jump height (Morin et al., 2018). A strong correlation between jump height and maximum power ($P_{max}$) has been reported (Markovic et al., 2014) leading to the development of various jump protocols which have been used to assess lower limb power producing capabilities (Cormie, et al., 2020; Hunter & Marshall, 2002). Despite interesting findings and potential implications purported by authors of correlational studies, jump height may provide limited insight into external power measurements due to a variety of factors which may not easily be accounted for, such as individual push-off distance, movement loading characteristics, and body mass (Linthone, 2020). Without accounting for the effects of these variables, the calculation of key metrics may be susceptible to estimation error and misrepresent the athlete's capabilities, creating a need for a more comprehensive and accurate evaluation.

The most common method of FV profiling includes a series of squat jumps (unloaded and loaded), in conjunction with system mass, push-off distance, and jump height (from flight time) from any method of jump height collection (Feeney, et al., 2016; Giroux, et al., 2016; Jimenez-Reyes, et al., 2017; Samozino, et al., 2013). The information from each load condition is then used to create two FV relationship curves using Samozino and Morin's (2008) validated predictive equation. The first curve is the "actual" FV curve, that encompasses the entire FV spectrum, from a theoretically derived maximal force at minimal velocity ($F_0$) to a theoretically derived maximal velocity at minimal force ($V_0$). While the second relationship represents a mathematically derived, theoretical, "optimal" FV curve that is individualized based on the vertical displacement of the individual's center of mass and maximal power output (Samozino et al., 2013). The actual FV curve is then compared to the theoretically optimal curve to assess the relative difference in magnitude and direction ($FV_{IMB}$), which determines the deficiencies in the athlete's FV characteristics (Escobar Alvarez, et al., 2020; Jimenez-Reyes et al., 2017; Jimenez-Reyes, et al., 2019; Samozino et al., 2013). Quantifying the magnitude and direction of $FV_{IMB}$ to inform and drive training has been suggested to be an effective method for reducing deficiencies and increasing $P_{max}$ on an individual level (Jimenez-Reyes et al., 2017; Jimenez-Reyes et al., 2019). Interestingly, when comparing this method of individualized training based on force-velocity profile outputs to traditional training, individualized training based on force-velocity profile was more efficient at reducing $FV_{IMB}$, increasing $P_{max}$ and jump performance (jump height) (Jimenez-Reyes et al., 2017).

Current literature on FV profiling has only examined its utility and effectiveness for direct interventions based on $FV_{IMB}$ and $P_{max}$, while neglecting to consider previous training (Escobar Alvarez et al., 2020; Jimenez-Reyes et al., 2017; Jimenez-Reyes et al., 2019). To date, there is a paucity of observational research examining individual FV profile alterations as a result of a long-term periodized training plan, without interventions based on FV profile parameters. Therefore, the aim of this study is to retrospectively examine FV profile alterations following a 15-week, block periodized training plan.

## Materials and Methods

### *Subjects*

Data from 21 male athletes (n = 21, age 19.8 ± 1.21 years, height 1.83 ± 0.08 m, weight 83.49 ± 11.54 kg) with a minimum of one-year training experience were included in this study. All athletes were competitive at the National Collegiate Athletic Association (NCAA) Division I level in the sport of Baseball. All athlete data were previously collected as part of an ongoing athlete monitoring program. Participants indicated their compliance and agreement with all study methods and consented to the anonymous use of data and results by reviewing and signing an informed consent document. All study methods and materials received expressed approval by the university's Institutional Review Board.

### *Initial Testing*

This retrospective study was designed to examine Force-Velocity profile alterations after 15 weeks of off-season resistance training. Pre-testing was conducted 72 hours before the initiation of the first week of training and post-testing was conducted at the end of the final week of training, following 48 hours rest.

Hydration, body mass, body composition, and anthropometric data were collected prior to the first testing session. Hydration was collected and analyzed using urine specific gravity, acceptable hydration was deemed any value ≤ 1.020. Body mass and body composition was assessed using bioelectrical impedance (SECA, mBCA 515). Push-off distance was measured by measuring and subtracting initial height (distance from greater trochanter to ground) when internal knee angle is 90 degrees, from lower limb length (greater trochanter to toe while plantarflexed) (Samozino, et al., 2008). Three measurements for push-off distance were collected by the same researcher and averaged. All jump testing was conducted on dual AMTI force plates collecting at 1000 Hz and analyzed (Vald Performance, Brisbane, Queensland, Australia).

Immediately following anthropometric data collection, athletes underwent a standardized warm-up of 25 jumping jacks, mid-thigh pulls (1x5 0 kg and 3x5 60 kg) and two bodyweight warm-up squat jumps. During the warm-up, athletes had their internal knee angle measured to 90 degrees and standardized across all trials as their starting position. The barbell for loaded conditions and polyvinyl chloride pipe (PVC) was placed across the trapezius muscles for each trial. After the warm-up, each athlete completed two trials at each of the 5 loading conditions (0 kg, 20 kg, 40 kg, 60 kg, and 80kg) with 2 minutes rest between trials and 5 minutes rest between conditions. For each jump, athletes followed strict instructions regarding their starting positions, and the starting position was held for two-to-five seconds prior to the jump. Athletes were verbally instructed to jump and land back on the force platforms. Any jump with a countermovement was discarded and the trial repeated.

### *Resistance and Athletic Training*

A 15-week off season training program utilizing concentrated loading was administered for the 15-week off-season training period (Table 1). Strength training was performed three times per week, averaging approximately 60 minutes per session. The training program is shown in Table 3 and Supplementary Table 1. Sport specific field sessions were also implemented 5 to 6 days per week by the head sport coach. Weekly hours were strictly regulated to 20 hours of athletic activity per week by the NCAA and each resistance training session was separated by 48 hours and 24 hours between sport specific practice. All resistance training sessions were supervised by two Certified Strength and Conditioning Specialists (NSCA-CSCS) and verbal feedback was given throughout each session.

**Figure 3.1**

***General Overview of 15 Weeks Training***

| Annual Plan | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Test 1 | Week 1 | Week 2 | Week 3 | Week 4 | Week 5 | Week 6 | Week 7 | Week 8 | Week 9 | Week 10 | Week 11 | Week 12 | Week 13 | Week 14 | Test 2 |
| OFF | Accumulation 1 | | | | | | | Accumulation 2 | | Transmutation | | | | | |
| OFF | Return to Fitness | | | Strength Endurance | | | | Basic Strength | | Max Strength | | | | Speed-Strength | |
| OFF | VL: 6,309 ± 3,754 | | | VL: 21,380 ± 8,150 | | | | VL: 16,850 ± 5,786 | | VL: 12,415 ± 4,132 | | | | VL: 4,434 ± 4,245 | |

*Volume Load calculations include sport specific practice/training, speed and conditioning, and all accessory exercises. Data are presented in mean ± SD (kg).*

**Figure 3.2**

***Programming Overview***

| Periodization Phase: | Accumulation 1 | | Accumulation 2 | Transmutation*** | |
|---|---|---|---|---|---|
| **Fitness Phase:** | **Return to Fitness** | **Strength Endurance** | **Basic Strength** | **Max Strength** | **Speed-Strength** |
| **Day 1** | BS 3x5 | BS 3x10 | BS 3x5 | Plyometrics** | Plyometrics** |
| | BB BP 3x8 | BB BP 3x10 | BB BP 3x5 | Complex: BS 3x3/CMJ 3x2 | Complex: BS CS 3x2x2/DJ 3x1 |
| | DB Lateral Lunge 3x8 | SB Step Up 3x10 | BB SS 3x5 | BB BP 3x3* | BB BP CS 3x2x2* |
| | DB Tricep Ext, 3x10 | MS | LMP 3x5 each | BB SS 3x3 | BB SS 3x3 |
| | | | | RLMP 3x3 | RLMP 3x3 |
| **Day 2** | CGDL 3x5 | TBDL 3x10 | TBDL 3x5 | Accel/Decel Drills** | COD Drills** |
| | PU 3x8 | BB Row 3x10 | BBl SLDL 3x5 | TBDL 3x3* | MTP 3x3* |
| | DB SLDL 3x8 | Neutral PU 3x10 | Neutral PU 3x5 | BB Row 3x5 | TBDL 3x3* |
| | DB Rear Delt Fly 3x10 | MS | DB SA Row 3x10 | Neutral PU 3x5 | BB Pendlay Row 3x3 |
| | | | | NC 3x5 | Neutral PU 3x3 |
| | | | | | NC 3x3 |
| **Day 3** | FS 3x5 | BS 3x5 | Complex: (CGDL, CP, MTP) 3x3 | MTP 3x3 | Plyometrics** |
| | BB OHP 3x5 | BB SLDL 3x10 | FS 3x5 | BS 3x3 | MTP 3x3* |
| | TRX Hamstring Curls 3x8 | BB OHP 3x10 | BB PP 3x5 | BB PP 3x3 | Complex: BS CS 2x2x2/DJ 3x1 |
| | TRX Inverted Row 3x10 | MS | BB Row 3x5 | BB SLDL 3x5 | BB Pendlay Row 3x3 |
| | | | | | NC 3x3 |

BB = barbell, DB = dumbbell, CS = cluster set, BS = back squat, FS = front squat, SS = split squat, BP = bench press, LMP = landmine press, RLMP = rotational landmine press, OHP = overhead press, MTP = mid-thigh pull, CP = clean pull, PP = push press, CLDL = clean grip dead lift, TBDL = trap bar dead lift, SLDL = stiff-legged dead lift, SA = single arm, PU = pull ups, NC = nordic curl, CMJ = countermovement jump, DJ = drop jump, COD = change of direction, MS = midsection
* Indicates 1-3 down sets were performed.
***Indicates beginning of plyometric work

## *Data Analysis*

Mean force and mean velocity were calculated using two equations based on the variables body mass, push-off distance, and jump height from flight time (Samozino et al., 2008). A linear regression was fitted to the average force and velocity for each loading conditioning. The variables $F_0$ and $V_0$ were established as the intercepts from the linear regression at the corresponding force and velocity axis, and then used to calculate $P_{max}$ (($F_0$ * $V_0$)/4) (Samozino et al., 2013). The force-velocity profile imbalance, percent of optimal, was calculated using Samozino's method (Samozino et al., 2013).

### *Statistical Analysis*

Force-velocity profiles for each of the 21 athletes were created for both testing sessions (pre- and post-training). Paired samples *t*-tests were used to assess the changes in all FV-variables between testing sessions ($F_0$, $V_0$, $F_{0\text{-}Rel}$, SFV, $SFV_{opt}$, $P_{max}$, and $FV_{IMB}$). Alpha level was set as $p<0.05$. A Bonferroni adjustment was used to address multiple comparisons. FV-variable alterations were also assessed using standardized effect size outlined in Hopkins et al. (2009). Percent change was calculated to further evaluate changes in each mechanical output. All statistical analyses were performed using the Statistical package for Social Sciences (IBM SPSS for Windows, Version 27, SPSS Inc., Chicago IL).

## Results

None of the variables associated with the created force-velocity profiles were statistically different between the two testing conditions, which is supported by the reported 95% CI's and associated *p*-values. However, variables $V_0$ and $P_{max}$ both incurred moderate non-statistically significant changes, while SFV, $SFV_{opt}$, $F_0$, and $F_{0\text{-}rel}$ demonstrated small non-statistically significant changes. $FV_{imb}$ also exhibited a small non-statistically significant change (Table 3). $V_0$ and $P_{max}$ exhibited the greatest pre-post percent change, while $F_0$ and $F_{0\text{-}rel}$ remained relatively stable with small decreases in percent change (Table 4).

**Table 3**.

***Changes in variables associated with Force-Velocity profiles***

| | | | 95% CI for Cohen's d | | |
|---|---|---|---|---|---|
| **Variable** | **p** | **Cohen's d** | **Lower** | **Upper** | **Effect Size Change** |
| $F_0$ | 0.303 | 0.231 | -0.206 | 0.662 | Small |
| $F_{0\text{-}rel}$ | 0.314 | 0.226 | -0.211 | 0.656 | Small |
| $V_0$ | 0.123 | 0.351 | -0.788 | 0.094 | Moderate |
| $P_{max}$ | 0.183 | 0.301 | -0.735 | 0.14 | Moderate |
| $FV_{imb}$ | 0.266 | 0.25 | -0.188 | 0.681 | Small |
| SFV | 0.269 | 0.248 | -0.68 | 0.189 | Small |
| $SFV_{opt}$ | 0.518 | 0.144 | -0.288 | 0.572 | Small |

*$F_0$ (N), theoretically maximal force; $F_{0\text{-}rel}$ (N/kg), theoretically maximal force relative to body mass; $V_0$ (m/s), theoretically maximal velocity; $P_{max}$ (W), maximal power; $FV_{imb}$, imbalance between actual profile and optimal profile; SFV, slope of actual force velocity profile; $SFV_{opt}$, slope of optimal force velocity profile.*
*Alpha-Bonferroni = 0.007*

**Table 4.**

***Mechanical Outputs***

| **Variable** | **Pre ± SD** | **Post ± SD** | **%Δ ± SD** |
|---|---|---|---|
| $F_0$ | 2582.94 ± 383 | 2466.11 ± 394.81 | -2.79% ± 21.3 |
| $F_{0\text{-}rel}$ | 30.70 ± 3.49 | 29.27 ± 4.92 | -3.25% ± 21.77 |
| $V_0$ | 1.67 ± 0.33 | 1.80 ± 0.404 | 9.59% ± 23.34 |
| $P_{max}$ | 1062.18 ± 178.48 | 1095.47 ± 208.67 | 4.4% ± 17.76 |
| $FV_{imb}$ | 86% ± 35.27 | 77% ± 33.85 | -5% ± 39 |

*$F_0$ (N), theoretically maximal force; $F_{0\text{-}rel}$ (N/kg), theoretically maximal force relative to body mass; $V_0$ (m/s), theoretically maximal velocity; $P_{max}$ (W), maximal power; $FV_{imb}$, imbalance between actual profile and optimal profile*

**Discussion**

The aim of this study was to implement force-velocity profiling observationally and examine alterations in force-velocity profiles following a 15-week off season training plan. To the authors' knowledge, this is the first study to use force-velocity observationally during a planned off-season resistance training program. Previous literature evaluated the effectiveness of individualized training based on individual $FV_{imb}$, and found such methods beneficial in increasing performance indicators through individualized training compared to traditional/"non-optimized" training (Escobar Alvarez et al., 2020; Jimenez-Reyes et al., 2017; Simpson et al., 2020). However, these previous investigations determined the efficacy of training based on improvements in FV-variables, neglecting to consider the context of the most recent training block completed prior to post-training testing. In the present training study, athletes completed a strength speed training block immediately prior to the post-test session. This block uses low training volumes of velocity dominant exercises completed at a moderate-to-high loading intensities in order to enhance rate of force development (RFD) characteristics and muscular power while retaining strength adaptations emphasized in previous blocks of training (DeWeese et al., 2015; Suchomel et al., 2017). The observed increase in $V_0$ and $P_{max}$, and the increased force deficit reflected by the $FV_{imb}$ alterations are consistent with the emphasis of the most recent training block. de Lacey et al. (2014). observed a similar trend in FV profile mechanical outputs following a 21-day taper, where the training completed prior to the taper was predominantly force dominant movements with few explosive movements and largest mechanical output change following the taper was $F_0$. Based on these observations, the resulting alterations to mechanical outputs of force-velocity profiling following training may be indicative of the acute effects of training rather than the chronic effects, which would potentially explain why the last training block (speed-strength) exhibited alterations in mechanical outputs rather than mechanical output alterations expected from performing earlier training blocks (strength).

Interestingly, the mechanical output alterations observed in the current study were only small to moderate. This may have been due to an insufficient training duration during the final strength speed training block and lack of realization phase or taper, absent during this off-season training plan. A major goal of the taper is to diminish fatigue through the reduction of training volume and intensity which may facilitate the realization of latent residual training effects. This rationale has been supported in previous block periodization research with longer training duration, where the greatest performance alterations were observed immediately after a taper (Suarez et al., 2019; Wetmore et al., 2020). Therefore, further increases in performance would be expected if a taper were to be programmed and implemented. Interestingly, $F_0$ and $F_{0\text{-rel}}$, remained relative unchanged, despite a small decrease observed between testing sessions. The stability of the force values follows a similar trend seen in the work of Suarez and colleagues (2019) and Hornsby et al. (2017), despite the lack of realization phase in the current study which was present in these previous training studies which implemented block periodized training.

An additional consideration for the "optimization" (training designed specifically from $FV_{imb}$) of training is the consistency in individual response when $FV_{imb}$ serves as the basis for programming compared to a general traditional resistance training program after which had a relatively large, reported variability among the mechanical outputs ($F_0$, $P_{max}$, $FV_{imb}$) and was observed (Escobar Alvarez et al., 2020; Jimenez-Reyes et al., 2017; Simpson et al., 2020). Although inconsistent with "optimized" training, the inter-individual variability in the degree of adaptive response found in this study (change in $F_0$: -2.79% ± 21.3, $V_0$: 9.59% ± 23.34; $P_{max}$: 4.4% ± 17.76; $FV_{imb}$: -5% ± 39) is in line with previous literature that utilized a general training program to enhance a variety of characteristics or performance indicators (Cormie et al., 2010; Harris et al., 2000; McBride et al., 2002). However, it is important to distinguish whether this variability should be treated as a feature of the current training paradigm, or a flaw. When engaged in a program dedicated to the dissolution of $FV_{imb}$, the developer of the training program presupposes that a force or velocity imbalance is a flaw that requires dedicated focus and correction to optimize performance (Samozino et al., 2013). At this point, it is unclear that training dedicated to diminishing $FV_{imb}$ will facilitate the development of training adaptations and residuals that may be necessary to promote optimal athletic performance (Mallo, 2012; Ronnestad et al., 2018; de Souza et al., 2006). Further, Giroux and colleagues (2016) observed athletes of different sports exhibiting differing balanced force-velocity profiles, highlighting the diversity of each sporting endeavor, and suggesting that a natural and beneficial $FV_{imb}$ may be sport-specific. Although comparisons between sports is beyond the scope of this study, the majority (16 out of 21) of athletes tested had a pre-training $FV_{imb}$ favoring velocity. This may be a sport specific $FV_{imb}$ that occurs as a byproduct of specific sporting skill development, supporting the findings of Giroux et al. (2006).

Although this is the first study to use force-velocity profiling observationally over the course of a 15-week resistance training plan, and not a method to drive intervention, there are limitations that must be discussed. First, the population in this study contains athletes of varying degrees of training experience beyond one year. This leads to a discrepancy of both strength levels and experience with exercises and testing methods. As a result, some of the athletes were required to spend time learning new movements, which may have compromised the optimal progression of fitness characteristics compared to more experienced individuals. Second, as this training plan was implemented during an off-season period, the training plan did not include a realization block, which may be necessary to realize adaptations and F-V profiles which baseball athletes would ideally experience closer to competition (Suarez et al., 2019; Wetmore et al., 2020). Third, during the training period, athletes were also engaged in extensive sport specific training that included varying ranges of sport/position specific activity that culminated the night prior to the second testing session. We speculate this additional training may have induced position-specific fatigue which may have affected performance during resistance training sessions and may have influenced the force-velocity profile for each athlete.

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# Chapter 6. Summary and Future Directions

The overall purpose of this investigation was to observe and assess the utility of force-velocity profiling through the mechanical output changes after non-individualized resistance training. To complete this task, the following were completed as individual research projects: 1) an assessment of the agreement of double integration method for push-off distance estimation from static jumps, 2) an examination of the alterations in push-off distance between jump conditions when force-velocity profiling, and 3) a retrospective examination of alterations in force-velocity profile after 15-weeks of an off-season training program.

The results of study I indicated that double integrating force-time data using the trapezoidal method sufficiently estimated push-off distance in place of using hand measurements for the anthropometric information that accounts for push-off distance. The integration method allows for retrospectively creating force-velocity profiles in addition to accounting for push-off distances confounding of the key performance indicator peak power. An interesting additional finding of this study was the small systematic bias when double integrating, where push-off distance was slightly underestimated. However, the impact of the underestimation should be negligible on calculations of power as well as the creation of force-velocity profiles. Therefore, this method was found to be a reliable method of estimating push-off distance for future utilization by practitioners and researchers.

In the initial methodology and research on force-velocity profiling, push-off distance is assumed constant throughout loading conditions. However, variances in the push-off distance across the loading conditions within research and conflicting results between studies have been reported. Therefore, study II sought to determine the alterations in push-off distance between loading conditions. The results of study II indicate the largest changes in push-off distance occurs between the bodyweight condition and 20 kg, as well as bodyweight and 40 kg. Interestingly, the results also indicated a 5-10% variance between loading conditions across all participants, despite maintaining a standardized internal knee angle. It is speculated that the change in push-off distance may be due to a difference in hip extension or limited plantar flexion during the push-off phase.

Studies I and II were successful in 1) identifying the reliability and utility of double integration using the trapezoidal method for push-off distance estimation, and 2) identifying push-off distance alterations between loading conditions for force-velocity profiling. Study III sought to retrospectively observe alterations in mechanical outputs of force-velocity profiling following a 15-week off-season training program. Throughout the literature on force-velocity profiling, creating individualized training interventions aimed at reducing the result imbalance between the actual force-velocity slope and the optimal force-velocity slope, has been the primary focus. Consequently, this study aimed to fill the current void of observational research on traditional and non-individualized training. However, Study III was unable to find any significant changes after the 15-weeks of training, with only small changes in the mechanical outputs associated with force variables that were the focus of early training phases, and moderate changes in the mechanical outputs associated with the velocity and power variables that were the focus of the training immediately prior to testing. Despite the lack of meaningful changes, the results suggest that force velocity profiling may reflect the training emphasis immediately prior to jump testing, and not chronic training adaptations.

Although this dissertation was successful in providing potential avenues for researchers and practitioners to critically examine and implement force-velocity profiling, future research is necessary for expanding the current knowledge and utility of force-velocity profiling. One particular area of interest is how the variation in push-off distance alters the force-velocity profile and the potential training prescription that follows. Another area of interest is implementing force-velocity profile testing at the end of each training phase, throughout an entire periodized annual plan. This would help elucidate whether force velocity profiling predominantly assesses acute or chronic adaptations from training programs. Providing this additional information will aid in the creation of testing batteries and monitoring programs that can further enhance the training and understanding of training responses that are necessary for further athletic improvement.

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