Using Vertical Force-Velocity Profiling to Predict Swim Start Performance

by

Kieran Phillips

Bachelor of Science (Honours), University of Victoria, 2023

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

in the School of Exercise Science, Physical & Health Education

University of Victoria

We acknowledge and respect the Ləkʷəŋən (Songhees and Esquimalt) Peoples on whose territory the university stands, and the Ləkʷəŋən and W̱ SÁNEĆ Peoples whose historical relationships with the land continue to this day.

Using Vertical Force-Velocity Profiling to Predict Swim Start Performance

by

Kieran Phillips

Bachelor of Science (Honours), University of Victoria, 2023

Supervisory Committee

Dr. Marc Klimstra, School of Exercise Science, Physical & Health Education

Supervisor

Dana Agar-Newman, University of Victoria Strength and Conditioning Coordinator

Co-Supervisor

Abstract

Key Words: *Strength and conditioning, resistance training, power*

The purpose of this study was to investigate the relationship between vertical force-velocity profiles (FVP) and swimming start performance. Twenty-four varsity-level swimmers (14 females and 10 males) with a mean age of 19.84 ± 1.50 years and body mass of 72.34 ± 7.39 kg were sampled from a varsity swimming program. Participants completed a FVP consisting of loaded squat jumps on force plates across four loads (female: 0.5 kg, 15 kg, 30 kg, 45 kg; male: 0.5 kg, 20 kg, 40 kg, 60 kg) and two maximal swimming starts during the same training week. Swim start performance was quantified using dive distance and time to 10 m. Multiple linear regression identified theoretical maximal force (F_0) as a significant predictor of dive distance ($\beta = 0.0212$, R^2 adjusted = 0.61, $p < 0.001$) with no interaction effect being found for F_0 and Sex. In contrast, none of the FVP variables significantly predicted time to 10 m, likely due to a high variability in underwater technique. This study highlights the importance of maximal strength for improving dive distance. However, for an athlete's strength and power capacities to transfer to overall start performance, athletes must also dedicate time to practicing the start action itself.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I would like to acknowledge the individuals who made this project possible. First, thank you to my academic supervisors, Dr. Marc Klimstra and Dana Agar-Newman for both their support in this project, and for their guidance and mentorship across all aspects of my academic and professional journey. I would also like to thank the University of Victoria Vikes swim coaches Peter Vizsolyi and Ryan Clouston for being so willing to engage in research and share their expertise. Finally, my biggest thank you goes to the athletes for taking part in this study, for making the early morning and late-night sessions so fun, and for growing with me over the last 3 years.

Chapter 1. Introduction

Swimming Start Performance

The swimming start is a ballistic movement that is essential for maximizing performance in the sport, especially for short distance events, as the start can account for up to 26% of the total race time (Cossor & Mason, 2001; Garcia-Hermoso et al., 2013). At the highest level of competitive swimming, medals are often decided by as little as 0.01 s. Therefore, small improvements in starting performance can potentially alter medal outcomes for swimmers, highlighting the importance of optimizing start performance though specific training. The swimming start is usually defined as the time from the starting signal to when the swimmer crosses the 15 m line as this is the distance a swimmer is allowed to travel underwater before breaking the surface and beginning the free swim phase in freestyle, backstroke, and butterfly (Cossor & Mason, 2001; Slawson et al., 2013). Despite accounting for less overall time than the free swim phase, the start is crucial in swim events, as swimmers reach peak velocities of up to 4.48 m/s, more than twice the typical 1.8 - 2 m/s achieved during free swimming (Cossor et al., 2011; Honda et al., 2010).

The swim start is typically divided into 3 phases: the block phase, flight phase, and underwater phase (Tor et al., 2015). The block phase is described as the time from the starting signal to when the swimmer leaves the block, the flight phase is from when the swimmer leaves the block to when they enter the water, and the underwater phase is from when the swimmer enters the water until they resurface to begin free swimming, with each phase contributing approximately 11%, 5%, and 84% to the total start time, respectively (Slawson et al., 2013; Tor et al., 2015). A deterministic model of each of these phases and their biomechanical and anthropometric determinants is presented in Figure 1 (Thng et al., 2019).

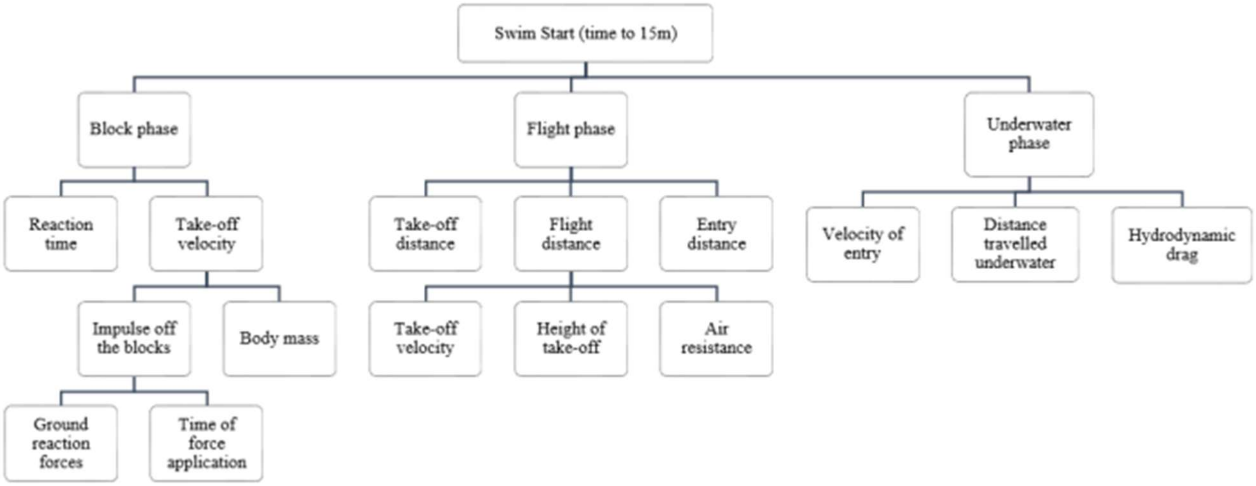

Figure 1. Deterministic model of swimming start performance (Thng et al., 2019).

Block Phase

During the block phase, the swimmer must react to the start signal quickly and maximize horizontal take-off velocity. The technical execution of the block phase involves the swimmer beginning the action by pulling on the blocks with the arms while simultaneously executing a ballistic extension of the lower body to maximize horizontal take-off velocity. A ballistic action in the context of this paper is defined as a movement where the goal is to maximally accelerate a mass, typically resulting in a take-off phase (Samozino et al., 2012)

A large horizontal take-off velocity during the block phase has been shown to be one of the most important kinematic parameters of start performance because it affects both flight distance during the flight phase and underwater velocity during the underwater phase, which are both important determinants of start performance (Galbraith et al., 2008; Matúš et al., 2021; Peterson Silveira et al., 2018; Tor et al., 2015). Take-off velocity is directly proportional to the impulse (product of ground reaction force and block time) relative to body mass applied during the block phase, and therefore a large amount of force applied against the blocks quickly is a determining factor of performance (Slawson et al., 2013). Importantly, a short block time is also associated with increased start performance (Mason et al., 2007; Vantorre et al., 2010). It takes swimmers approximately 0.12 - 0.14 seconds to respond to the start signal with a total time of 0.75-0.77 seconds on the block (Papic et al., 2019; Tor et al., 2015). Dedicated training of the start may improve reaction time among adolescent swimmers which may allow for increased time to apply force during the block phase without extending overall block time (Papic et al., 2019). Due to the need for short block times, the ability to produce a large amount of force quickly is necessary for the swimmer to produce a large impulse without extending block time and is thus important for performance.

Takeoff velocity during the block phase is also affected by start technique (Ozeki et al., 2012). Classically, the two most common start techniques include the grab start, where both feet are placed at the front edge of the starting block, and the track start, where one foot is placed at the front edge of the starting block while the other foot is positioned near the back with the athlete in a staggered stance (Dassoff et al., 2017). In 2008, FINA (Fédération Internationale de Natation) introduced the OSB11 starting block (OMEGA, Zurich, Switzerland) which included the addition of an adjustable kick plate slanted at a fixed angle of 30° at the rear of the block. Swimmers are able to utilize the angled kick plate to increase horizontal force application through the rear leg, resulting in a larger horizontal takeoff velocity (Beretić et al., 2012; Honda et al., 2010; Ozeki et al., 2012). Utilizing this technique (termed the kick start) can significantly improve time to 5 m and 15 m compared with the track start technique performed on the previous staring block and has thus become the standard start technique among competitive swimmers (Ozeki et al., 2012).

Flight Phase

The flight phase of the start is defined as the time between the swimmer's feet leaving the block until the time the apex of the head contacts the water (Tor et al., 2015). An increased dive distance has been shown to be positively related to start performance (Cossor & Mason, 2001), as maximizing the time and distance where the swimmer is not experiencing the drag forces imparted by water is important. Following the laws of projectile motion, dive distance is primarily determined by height of the blocks, take-off velocity, and launch angle. Because height of the blocks remains constant in all strokes except backstroke, takeoff angle plays a significant role in jump distance (Matúš et al., 2021). Take-off angles for competitive male swimmers are approximately 40° (Matúš et al., 2021). Entry angles similarly range from approximately 35-48°, with some researchers suggesting that flatter entry angles are associated with an increase in start performance, up to a minimum of approximately 35° (Alptekin, 2014; Dijk et al., 2020; Tor et al., 2014). A shallow entry angle is important in order to maintain horizontal velocity, although entry angles which are too steep result in an increase in surface area when contacting the water, resulting in a significant loss of velocity upon entry (Dijk et al., 2020; Takeda et al., 2014).

Underwater Phase

The underwater phase is defined as the time from when the swimmer’s head breaks the surface of the water to when they re-surface and begin the free swim phase. The velocity achieved during the underwater phase is a key determinant of the velocity achieved during the free swim phase, highlighting the importance of optimizing the underwater phase for swimming performance (Veiga & Roig, 2016). Further, the underwater phase of the start is the phase where the swimmer is travelling at the highest velocity underwater (Tor et al., 2015; Veiga & Roig, 2016). The greater velocities observed during the underwater phase are primarily determined by 1) the entry angle and velocity following the flight phase and 2) the drag forces affecting the swimmer.

There are three primary sources of drag that act on a swimmer as they move through the water: friction drag (also called skin drag), form drag (also called pressure drag), and wave drag (Tor et al., 2015). Friction drag represents the resistance produced by the frictional force between the water and the surface of the swimmer and can be modified by external factors that can reduce surface roughness such as racing suits or shaving (Naemi et al., 2010). Form drag is the result of the differences between pressure at the leading and trailing edges of the body (Naemi et al., 2010). Minimizing form drag requires the swimmer to adopt an effective streamline position with their arms outstretched above their head in order to reduce cross-sectional area (Marinho et al., 2009). Finally, wave drag represents the energy lost by creating waves around the swimmer and is therefore only significant at or near the surface (Vennell et al., 2006). Wave drag can have the strongest detrimental effect on the swimmer's underwater velocity compared with skin and form drag and thus it is important that swimmers maintain an adequate depth (approximately > 0.6 m) for as long as possible during the underwater phase (Vennell et al., 2006). Swimmers are also allowed unlimited undulatory kicks (except in breaststroke where they are allowed a single kick) which can contribute to propulsive forces and reduce the overall loss in velocity while underwater (Von Loebbecke et al., 2009).

Differences Between Strokes

For the three ventral strokes (freestyle, butterfly, and breaststroke), start techniques are generally very similar. All three events begin from the elevated starting block using whichever start technique they prefer and technique during the block and flight phases are similar. However, there are differences during the underwater phase which can affect start performance between strokes. Specifically, in freestyle and butterfly events, there is no limit to how many leg undulations that are permitted during the underwater phase, whereas for breaststroke, only a single undulation of the legs and a single arm pull are allowed before the athlete is required to surface and begin the breaststroke movement. Thus, freestyle and butterfly starts allows swimmers to maintain a streamline position for longer, increase propulsion through more undulatory kicking, and remain farther below the surface of the water where drag forces are minimized (Tor et al., 2014). These differences result in start times for freestyle and butterfly being significantly faster compared with Breaststroke (Born et al., 2021; Morais et al., 2019). The backstroke start is unique in that it begins with the swimmer partially submerged in the water. Backstroke also has slower overall start times compared with freestyle and Butterfly because swimmers achieve lower takeoff velocities and must spend less time in the air (Born et al., 2021).

Summary of Swim Starts

In summary, maximizing performance in the start can significantly improve overall swimming performance. Start performance is primarily determined by the takeoff velocity off the blocks, takeoff and entry angles, and reduction of drag forces underwater to maintain velocity into the free swim phase.

Importance of Muscular Strength and Power for Swimming Performance

Generating a high horizontal takeoff velocity off the starting blocks is one of the key indicators of performance for swimming starts. Take-off velocity is determined by the impulse relative to body mass applied to the block. Because of the importance of minimizing block time (Matúš et al., 2021), increasing the amount of horizontal force that can be applied to the starting blocks seems to be an effective method of increasing horizontal takeoff velocity. It has been suggested that resistance training could improve the swimmer's ability to produce force against the starting blocks through development of specific neuromuscular qualities related to maximal force production

(Miller et al., 1984) and many researchers have examined which strength and power measures are the most closely related to swimming start performance in order to help design effective training prescriptions to improve force application during the start.

There is considerable evidence that measures of dry-land strength and power are associated with swimming start performance. Jump performance (e.g. height, distance) in vertical and horizonal jumping tasks is among the most frequently compared measurement to start performance, perhaps because of its similarity to the swim start itself, with both dry-land jump tests and swim starts being ballistic actions resisted only by body mass. Bodyweight vertical jumps such as countermovement jumps (CMJ) and squat jumps (SJ) have shown large to nearly perfect correlations (r = 0.69 - 0.96) to swim start performance (Benjanuvatra et al., 2007; Calderbank et al., 2020; Keiner et al., 2015; Santos et al., 2022; West et al., 2011). Horizontal jumping tests are also strongly correlated with entry distance, (r = 0.85) (Calderbank et al., 2020). Jump height achieved during loaded squat jumps (25%, 50%, 75%, and 100% of body mass) have also shown strong correlations with time to 5 m, 10 m, and 15 m (García-Ramos, Padial, et al., 2016). In a study investigating which the force-time characteristics derived from SJ measured using force plates, Thng et al. (2020) found that concentric impulse was the most important kinematic variable for predicting times to 5 m and 15 m in both males and females (R^2 = 0.66 - 0.84), which is likely due to the importance of impulse applied to the blocks, and because swim starts consistent of primarily a concentric muscle action (Tor et al., 2015).

Many studies have shown similar relationships of vertical jump tests to start performance across various distances, typically 5 m, 10 m, or 15 m. However, some studies have observed much stronger relationships between dry-land tests and time to 5 m compared with times to 10 m or 15 m using freestyle grab and track start techniques (Benjanuvatra et al., 2007; García-Ramos, Tomazin, et al., 2016). It is suggested that vertical jump ability may not have a strong impact on the underwater phase of the start due to the importance of other factors including anthropometric characteristics and underwater technique (García-Ramos, Tomazin, et al., 2016). In contrast, Thng et al. (2020) found that force-time variables derived from a SJ explained a greater proportion of the variance of time to 15 m than time to 5 m, potentially due to the contribution of the legs to the undulatory kicking motion during the underwater phase using freestyle kick start technique. These contradictory findings could be explained by methodological differences including different start techniques, level of athlete, or sex of samples (Benjanuvatra et al., 2007; García-Ramos, Tomazin, et al., 2016).

Traditional strength exercises and measures of maximal lower limb strength such as barbell back squat and barbell deadlift also have large correlations with time to 15 m (Keiner et al., 2015). Among moderately trained male swimmers, barbell bench press and back squat was able to explain 50% of the variance in time to 15 m (Keiner et al., 2021). In line with these findings, peak force and rate of force development achieved during a maximal isometric contraction of the knee extensors can predict time to 10 m in high-level male swimmers ($R^2 = 0.75$) (Beretić et al., 2013).

There is a comparatively small number of studies that have investigated the relationships of in-water starts (i.e. backstroke) and dry land tests. DeBruyn (1979) found that backstroke, butterfly, and breaststroke all had moderate ($r = 0.51 - 0.60$) correlations to vertical jump tests while freestyle showed large correlation ($r = 0.73$). More recently, Keiner et al. (2015) observed that backstroke performance had the weakest correlations with CMJ and SJ jump height, bench press, bent-over row, and deadlift 1-repeition maximum tests compared with freestyle and breaststroke. Because the backstroke start begins partially submerged and exhibits very different takeoff angels, more research is needed to understand how the physical determinants of in-water starts differ from block starts.

Several studies have also observed an improvement in swim start performance following plyometric or resistance training programs (Yu Kwok et al., 2021). Bishop et al. (2009) completed an 8-week plyometric program in a group of adolescent swimmers and found a significant improvement in start time compared with controls. Rejman et al. (2017) completed a similar 8-week plyometric training intervention in nine national level swimmers and found an increased start performance compared to pretesting values, however no control group was included in this study. Unfortunately, the authors of both studies did not measure dry land vertical jump performance before or after the training intervention which limits the ability to draw conclusion about any causal relationship between improvements in muscular capacity and swim starts. Breed & Young (2003) implemented an 8-week resistance training intervention in a group of 23 non-competitive swimmers and found that resistance training improved horizontal impulse and performance when using the track start technique, but not in the grab start technique, compared with controls. Since the track start allows for a greater force application (Honda et al., 2010), it is possible that athletes can better utilize improvements in neuromuscular ability to enhance their performance in the track start compared to the grab start. Lastly, improvements have been observed following a 17-day training camp at high altitude (García-Ramos, Padial, et al., 2016). However, because the primary objective of the study was to investigate the effects of altitude and because of its short duration, it is difficult to draw conclusions from this study.

A limitation in the current body of literature is that most studies comparing dry land tests to start performance use only correlational analyses (García-Ramos, Padial, et al., 2016; García-Ramos, Tomazin, et al., 2016; Keiner et al., 2015, 2021; Santos et al., 2022; West et al., 2011).

While correlations can describe the nature of the relationship between two variables, they are unable to explain the direction of the relationship. Furthermore, many studies exclusively compare performance outcomes of dry-land tests such as jump height, and do not assess the movement strategy (e.g. the kinematic components of the jump such as force, velocity, time, and impulse) (Bishop et al., 2023). Further research is needed to investigate which muscular characteristics contribute most to start performance.

In summary, there is strong evidence to support the relationship between dry-land exercises such as unloaded vertical and horizontal jumps, plyometrics, loaded jumps, and traditional strength training exercises such as back squat and deadlifts. If the goal is improving start performance, practitioners should implement strength training programs which have the goal of increasing maximal force production and jumping ability. While specific training recommendations for improving these capacities is beyond the scope of this paper, practitioners should follow general principles of strength and power training, first developing basic strength using full range of motion strength exercises, then building on these qualities by developing power using exercises such as plyometrics and Olympic weightlifting movements (Wirth et al., 2022). Concurrent to these dry-land training modalities, it is likely important that swimmers have direct and purposeful practice of the starts for these adaptions to transfer to a sport-specific context (Wirth et al., 2022).

Force-velocity Profiling as a Measure of Ballistic Performance

Performance in ballistic actions, such the swimming start, is determined by both an athlete's maximal power capacity as well and their individual force-velocity profile (FVP) (Morin & Samozino, 2016). To calculate an athlete's FVP, a series of jumps must be completed across a spectrum of loads. Utilizing a three-factor model consisting of jump height, system mass (sum of subject mass and external load), and the push-off distance, the average force, average velocity and average power produced in of each jump can be calculated (Samozino et al., 2008). The slope of the linear relationship between the average force and average velocity values (Sfv) is calculated, and then using Sfv, the intercepts of the force and velocity axis can be calculated which represent the theoretical maximal force at zero velocity (F_0), and the theoretical velocity at zero force (V_0), respectively (Samozino et al., 2012). Theoretical maximal power (P_{max}) can also be calculated from F_0 and V_0 using the equation defined in (Samozino et al., 2012).

$$P_{max} = (F_0 * V_0) / 4$$

It has also been shown that an optimal slope of the FVP (Sfv_{Opt}) exists for specific lower body multi-joint ballistic actions which represents the optimal relationship of F0 and V0 for a given individual and task and can be calculated using P_{max}, push-off distance, and body mass (Morin & Samozino, 2016). The ratio of Sfv and Sfv_{Opt}, termed force-velocity profile imbalance (FVP_{IMB}), represents the magnitude of difference between the Sfv_{Opt} and the athlete's measured Sfv (Morin & Samozino, 2016). There is also a simple alternative calculation of Sfv which accounts for ballistic movements of different takeoff angles (i.e. a greater horizontal component) such as sprinting or swimming starts (Samozino et al., 2012). However, to the best of the author's knowledge, the relationship between performance in these horizontal tasks and the modified Sfv and FVP_{IMB} calculations have yet to assessed.

Individualized training with the goal of bringing the athlete's Sfv closer to Sfv_{Opt} is an effective way to increase performance in the measured task (Jiménez-Reyes et al., 2017). Force-velocity imbalances (relative to Sfv_{Opt}), can be responsible for as much as a 30% reduction in performance for vertical jumping tasks (Morin & Samozino, 2016; Samozino et al., 2013). Therefore, in order to maximize ballistic performance, practitioners can make athlete-specific training recommendations to target deficiencies in F_0 or V_0 which is effective at improving jump height and sport performance, without necessarily affecting P_{max} (Jiménez-Reyes et al., 2017; Samozino et al., 2013; Simpson et al., 2021).

FVP metrics have been shown to have acceptable reliability between sessions. F_0 and P_{max} demonstrate good to excellent reliability and V_0 and Sfv demonstrate moderate to excellent reliability (F_0 [CV: 4.85%, ICC: 0.87], V_0 [CV: 6.10%, ICC: 0.82], Sfv [CV: 10.5%, ICC: 0.81], and Pmax [CV: 3.5%, ICC: 0.93]) (García-Ramos et al., 2017). Some studies have observed poor reliability of FVP between session (Lindberg et al., 2021; Valenzuela et al., 2021). However, Samozino et al. (2022) have argued that these studies had several limitations including a lack of participant familiarity, variable jump heights and starting positions, and mixing constrained and unconstrained movements. As such, the authors highlight the importance of ensuring reliability of input variables through consistent and well-defined testing protocols including ensuring appropriate familiarization, rest times, and consistent depth of the SJ (Samozino et al., 2022). It is also important to note that there will always be some variability in human performance outcomes both within and between session. In order to account for this variability and ensure validity of the FVP metrics, athletes presenting an FVP with $R^2 < 0.95$ should be removed (Samozino et al., 2022).

There has been a well-documented relationship between vertical FVP assessments and sport tasks which require vertical, maximal lower body ballistic actions such as soccer (Haugen et al., 2020; Manson et al., 2021), and dance (Escobar Álvarez et al., 2020), as well as other tasks such as maximal speed sprinting and change of direction (Baena-Raya et al., 2021; Manson et al., 2021). Further, among field hockey players, males and females have significantly different FVPs depending on their position (Hicks et al., 2023), highlighting that there may be an effect of sex on the relationship between the FVP variables and sport performance. To the best of the author's knowledge, no study has investigated the relationship between swimming starts and FVPs.

Summary

In conclusion, takeoff velocity leaving the starting blocks has been identified as being a determining factor of success to starts, as it influences both the flight distance achieved during the flight phase and the underwater velocity of the underwater phase. Increasing the athletes' capacity to produce force quickly and their peak force may increase the impulse applied to the blocks and consequently improve takeoff velocity. There is a large body of evidence supporting the relationship between dry-land tests of strength and power such as vertical jumps, plyometrics, and free weight movements to start performance. However, no study has investigated relationship between an athlete's FVP and their swim start performance. Because swimming starts are a ballistic movement, performance is determined by the maximal power the athlete can produce, as well as the relationship between their force and velocity capacities (Morin & Samozino, 2016). Therefore, the goal of this research project will be to investigate the relationship between the vertical FVP and swimming starts among university-aged varsity athletes. This research should also provide a baseline for further studies investigating the use of FVP in different populatinos such as elite or adolescent swimmers. Lastly, this study will aim to provide practical suggestions for dry landing testing protocols for strength and conditioning practitioners and coaches working in swimming.

Chapter 2. Using Force-Velocity Profiling to Predict Swimming Start Performance

Introduction

Swimming start execution is an important factor in overall swimming performance as it is the component of the race where the swimmer can achieve and maintain their highest velocities (Cossor & Mason, 2001; Tor et al., 2014). There are three phases of the start, the block phase, flight phase, and underwater phase (Slawson et al., 2013). During the block phase, swimmers must maximize horizontal takeoff velocity in order to achieve the greatest dive distance and velocity entering the water (Garcia-Hermoso et al., 2013). Takeoff velocity is determined by the impulse (product of force and time) relative to body mass applied to the blocks. Since block times must remain short to maximize performance (Mason et al., 2007; Vantorre et al., 2010), the ability to produce large forces quickly is essential for optimizing start performance (Slawson et al., 2013). The velocity achieved during the underwater phase has a large impact on the velocity of the free swim phase and is dependent on the take-off velocity achieved during the block phase as well the athlete's technical ability to minimize drag forces (Tor et al., 2015).

Performance in ballistic actions such as vertical jumping or swimming starts is determined by an athlete's maximal power capacity which is related to their individual force and velocity capabilities that can be measures using a vertical force-velocity profile (FVP) (Morin & Samozino, 2016). The FVP for an athlete is developed by quantifying the force velocity relationship for an athlete using specialized testing. The profile, in a vertical direction, is developed by measuring force and velocity outputs during multiple squat jumps across incremental loads to create an athlete specific model that includes the variables of theoretical maximal force capacity (F_0), theoretical maximal velocity (V_0), and theoretical maximal mechanical power (P_{max}) (Samozino et al., 2008, 2012). Additionally, for ballistic tasks, such as vertical jumping, there exists an optimal relationship (Sfv_{opt}) between force and velocity (Morin & Samozino, 2016). Differences in the slope of the athlete's calculated force-velocity relationship (Sfv) compared to Sfv_{opt} describes the imbalance in the athlete's FVP (FVP_{IMB}) and identify potential training areas of opportunity. Imbalances in the force-velocity profile can be responsible for as much as a 30% reduction in performance for ballistic tasks such as vertical jumping (Morin & Samozino, 2016; Samozino et al., 2013). Vertical FVP assessments have has also been shown to be related to performance in other horizontal tasks such as maximal speed sprinting and change of direction (Baena-Raya et al., 2021; Manson et al., 2021). Further, training designed to address athlete's FVP_{IMB} have shown promise in improving an athlete's jumping performance (Jiménez-Reyes et al., 2017; Simpson et al., 2021). Therefore, FVP are considered a valuable testing approach to support an understanding of athlete capacity. FVP profile metrics have been compared to sport specific tasks to evaluate the dynamic determinants of sport specific movement to support the development of optimized training programs.

There have been several studies that have assessed the relationship between dry-land performance tests and swimming start performance. Unweighted vertical and horizontal jumps have shown very large to nearly perfect correlations with start performance (r = 0.69 to 0.96) (Benjanuvatra et al., 2007; Calderbank et al., 2020; Keiner et al., 2015, 2021; Santos et al., 2022; West et al., 2011). Traditional barbell strength exercises such as back squat and deadlift 1-repitition maxes also demonstrate strong correlations with start time to 15 m (Keiner et al., 2015, 2021). When assessing the kinematic variables of swimmers on a forceplate, concentric impulse observed during an unweighted squat jump (SJ) was the best kinematic variable to predict time to 5 m and time to 10 m in males and females (Thng et al., 2020). Finally, jump height achieved during loaded

SJs (25%, 50%, 75%, and 100% body mass) have also shown moderate correlations with time to 5 m, 10 m, and 15 m, and across all loads appear to be stronger predictors of swimming start performance than unweighted SJs or countermovement jumps, potentially due to the increased force required to ballistically lift the heavier loads being more closely related to the physical determinants of the swim start (García-Ramos, Padial, et al., 2016; García-Ramos, Tomazin, et al., 2016). While variables from dryland testing have shown good comparisons to swim start performance, there has been no study that has investigated the relationship between FVPs and swimming start performance. The potential ability to compare the relationship between FVP variables and phases of the swimming sprint can help to support a greater understanding of the determinants of swim start performance that can be augmented through optimized strength and conditioning training programs.

The primary objective of this investigation was to determine the association between the mechanical variables derived from the FVP (F_0, V_0, P_{max}, and FVP_{IMB}) and swim start performance metrics of dive distance and time to 10 m using the kick start technique among male and female university level swimmers. Considering the importance of impulse and force production relative to body mass during the block phase (Slawson et al., 2013; Tor et al., 2015), and the strong relationship between dry-land strength and power tests and start performance, it was hypothesized that F_0 would be able to predict start performance. Due to the differences in FVP between males and females in other sports, it was also hypothesized that differences would be observed in the relationship between FVP_{IMB} and swimming start performance between males and females with males displaying a more force-oriented FVP than females (Hicks et al., 2023). Results from this investigation could allow practitioners to design more effective dry land strength and power training for improving swimming start performance.

Methods

Experimental Approach to the Problem

A cross-sectional study design was used to quantify the relationship between characteristics derived from the vertical FVP and swimming start performance of university-aged varsity level swimmers. The independent variables assessed were absolute F_0, V_0, P_{max}, and the FVP_{IMB} using a push-off angle of 40° (FVP_{IMB40}) and the dependant variables were dive distance (m) and time to 10 m (s). The FVP test and the swim start tests were completed during the same training week, with all participants completing the FVP test approximately 24 hours prior to the swim start tests. Data was collected as part of the team's regular testing within a typical off-season training week. The data was anonymized and analyzed retrospectively.

Subjects

Twenty-four varsity-level swimmers (14 females and 10 males) who competed at a local, regional, or national level were recruited for this study. Four female participants were excluded due to inability to complete the vertical FVP test with sufficient reliability ($R^2 > 0.95$) for a final sample of 10 females and 10 males used for analysis. The subjects had a mean age (± SD) of 19.84 ± 1.50 years (females 20.28 ± 1.08 years, males 19.64 ± 1.87 years), a body mass of 72.34 ± 7.39 kg (females 69.69 ± 5.54 kg, males 74.98 ± 8.31 kg), and a height of 176.2 ± 7.9 cm (females 170.1 ± 3.4 cm, males 182.4 ± 6.0 cm). Subjects were required to have at least 1 year of resistance training experience under a certified strength and conditioning coach. Ethical approval was obtained from the University of Victoria's Human Research Ethics Board, and the study adhered to the principles outlined in the Declaration of Helsinki.

Anthropometric Measures

Body mass was measured using a bilateral force platform (Advanced Mechanical Technology, Inc. (AMTI), Watertown, USA), which were zeroed before the subject stepped onto the plates for the unloaded trial. The average force during a quite-standing period was selected and divided by 9.81 m/s to determine the subjects' body mass. Height was collected using a portable stadiometer (Seca, Hamburg, Germany).

Force Velocity Profile

Prior to the FVP test, swimmers completed a 10-minute standardized general warm-up consisting of skipping, general movement, and dynamic stretching before completing a specific warm-up of 2 sets of 3 unloaded SJs under the supervision of a strength and condition coach. Participants were familiarized with the testing procedure and equipment prior to the tests.

Participants began by standing upright on the force platform, feet approximately shoulder width apart, with a dowel or barbell resting across the shoulders. For all SJs, the athletes were instructed "to jump as high as possible". SJs were completed across four loads, beginning at 0.50 kg (wooden dowel). Male subjects completed jumps in the sequence of 0.5 kg, 20 kg, 40 kg, 60 kg and female subjects completed jumps in the sequence of 0.5kg, 15 kg, 30 kg, 45 kg. These loads were chosen as they would theoretically cover a large spectrum of takeoff velocities. If an athlete could not jump higher than a pre-defined cut-off of 0.10 m at a given load, no further jump trials were allowed (Morin & Samozino, 2016). Participants were excluded if they were unable to complete fewer than three load increments. Additionally, testing was stopped if technique became compromised such as an extreme valgus of the knee during landing. Three reps were completed at each load, with 10-15 second rest between reps and approximately three minutes rest between loads. To standardize push off distance across SJs, the subjects lowered themselves to a standardized depth of 0.50 m. Depth was confirmed by a resistance band positioned over the posterior edge of the force plate, which equated to a knee angle of ≈ 90 degrees. This was done to eliminate any changes in squat depth as the loads increased. Moreover, this depth mimics the knee flexion angle observed in swim start performed on the OSB11 starting platform, where swimmers should have a knee angle of approximately 90-100° (Slawson et al., 2012). For each SJ, a 3 second pause at the bottom position was counted aloud by the tester before the tester gave the verbal cue to 'jump'.

All jumps were collected using AMTI (AMTI©, OR6-7, Watertown, USA) force plates sampling at 1000Hz, and data was processed using custom script written in LabVIEW 2015, National Instruments (Austin, Texas) software. As a countermovement has been shown to affect jump height (Harman et al., 1990), the analysis software removed any jumps with an unweighting greater than 2.5% body mass prior to the propulsive phase as assessed by the force-time trace. Jump height was then calculated using the impulse-momentum method (Linthorne, 2001). The average jump height was used for further analysis as it is more reliable than a single trial (Claudino et al., 2017). Test-retest reliability in our laboratory for SJ height demonstrated an ICC of 0.98 (95% CI = 0.93 – 1.00) and TEM of 0.02 m.

The vertical FVP was calculated using the previously validated three-factor model which uses jump height, system mass (athlete mass + external load), and push-off distance (Samozino et al., 2008). Briefly, this technique calculates the athletes' average force (N), average velocity ($m \cdot s^{-1}$), and average power (W) for each jump. Theoretical maximal force (F_0), and theoretical maximal velocity (V_0) correspond to the intercepts of the force-velocity slope with the force and velocity axes respectively. Maximal Power (P_{max}) was calculated using the equation $P_{max} = (F_0 * V_0) / 4$ (Morin & Samozino, 2016). The vertical push-off distance was calculated using the difference between the moment of toe-off and the initial starting position (Agar-Newman et al., 2022). The slope of the optimal force-velocity profile was calculated for each athlete using a push-off angle of 40° (Samozino et al., 2012). This push-off angle was chosen as is mimics the take-off angle observed in competitive swimmers using the kick start technique (Matúš et al., 2021). The difference between the actual and optimal FVP slopes represents the FVP imbalance (FVP_{IMB40}) where a value of 1 indicates a FVP equal to the optimal slope at push-off angle of 40° and values higher or lower represent a profile too oriented towards force or velocity, respectively. The use of this three-factor model was chosen as it can be calculated accurately with easily accessible equipment such as a contact mats or video and thus may have more practical applications for practitioners. To ensure that all trials were above the acceptable threshold for reliability, FVP models with an R^2 of < 0.95 were excluded (Samozino et al., 2022).

Swimming Start Performance

Participants completed a typical competition style warm-up before completing two maximal effort swim starts. Each trial was completed under competition style conditions and instructions on an OSB11 starting block using the kick start technique. Swimmers were instructed to swim to a distance beyond the 15 m mark, in order to achieve a maximal effort up to the 10 m line. Between trials, swimmers were given 1 minute of passive recovery. The two starts for each athlete were compared to the athlete's FVP metrics individually in order to increase the effective sample size of this study. Swim start performance was measured using two high speed digital phone cameras (Apple, 2022) at 120 fps positioned ~1 m above the surface of the water and ~3 m away from the side of the pool, one at approximately 3 m from the starting edge of the pool, used to capture dive distance, and a second at a distance of 10 m from the starting edge of the pool to capture time to 10 m. Both cameras were synchronised to each other using the instant the swimmer's hands left the starting block. Dive distance was defined as the horizontal distance along the level of the water surface between the edge of the pool and to apex of the head the instant the head entered the water. Distance was calculated using a video analysis software (Kinovea version 0.9.5). The grid tool was calibrated using the base of the flag poles (measured as 5.0 m from the edge of the pool) to the edge of the pool (Figure 2). Time to 10 m was defined as the time elapsed from the instant that the hands left the starting block until the instant that the apex of the swimmers' head crossed the 10 m mark (Tor et al., 2015). Using the instant of the hands left the starting block was chosen in order to ignore the effect of reaction time and to increase the reliability of the time to 10 m measurement.

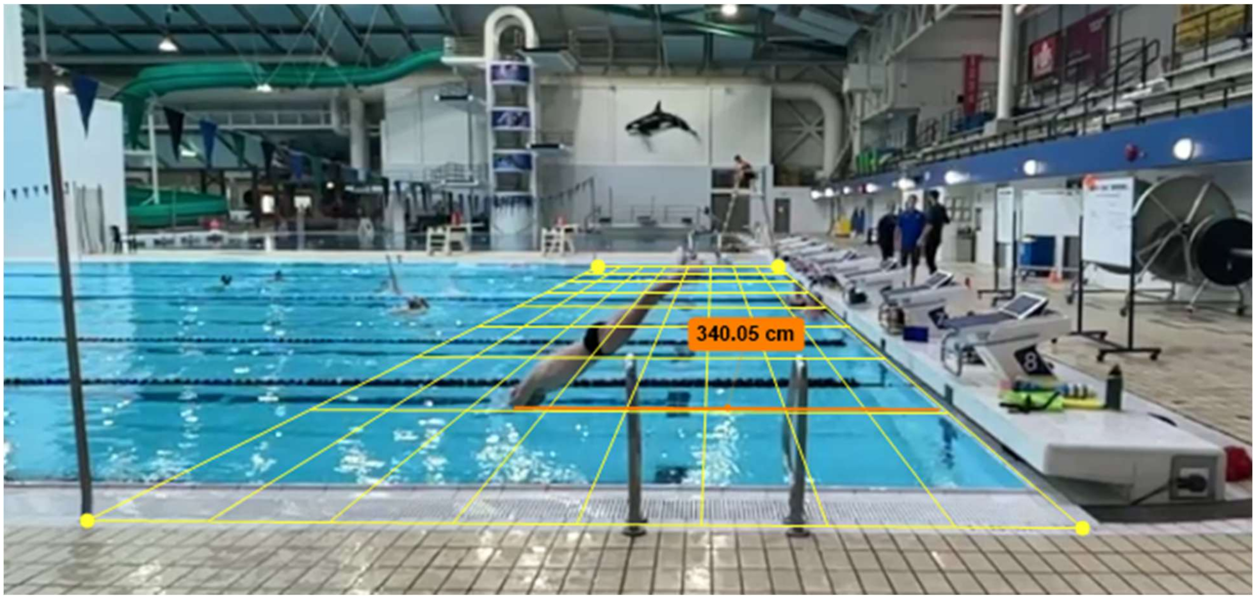

Figure 2. Screenshot of measurement of dive distance using Kinovea video analysis software.

Statistical Analyses

Multiple linear regression analyses were conducted using a backward stepwise method to identify potential predictors of the two outcome variables: dive distance and time to 10 m. If

FVP metrics were identified as significantly contributing to the regression model, a second linear regression was performed to examine potential interaction effects of sex. The assumptions of normality and homoscedasticity of residuals were verified. Multicollinearity was assessed using correlation matrix of independent and dependent variables. Due to the implicit relationship between P_{max}, FVP_{IMB40}, F_0, and V_0, a strong multicollinearity was observed and only F_0 and V_0 were included out of the FVP metrics in the linear regression model. Data was analyzed with Python version 1.4 (Beaverton, USA). Alpha was set to 0.05 for all statistical tests.

Results

Table 1 shows results for the descriptive statistics of the start and FVP measures. Significant differences were observed for all FVP variables, height, weight, dive distance, and time to 10 m between males and females.

Table 1. Descriptive statistics of start and FVP characteristics (Mean ± SD).

	Males	Females	p
F_0 (N)	1933.58 ± 356.26	1721.91 ± 219.40	0.044
V_0 (m/s)	3.27 ± 0.62	2.38 ± 0.77	< .001
P_{max} (W)	1542.44 ± 196.10	1002.47 ± 247.38	< .001
FVP_{IMB40}	0.80 ± 0.23	0.95 ± 0.36	0.136
Height (m)	1.83 ± 0.05	1.70 ± 0.03	< .001
Body mass (kg)	74.84 ± 8.47	69.51 ± 5.48	0.035
Time to 10 m (s)	3.62 ± 0.25	4.26 ± 0.16	< .001
Dive distance (m)	3.09 ± 0.15	2.73 ± 0.14	< .001

Table 3 shows the results of the multiple regression analysis between dive distance and the FVP and anthropometric measurements. The best model to predict dive distance included Sex and F_0 (R^2 adjusted = 0.61, F = 27.85, p < 0.001). The equation for predicting dive distance was obtained:

$$\text{Dive distance (m)} = 2.74 + (0.01 * F_0) - (0.31 * \text{Sex})$$

Table 2. Multiple linear regression analysis of the relationship of dive distance (m) with significant predictor variables.

Variable	**β**	**t**	**p**	***R*²**	***R*² adjusted**	**F**	**p**
F_0 (N)	0.01	2.41	0.02				
Sex	-0.31	-5.59	<.001				
				0.64	0.61	27.85	<.001

A second linear regression was performed to investigate potential interactions of sex using the independent variables F_0, Sex, and the F_0 : Sex interaction which found no interaction between F_0 and Sex. The results of this regression are shown in Table 4.

Table 3. Linear regression analysis of dive distance (m) with interaction effects.

Variable	**β**	**t**	**p**	***R*²**	***R*² adjusted**	**F**	**p**
F_0 : Sex	-0.01	-1.04	0.31				
F_0 (N)	0.01	2.41	0.02				
Sex	0.04	0.11	0.91				
				0.64	0.61	20.94	<.001

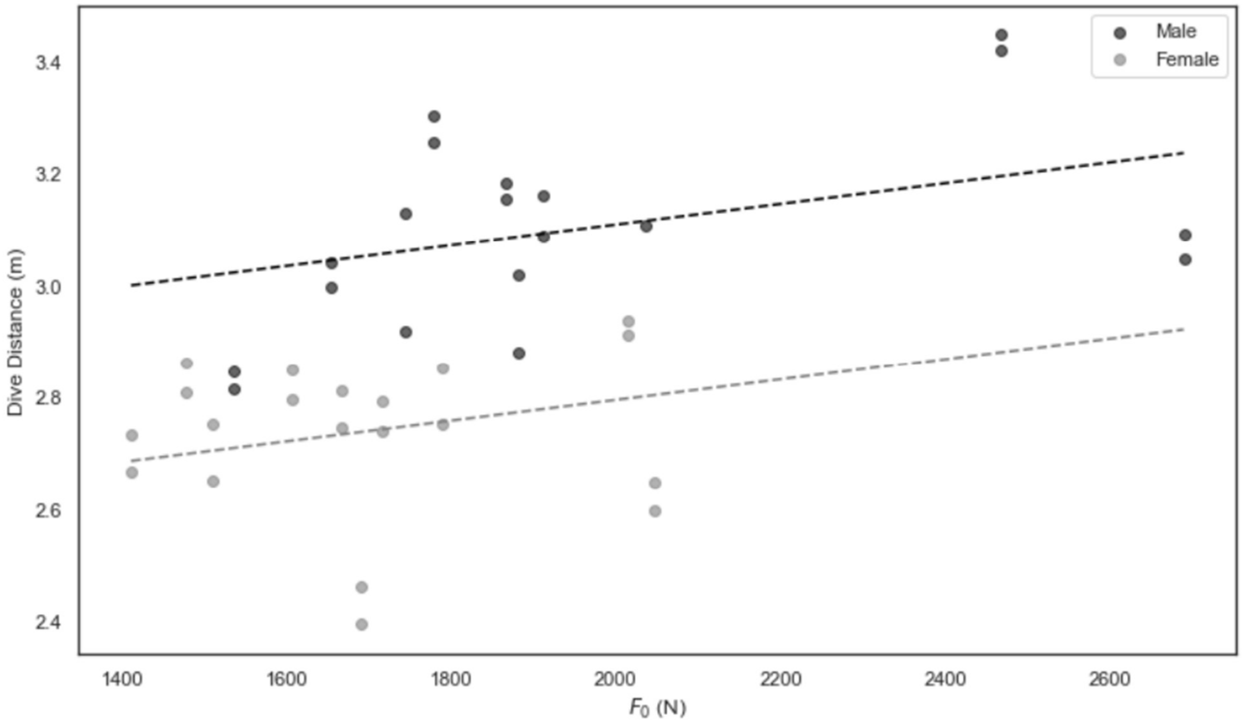

Figure 3. Relationship between F_0 and dive distance.

Table 5 shows the results for the multiple regression between time to 10 m and the FVP and anthropometric measures. For time to 10 m, only Sex and Body Mass contributed significantly to the model (R^2 adjusted = 0.75, F = 57.70, $p < 0.001$). Because none of the FVP metrics contributed significantly to the model, no other linear regressions were performed.

$$\text{Time to 10 m (s)} = 4.53 + (0.60 * \text{Sex}) - (0.01 * \text{Body Mass})$$

Table 4. Multiple linear regression of the relationship of time to 10 m (s) with significant predictor variables.

Variable	β	t	p	R^2	R^2 adjusted	F	p
Body mass (kg)	-0.01	-2.65	0.01				
Sex	0.60	8.69	<.001				
				0.76	0.75	57.70	<.001

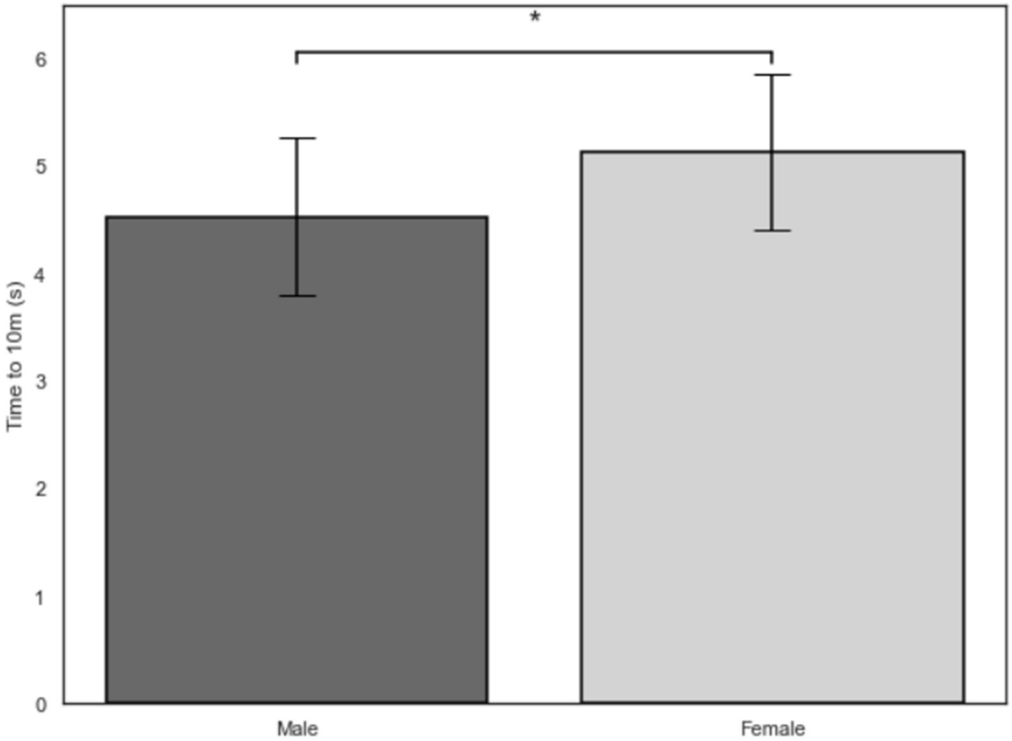

Figure 4. Relationship between sex and time to 10 m.

Discussion

This is the first study to examine the relationship of FVP metrics to swimming start performance. Results of the linear regression model reveal that F_0 significantly predicts dive distance (Figure 3; $\beta = 0.02$, R^2 adjusted = 0.61, $p < 0.001$), whereas V_0 does not. Dive distance in the swimming start is determined primarily by the swimmer's takeoff velocity. In order to maximize takeoff velocity, swimmers must apply large force quickly against the starting block to maximize impulse. Achieving a large dive distance is important for overall swimming performance because the athlete can achieve much higher velocities than during the underwater phase due to the lack of hydrodynamic drag (Shepherd et al., 2023). Previous studies have observed strong positive correlations between dive distance and vertical jumps, horizonal jumps, and isometric peak force, highlighting the importance of strength and power qualities for maximizing dive distance (Calderbank et al., 2020). Importantly, the dive off the starting block is a ballistic task and is therefore also affected by the athlete's force-velocity relationship. Regarding this force-velocity relationships, this study found that F_0 was more important than V_0 for increasing dive distance, highlighting the fact that maximal force may contribute more to the initial components of the swimming start task. When examining how these relationships differ between sex, this study observed no interaction effect between F_0 and Sex for predicting dive distance. These results indicate that while absolute dive distance is different between males and females, likely due to other differences in anatomical and anthropometric factors, the relationship between F_0 and dive distance is not different between males and females. The results of this study show that the capacity to produce increased maximal force may be more important than other neuromuscular qualities for increasing dive distance among males and females.

It was hypothesized that time to 10 m would be significantly related to the FVP variables as much of the previous literature has observed strong correlations of loaded and unloaded jumping, squats, and lower body isometric testing with swim start performance measured as time to 10 m or time to 15 m (Beretić et al., 2013; García-Ramos, Padial, et al., 2016; Keiner et al., 2015, 2021; Thng et al., 2020; West et al., 2011). In contrast to the initial hypothesis, none of the FVP metrics significantly predicted time to 10 m (Figure 4). These results are consistent with that of Benjanuvatra et al. (2007) and García-Ramos, Tomazin, et al. (2016) who found that takeoff velocity and jump performance of vertical and horizontal jumps showed significant correlations to time to 5 m but not time to 15 m. One explanation for this mixed findings is that time to 10 m and time to 15 m are highly impacted by other factors related to the flight and underwater phase such as the swimmer's technical proficiency at minimizing surface area during water entry, maintaining an effective streamline position, and undulatory kicking (García-Ramos, Tomazin, et al., 2016; Tor et al., 2015). The current study measured sub-elite athletes completing at the local or regional level, meaning participants may have been less technically consistent than elite athletes. Since the underwater phase can account for as much as 84% of overall start duration (Tor et al., 2014), variations in technical execution of these movements may have a large impact on start time measured to longer distances such as 10 m or 15 m and potentially explain these contradictory findings.

There are some limitations of this study that should be addressed in future research. Firstly, the participants sampled in this study consisted solely of non-elite swimmers. Future research should examine the relationship between FVP metrics and start performance in elite swimmers to elucidate whether the conflicting finding for dive distance and time to 10 m are due to differences in technical ability or reflect distinct physical demands of each action. Secondly, future work should assess how training interventions aimed at modifying the athlete's individual FVP affect swimming start performance longitudinally.

Practical Applications

This study identified that F_0 was able to significantly predict dive distance of the swim start in male and female varsity level swimmers. Therefore, swimmers looking to improve their start performance may benefit from exercises that develop the lower body's capacity to produce maximal force such as barbell squats. However, overall start performance measured as time to 10 m showed no relationship to any of the FVP metrics, potentially due to variability in technique within the varsity population. Due to the importance of technique, the start must also be practiced purposefully for gains in strength and power to transfer effectively.

References

Agar-Newman, D. J., Tsai, M.-C., & Klimstra, M. (2022). The validity of applying a simple three-factor computational model to calculate force, power, and speed using hexagonal bar jumps. *Journal of Strength and Conditioning Research*, *36*(8), 2108–2114. https://doi.org/10.1519/JSC.0000000000003581

Alptekin, A. (2014). Body composition and kinematic analysis of the grab start in youth swimmers. *Journal of Human Kinetics*, *42*, 15. https://doi.org/10.2478/hukin-2014-0057

Baena-Raya, A., Soriano-Maldonado, A., Conceição, F., Jiménez-Reyes, P., & Rodríguez-Pérez, M. A. (2021). Association of the vertical and horizontal force-velocity profile and acceleration with change of direction ability in various sports. *European Journal of Sport Science*, *21*(12), 1659–1667. https://doi.org/10.1080/17461391.2020.1856934

Benjanuvatra, N., Edmunds, K., & Blanksby, B. (2007). Jumping ability and swimming grab-start performance in elite and recreational swimmers. *International Journal of Aquatic Research and Education*, *1*, 231–241. https://doi.org/10.25035/ijare.01.03.06

Beretić, I., Durovic, M., & Okičić, T. (2012). Influence of the black plate on kinematical starting parameter changes in elite male serbian swimmers. *Physical Education and Sport*, *10*(2).

Beretić, I., Đurović, M., Okičić, T., & Dopsaj, M. (2013). Relations between lower body isometric muscle force characteristics and start performance in elite male sprint swimmers. *Journal of Sports Science & Medicine*, *12*(4), 639.

Bishop, C., Jordan, M., Torres-Ronda, L., Loturco, I., Harry, J., Virgile, A., Mundy, P., Turner, A., & Comfort, P. (2023). Selecting metrics that matter: Comparing the use of the countermovement jump for performance profiling, neuromuscular fatigue monitoring, and injury rehabilitation testing. *Strength & Conditioning Journal*, *45*(5), 545–553. https://doi.org/10.1519/SSC.0000000000000772

Bishop, D. C., Smith, R. J., Smith, M. F., & Rigby, H. E. (2009). Effect of plyometric training on swimming block start performance in adolescents. *The Journal of Strength & Conditioning Research*, *23*(7), 2137. https://doi.org/10.1519/JSC.0b013e3181b866d0

Born, D.-P., Kuger, J., Polach, M., & Romann, M. (2021). Start and turn performances of elite male swimmers: Benchmarks and underlying mechanisms. *Sports Biomechanics*, 1–19. https://doi.org/10.1080/14763141.2021.1872693

Breed, R. V. P., & Young, W. B. (2003). The effect of a resistance training programme on the grab, track and swing starts in swimming. *Journal of Sports Sciences*, *21*(3), 213–220. https://doi.org/10.1080/0264041031000071047

Calderbank, J. A., Comfort, P., & McMahon, J. J. (2020). Association of jumping ability and maximum strength with dive distance in swimmers. *International Journal of Sports Physiology and Performance*, *16*(2), 296–303. https://doi.org/10.1123/ijspp.2019-0773

Claudino, J. G., Cronin, J., Mezêncio, B., McMaster, D. T., McGuigan, M., Tricoli, V., Amadio, A. C., & Serrão, J. C. (2017). The countermovement jump to monitor neuromuscular status: A meta-analysis. *Journal of Science and Medicine in Sport*, *20*(4), 397–402. https://doi.org/10.1016/j.jsams.2016.08.011

Cossor, J., & Mason, B. (2001). Swim start performance at the Sydney 2000 Olympic games. *ISBS - Conference Proceedings Archive*. https://ojs.ub.uni-konstanz.de/cpa/article/view/3870

Cossor, J., Slawson, S., Shillabeer, B., Conway, P., & West, A. (2011). Are land tests a good predictor of swim start performance? *ISBS - Conference Proceedings Archive*. https://ojs.ub.uni-konstanz.de/cpa/article/view/4803

Dassoff, A. S., Forward, N. R., & Katica, C. P. (2017). Differences between the grab start and track start in collegiate swimmers. *International Journal of Exercise Science*, *10*(4), 515–521. https://doi.org/10.70252/KJWP9603

DeBruyn, F. W. (1979). *The relationship between vertical jump and reach performance and sprint speed in four swimming strokes*.

Dijk, M. P. van, Beek, P. J., & Soest, A. J. K. van. (2020). Predicting dive start performance from kinematic variables at water entry in (sub-)elite swimmers. *PLoS ONE*, *15*(10), e0241345. https://doi.org/10.1371/journal.pone.0241345

Escobar Álvarez, J. A., Reyes, P. J., Pérez Sousa, M. Á., Conceição, F., & Fuentes García, J. P. (2020). Analysis of the force-velocity profile in female ballet dancers. *Journal of Dance Medicine & Science*, *24*(2), 59–65. https://doi.org/10.12678/1089-313X.24.2.59

Galbraith, H., Scurr, J., Hencken, C., Wood, L., & Graham-Smith, P. (2008). Biomechanical comparison of the track start and the modified one-handed track start in competitive swimming: An intervention study. *Journal of Applied Biomechanics*, *24*(4), 307–315. https://doi.org/10.1123/jab.24.4.307

Garcia-Hermoso, A., Escalante, Y., Arellano, R., Navarro, F., Domínguez, A. M., & Saavedra, J. M. (2013). Relationship between final performance and block times with the traditional and the new starting platforms with a back plate in international swimming championship 50-m and 100-m Freestyle events. *Journal of Sports Science & Medicine*, *12*(4), 698–706.

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

García-Ramos, A., Padial, P., de la Fuente, B., Argüelles-Cienfuegos, J., Bonitch-Góngora, J., & Feriche, B. (2016). Relationship between vertical jump height and swimming start performance before and after an altitude training camp. *Journal of Strength and Conditioning Research*, *30*(6), 1638–1645. https://doi.org/10.1519/JSC.0000000000001242

García-Ramos, A., Tomazin, K., Feriche, B., Strojnik, V., Fuente, B. de la, Argüelles-Cienfuegos, J., Strumbelj, B., & Štirn, I. (2016). The relationship between the lower-body muscular profile and swimming start performance. *Journal of Human Kinetics*, *50*(1), 157–165. https://doi.org/10.1515/hukin-2015-0152

Harman, E. A., Rosenstein, M. T., Frykman, P. N., & Rosenstein, R. M. (1990). The effects of arms and countermovement on vertical jumping. *Medicine and Science in Sports and Exercise*, *22*(6), 825–833. https://doi.org/10.1249/00005768-199012000-00015

Haugen, T. A., Breitschädel, F., & Seiler, S. (2020). Sprint mechanical properties in soccer players according to playing standard, position, age and sex. *Journal of Sports Sciences*, *38*(9), 1070–1076. https://doi.org/10.1080/02640414.2020.1741955

Hicks, D. S., Drummond, C., Williams, K. J., & van den Tillaar, R. (2023). Force-velocity profiling in club-based field hockey players: Analyzing the relationships between mechanical characteristics, sex, and positional demands. *Journal of Sports Science & Medicine*, *22*(1), 142–155. https://doi.org/10.52082/jssm.2023.142

Honda, K., Sinclair, P. J., Mason, B. R., & Pease, D. L. (2010). A biomechanical comparison of elite swimmers start performance using the traditional track start and the new kick start. *Biomechanics and Medicine in Swimming*, *11*, 94–98.

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

Keiner, M., Wirth, K., Fuhrmann, S., Kunz, M., Hartmann, H., & Haff, G. G. (2021). The influence of upper- and lower-body maximum strength on swim block start, turn, and overall swim performance in sprint swimming. *Journal of Strength and Conditioning Research*, *35*(10). https://doi.org/10.1519/JSC.0000000000003229

Keiner, M., Yaghobi, D., Sander, A., Wirth, K., & Hartmann, H. (2015). The influence of maximal strength performance of upper and lower extremities and trunk muscles on different sprint swim performances in adolescent swimmers. *Science & Sports*, *30*(6), e147–e154. https://doi.org/10.1016/j.scispo.2015.05.001

Lindberg, K., Solberg, P., Bjørnsen, T., Helland, C., Rønnestad, B., Frank, M. T., Haugen, T., Østerås, S., Kristoffersen, M., Midttun, M., Sæland, F., & Paulsen, G. (2021). Force-velocity profiling in athletes: Reliability and agreement across methods. *PLOS ONE*, *16*(2), e0245791. https://doi.org/10.1371/journal.pone.0245791

Linthorne, N. P. (2001). Analysis of standing vertical jumps using a force platform. *American Journal of Physics*, *69*(11), 1198–1204. https://doi.org/10.1119/1.1397460

Manson, S. A., Low, C., Legg, H., Patterson, S. D., & Meylan, C. (2021). Vertical force-velocity profiling and relationship to sprinting in elite female soccer players. *International Journal of Sports Medicine*, *42*(10), 911–916. https://doi.org/10.1055/a-1345-8917

Marinho, D. A., Reis, V. M., Alves, F. B., Vilas-Boas, J. P., Machado, L., Silva, A. J., & Rouboa, A. I. (2009). Hydrodynamic Drag during Gliding in Swimming. *Journal of Applied Biomechanics*, *25*(3). https://doi.org/10.1123/jab.25.3.253

Mason, B., Alcock, A., & Fowlie, J. (2007). A kinematic analysis and recommendations for elite swimmers performing the sprint start. *Proceedings of the 25th International Symposium on Biomechanics in Sports*. International Society of Biomechanics in Sports.

Matúš, I., Ružbarský, P., & Vadašová, B. (2021). Key parameters affecting kick start performance in competitive swimming. *International Journal of Environmental Research and Public Health*, *18*(22), 11909. https://doi.org/10.3390/ijerph182211909

Miller, J. A., Hay, J. G., & Wilson, B. D. (1984). Starting techniques of elite swimmers. *Journal of Sports Sciences*. https://doi.org/10.1080/02640418408729718

Morais, J. E., Marinho, D. A., Arellano, R., & Barbosa, T. M. (2019). Start and turn performances of elite sprinters at the 2016 European Championships in swimming. *Sports Biomechanics*, *18*(1), 100–114. https://doi.org/10.1080/14763141.2018.1435713

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

Naemi, R., Easson, W. J., & Sanders, R. H. (2010). Hydrodynamic glide efficiency in swimming. *Journal of Science and Medicine in Sport*, *13*(4), 444–451. https://doi.org/10.1016/j.jsams.2009.04.009

Ozeki, K., Sakurai, S., Taguchi, M., & Takise, S. (2012). Kicking the back plate of the starting block improves start phase performance in competitive swimming. *Conference of Biomechanics in Sports*.

Papic, C., Sinclair, P., Fornusek, C., & Sanders, R. (2019). The effect of auditory stimulus training on swimming start reaction time. *Sports Biomechanics*, *18*(4), 378–389. https://doi.org/10.1080/14763141.2017.1409260

Peterson Silveira, R., Stergiou, P., Figueiredo, P., Castro, F. D. S., Katz, L., & Stefanyshyn, D. J. (2018). Key determinants of time to 5 m in different ventral swimming start techniques. *European Journal of Sport Science*, *18*(10), 1317–1326. https://doi.org/10.1080/17461391.2018.1486460

Rejman, M., Bilewski, M., Szczepan, S., Rudnik, D., Klarowicz, A., & Maćkała, K. (2017). Assessing the impact of a targeted plyometric training on changes in selected kinematic parameters of the swimming start. *Acta of Bioengineering and Biomechanics*, *19*(2), 149–160. https://doi.org/10.5277/ABB-00627-2016-03

Samozino, P., Edouard, P., Sangnier, S., Brughelli, M., Gimenez, P., & Morin, J.-B. (2013). Force-velocity profile: Imbalance determination and effect on lower limb ballistic performance. *International Journal of Sports Medicine*, *35*(06), 505–510. https://doi.org/10.1055/s-0033-1354382

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

Samozino, P., Rejc, E., Di Prampero, P. E., Belli, A., & Morin, J.-B. (2012). Optimal Force–Velocity Profile in Ballistic Movements—Altius. *Medicine & Science in Sports & Exercise*, *44*(2), 313–322. https://doi.org/10.1249/MSS.0b013e31822d757a

Samozino, P., Rivière, J. R., Jimenez-Reyes, P., Cross, M. R., & Morin, J.-B. (2022). Is the concept, method, or measurement to blame for testing error? An illustration using the force-velocity-vower profile. *International Journal of Sports Physiology and Performance*, *17*(12), 1760–1768. https://doi.org/10.1123/ijspp.2021-0535

Santos, C. C., Barbosa, T. M., Marinho, D. A., & Costa, M. J. (2022). Association between the dry-land strength & power and the kick start kinetics in elite male and female swimmers. *Sports Biomechanics*, 1–11. https://doi.org/10.1080/14763141.2022.2158921

Shepherd, I., Lindley, M. R., Logan, O., Mears, A., Pain, M. T. G., & King, M. (2023). The effect of body position and mass centre velocity at toe off on the start performance of elite swimmers and how this differs between gender. *Sports Biomechanics*, *22*(12), 1659–1668. https://doi.org/10.1080/14763141.2021.1919750

Simpson, A., Waldron, M., Cushion, E., & Tallent, J. (2021). Optimised force-velocity training during pre-season enhances physical performance in professional rugby league players. *Journal of Sports Sciences*, *39*(1), 91–100. https://doi.org/10.1080/02640414.2020.1805850

Slawson, S. E., Chakravorti, N., Conway, P. P., Cossor, J., & West, A. A. (2012). The effect of knee angle on force production, in swimming starts, using the OSB11 block. *Procedia Engineering*, *34*, 801–806. https://doi.org/10.1016/j.proeng.2012.04.137

Slawson, S. E., Conway, P. P., Cossor, J., Chakravorti, N., & West, A. A. (2013). The categorisation of swimming start performance with reference to force generation on the main block and footrest components of the Omega OSB11 start blocks. *Journal of Sports Sciences*, *31*(5), 468–478. https://doi.org/10.1080/02640414.2012.736631

Takeda, T., Itoi, O., Takagi, H., & Tsubakimoto, S. (2014). Kinematic analysis of the backstroke start: Differences between backstroke specialists and non-specialists. *Journal of Sports Sciences*, *32*(7), 635–641. https://doi.org/10.1080/02640414.2013.845678

Thng, S., Pearson, S., & Keogh, J. W. L. (2019). Relationships between dry-land resistance training and swim start performance and effects of such training on the swim start: A systematic review. *Sports Medicine*, *49*(12), 1957–1973. https://doi.org/10.1007/s40279-019-01174-x

Thng, S., Pearson, S., Rathbone, E., & Keogh, J. W. L. (2020). The prediction of swim start performance based on squat jump force-time characteristics. *PeerJ*, *8*, e9208. https://doi.org/10.7717/peerj.9208

Tor, E., Pease, D. L., & Ball, K. A. (2014). Characteristics of an elite swimming start. *Proceedings of Biomechanics and Medicine in Swimming 2014*, *1*, 257–263.

Tor, E., Pease, D. L., & Ball, K. A. (2015). Key parameters of the swimming start and their relationship to start performance. *Journal of Sports Sciences*, *33*(13), 1313–1321. https://doi.org/10.1080/02640414.2014.990486

Valenzuela, P. L., Sánchez-Martínez, G., Torrontegi, E., Vázquez-Carrión, J., Montalvo, Z., & Haff, G. G. (2021). Should we base training prescription on the force-velocity profile? Exploratory study of its between-day reliability and differences between methods. *International Journal of Sports Physiology and Performance*, *16*(7), 1001–1007. https://doi.org/10.1123/ijspp.2020-0308

Vantorre, J., Seifert, L., Fernandes, R. J., Vilas-Boas, J. P., & Chollet, D. (2010). Biomechanical influence of start technique preference for elite track starters in front crawl. *The Open Sports Sciences Journal*, *3*(1), 137–139. https://doi.org/10.2174/1875399X01003010137

Veiga, S., & Roig, A. (2016). Underwater and surface strategies of 200 m world level swimmers. *Journal of Sports Sciences*, *34*(8), 766–771. https://doi.org/10.1080/02640414.2015.1069382

Vennell, R., Pease, D., & Wilson, B. (2006). Wave drag on human swimmers. *Journal of Biomechanics*, *39*(4), 664–671. https://doi.org/10.1016/j.jbiomech.2005.01.023

Von Loebbecke, A., Mittal, R., Mark, R., & Hahn, J. (2009). A computational method for analysis of underwater dolphin kick hydrodynamics in human swimming. *Sports Biomechanics*, *8*(1), 60–77. https://doi.org/10.1080/14763140802629982

West, D. J., Owen, N. J., Cunningham, D. J., Cook, C. J., & Kilduff, L. P. (2011). Strength and power predictors of swimming starts in international sprint swimmers. *The Journal of Strength & Conditioning Research*, *25*(4), 950. https://doi.org/10.1519/JSC.0b013e3181c8656f

Wirth, K., Keiner, M., Fuhrmann, S., Nimmerichter, A., & Haff, G. G. (2022). Strength training in swimming. *International Journal of Environmental Research and Public Health*, *19*(9), 5369. https://doi.org/10.3390/ijerph19095369

Yu Kwok, W., So, B. C. L., Tse, D. H. T., & Ng, S. S. M. (2021). A systematic review and meta-analysis: Biomechanical evaluation of the effectiveness of strength and conditioning training programs on front crawl swimming performance. *Journal of Sports Science & Medicine*, *20*(4), 564–585. https://doi.org/10.52082/jssm.2021.564