

The Relationship Between Squat Jump Force–Velocity Profiles and 2 km
Rowing Ergometer Performance Across Split Intervals

By

Samson Kussauer

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

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

Dr. Ming-Chang Tsai, Canadian Sport Institute - Pacific

Academic Unit Member

Dr. Jim Martin, The University of Utah

External Examiner

Abstract

Force–velocity profiling (FVP) provides a practical assessment of neuromuscular capabilities, yet its application to rowing performance remains underexplored. This study investigated the relationship between squat jump–derived FVP metrics and 250 m split performance during a 2 km rowing ergometer test in male varsity rowers. Sixteen athletes (age = 21.12 ± 1.68 y; height = 1.88 ± 0.07 m; body mass = 86.58 ± 9.47 kg) completed a 2 km ergometer trial followed by loaded squat jumps to determine maximal force (F_0), maximal velocity (V_0), maximal power (P_{\max}), and the slope of the force–velocity relationship (S_{FV}). Linear regression analyses revealed that S_{FV} significantly predicted power output across all race segments ($r = -0.54$ to -0.82), while F_0 significantly predicted all but the first segment ($r = 0.51$ – 0.83). P_{\max} and V_0 showed no significant relationships with any segments. Across the race profile, the predictive strength of F_0 increased in later stages, suggesting that force production becomes more critical as fatigue accumulates. These findings highlight the utility of FVP, particularly F_0 and S_{FV} , for monitoring mechanical capabilities relevant to sustained rowing performance and for informing strength-oriented training interventions.

Key Words: Rowing performance, performance testing, Strength Training, Velocity Training

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1 Introduction

Physical performance tests are highly valued in sport, results are commonly used for talent identification, team selection, load monitoring, injury prevention, and the tracking of both neuromuscular and physiological adaptations over time. Test selection varies by level of play, athlete population, and sport-specific demands. While numerous performance characteristics contribute to athletic performance, muscular strength consistently forms a foundation for success across most sports (Suchomel et al., 2016). Rowing presents a unique combination of endurance, strength, power, and technical proficiency to optimize performance. For example, rowing athletes exhibit maximal oxygen uptake (VO_{2max}) levels (Klusiewicz et al., 2014) comparable to short-distance track athletes (Legaz-Arrese et al., 2007), while demonstrating leg strength like that of throwing and jumping athletes (Singh et al., 2002), despite stark differences in the physical demands of the sports. In rowing, ergometers are predominantly used for training and boat selection. Proven by their high reliability across various resistance levels and distances (MacFarlane et al., 1997; Metikos et al., 2015; Schabert et al., 1999; Soper & Hume, 2004), rowing ergometers utilize similar musculature and movement patterns, as compared to on-water rowing, making them integral to evaluating performance in rowing. Performance assessments in rowing frequently use ergometers to assess VO_{2max} (Akça, 2014; Bourdin et al., 2004; Riechman et al., 2002), maximal anaerobic power (Šmída et al., 2017), 30-second max power (Akça, 2014), 2000 m and 6000 m distance trials. Other assessments, such as 10-stroke peak power, 1-minute, and 20-minute time trials, are frequently utilized (Rowing Canada Aviron, 2018), though research on their specific applications remains limited. Although these sport-specific tests yield valuable information on aerobic and anaerobic capacities, they

provide little information on the strength requirements of rowing. Rowing specific strength and power tests primarily assess lower-body extension, while upper-body tests evaluate arm flexion by utilizing pulling movements (Lawton et al., 2011). To capture a broader range of strength qualities, multiple tests are required to accurately identify and address an athlete's performance strengths and weaknesses. Conducting multiple tests increases the physical load on athletes and reduces time available for training. Therefore, strategically selecting tests that assess multiple strength qualities can minimize the time demands on the athletes and staff. For approximately the last two decades, force-velocity profiling (FVP) has gained significant traction due to its ability to characterize mechanical capabilities of athletes through the evaluation of an athlete's theoretically maximal force production (F_0), extension velocity (V_0), and mechanical power output (P_{max}) across a range of movement conditions (Jiménez-Reyes et al., 2017; Samozino et al., 2008, 2016). In doing so, FVP provides a time-efficient method for assessing multiple strength qualities within a single testing session. While FVP's have been extensively studied across various sports (Baena-Raya et al., 2021; Giroux et al., 2016; Jiménez-Reyes et al., 2018), offering valuable insights into performance optimization, there remains limited research examining its relationship to rowing. Research by Giroux et al. (2017) examined the relationship between bench pull and squat jump FVPs and 1500 m rowing ergometer performance in young national-level male rowers (age: 15.3 ± 0.6 years). They found correlations between rowing performance and bench pull-derived metrics including F_0 , V_0 , S_{FV} , and P_{max} , as well as squat jump-derived F_0 and P_{max} . These findings suggest that rowers who exhibited the highest F_0 and P_{max} values in the squat jump and bench pull also produced the greatest

average power output during the 1500 m rowing ergometer trial. However, with the upcoming transition from a 2000 m to 1500 m distance at the 2028 Olympic games resulting in an expected 90-120s reduction across all event classes leading to a ~5-15% increase in relative anaerobic metabolism contribution (Astridge et al., 2023), targeted training interventions and monitoring strategies are likely to be more important than in previous years. In addition, a growing body of research has emerged highlighting the influence of biological maturation on FVP metrics. Given that Giroux et al.'s (2017) sample consisted of adolescent athletes, the potential confounding effects of maturation on strength and power output warrant consideration when interpreting their findings. Foremost, as maturity status increases, vertical FVP's exhibit higher V_0 and P_{max} values (Jiménez-Daza et al., 2023). As a result, the findings of Giroux et al. 2017 are difficult to extrapolate to more mature populations. Therefore, to better elucidate the relationship between FVP and rowing performance, the purpose of this literature review and study is to investigate the association between lower-limb FVP metrics and rowing ergometer performance in varsity-aged athletes. This review will examine current literature on the physical demands of rowing, commonly used strength assessments, and force-velocity profiling.

1.1 Physical Requirements of Rowing

With 70-75% of energy obtained from aerobic energy pathways during a 2km rowing performance (Hagerman, 1984) and higher levels of strength compared to other endurance sports (Grant et al., 2003; Jürimäe et al., 1997; Koutedakis et al., 1998), rowing athletes are required to develop exceptionally high levels of aerobic endurance and

muscular strength. Achieving concurrent adaptations for both high muscular power output and endurance capacity presents a physiological challenge. Endurance and strength training activate distinct molecular pathways with partially opposing adaptations. This conflict was first identified by Dr. Robert Hickson in 1980, who observed impaired strength development in untrained males performing concurrent strength and endurance training, a phenomenon now widely referred to as the “interference effect” (Hickson, 1980). Since Hickson’s initial findings, numerous studies have determined that concurrent resistance and endurance training can impair strength and hypertrophy gains, a consideration relevant for rowing athletes who require high levels of aerobic fitness and strength (Chtara et al., 2008; T. W. Jones et al., 2013; Rønnestad et al., 2012). Moreover, early research on drug-induced activation of AMPK in rats has shown a significant reduction in protein synthesis associated with decreased activation in mTOR signaling pathway, a key regulator in muscle hypertrophy, providing a mechanistic basis by how concurrent endurance training may blunt strength and muscle gains (Bolster et al., 2002). Specifically, strength training stimulates the mTOR pathway, driving muscle protein synthesis and hypertrophy (Yoon, 2017), while endurance training primarily activates the AMPK–PGC-1 α pathway, which promotes mitochondrial biogenesis and enhances oxidative capacity (Lira et al., 2010). Both pathways have a profound effect on muscle fiber type adaptations: strength and power training predominantly increases the size of type II fibers (Hughes et al., 2018), while endurance training promotes the development of type I fibers to support oxidative capacity (Howald et al., 1985). These contrasting stimuli also result in divergent neuromuscular adaptations. Strength and power training enhances motor unit recruitment

and firing rates to improve maximal strength (Del Vecchio et al., 2019), whereas endurance training prioritizes energy efficiency and fatigue resistance (Hughes et al., 2018). However, despite these conflicts, more recent research has contributed to a nuanced understanding of how to mitigate the effects of interfering adaptive processes (Wang & Bo, 2024). Training capacity, frequency, intensity, order, and the time interval between training sessions make up the primary factors to be considered when designing a concurrent training program (Wang & Bo, 2024). Each factor has an identified role in mitigating or aggravating localized or generalized fatigue obtained from acute exercise, thereby affecting the quality of subsequent training (Wang & Bo, 2024). Also known as the acute interference hypothesis, the residual fatigue incurred from the first training session can negatively impact subsequent training sessions to the point in which the ability for the muscles to gain sufficient stimulus becomes compromised, making for an unfavorable molecular environment for adaptations to occur, thereby magnifying the interference effect (Fyfe et al., 2014). Therefore, practitioners and rowing athletes should continuously monitor adaptations elicited by endurance, strength, and power training to optimize performance across the athlete's career (Van Der Zwaard et al., 2021). Monitoring rowing athletes is largely done with physical performance tests which are commonly broken into three groups: musculoskeletal tests, that evaluate muscular strength and power; anaerobic tests, which assess the ability to maintain high power outputs over short durations; and aerobic tests, which measure the cardiovascular capacity to sustain prolonged efforts.

1.1.1 Aerobic Contributions to Rowing Performance

Physiologically, aerobic fitness is typically reflected by an individual's VO_{2max} , which represents the maximal capacity of oxygen delivery and utilization by the cardiovascular, pulmonary, and muscular systems during exercise (Gao et al., 2021). Direct measurement of VO_{2max} typically requires a subject to complete a maximally graded exercise test with a metabolic gas measurement system to determine pulmonary oxygen and carbon dioxide exchange (Syahid, 2021). In contrast, indirect evaluations of VO_{2max} rely on performance data and are often bolstered with predictive modeling to estimate oxygen consumption (Jensen et al., 2021; Mazza et al., 2023). In rowing, both maximal power output from an incremental rowing ergometer test (Mazza et al., 2023) and average power during a 2 km rowing ergometer time trial (Jensen et al., 2021) have demonstrated effective prediction of VO_{2max} . Given that aerobic energy contributes approximately 70–75% of the total energy demand during a 2000m rowing race (Hagerman, 1984), and research has shown significantly higher VO_{2max} values in elite rowers compared to their non-elite counterparts (Secher et al., 1983), aerobic capacity testing has become standard practice in rowing performance assessments. Although aerobic capacity is consistently identified as a physiological correlate of rowing performance (Cerasola et al., 2020; Cosgrove et al., 1999; Gillies & Bell, 2000; Turnes et al., 2020), it is not the sole determinant of competitive success. Other physiological variables, such as lactate threshold, anaerobic power, and rowing economy, have also been identified as contributing to overall rowing performance (Ingham et al., 2002; Lawton et al., 2011). Commonly referred to as lactate threshold, specific derivatives such as aerobic threshold and the onset of blood-lactate accumulation mark the start of lactate appearance and rapid lactate accumulation

respectively (Jamnick et al., 2020). Both serve as critical markers to perform a given workload and sustain high power output throughout a 2000m race (Ingham et al., 2002). Anaerobic energy is particularly important during the start and sprint phases, where rapid, high-intensity efforts exceed the capacity of aerobic pathways to meet energy demands (Hagerman, 1984). Rowing economy, the oxygen cost of producing a given power output, relates to physiological adaptations that allow for sustained work with lower metabolic demand (Kane et al., 2012). Although limited research has examined this relationship in rowing, economy can be influenced by technique but is not a direct proxy for it; evidence from running athletes shows that individuals may achieve high economy even with suboptimal technique through long-term adaptation to a specific movement pattern (Moore, 2016). In contrast, efficiency refers to the total energy expenditure that is converted into useful mechanical work at the oar and should be considered separately from economy when evaluating performance (Fukunaga et al., 1986).

1.1.2 Strength Contributions to Rowing Performance

Strength contributes to rowing performance through a variety of physiological and biomechanical mechanisms. Unlike aerobic capacity, which is predominantly shaped by cardiorespiratory adaptations (Hellsten & Nyberg, 2015), strength and power stem from the development of muscle cross sectional area (E. J. Jones et al., 2008), muscle architecture (Blazevich et al., 2007) and neural factors (Carroll et al., 2011). Compared to amateurs, elite rowers exhibit significantly greater total body mass, fat-free mass, and superior strength performance in rowing-specific exercises such as the bench pull (Izquierdo-Gabarren et al., 2010). These strength-related advantages translate into faster 2

km ergometer times, greater peak power output during repeated strokes, and enhanced power at onset of blood lactate accumulation (Izquierdo-Gabarren et al., 2010). In addition to total lean mass, lower extremity lean mass has been found to be a strong predictor of maximal aerobic capacity (Haraldsdottir et al., 2022), emphasizing the importance of region specific development of the legs and hips for rowing performance. This underscores the interconnectedness of muscular strength, neuromuscular adaptations, and oxygen delivery systems, where strength training not only supports force production but also indirectly improves aerobic capacity by increasing muscle tissue available for oxygen extraction (McIntosh et al., 2024).

Although little research has examined this topic in rowing athletes, strength training likely leads to improvements in rowing economy, as increases in multiple aspects of strength would theoretically yield decreased relative effort and a lower associative oxygen cost to produce the same power output. A recent review by Llanos-Lagos et al., 2024 compared the effects of different strength training methods on the running economy of middle- and long-distance runners. They found moderate evidence for high load ($\geq 80\%$ 1RM), submaximal (40-79% 1RM), plyometric, and isometric training methods, suggesting that they may improve running economy. Although rowing economy lacks explicit research, numerous studies using high load strength tests have been correlated to rowing performance, thereby highlighting its relevance to success in the sport (Akça, 2014; Huang et al., 2007; Kramer et al., 1994; Lawton et al., 2013; Ledergerber et al., 2023). Likewise, the effects of concurrent plyometric training in teenage rowing athletes have shown comparable improvements in rowing economy to that of steady-state cycling training and

superior results in 500m rowing ergometer time and 15-second peak rowing power (Egan-Shuttler et al., 2017). Although speculative, this suggests that rowing athletes may incur similar benefits to rowing economy as running athletes to running economy despite stark differences in modality. Another aspect of strength that likely aids in rowing economy is explosive strength, although very limited research has examined this. A systematic review by Denadai and colleagues (2017) examined the effects of explosive (high velocity, $\leq 40\%$ 1RM) and heavy weight (≤ 10 repetitions, $\geq 70\%$ 1RM) training interventions on endurance athletes and demonstrated a significant beneficial effect on running economy. Although explosive training hasn't been explicitly examined in relation to rowing economy, explosive strength measurements such as RFD (James et al., 2023) have been correlated with 2 km rowing performance (Ledergerber et al., 2023). In particular, RFD measured during isometric tasks, such as the leg press (150ms and 350ms) and mid-thigh pull (300ms), have shown moderate to strong correlations with 2 km rowing ergometer performance (Ledergerber et al., 2023). Collectively, the above research highlights aspects of strength such as maximal dynamic (both fast and heavy), reactive, and explosive strength as defined by James et al. (2023), as contributing factors to rowing economy, albeit not all of them explicitly measured. Thus, strength should be viewed not as a supplementary attribute, but as a core physical capacity essential for optimizing rowing efficiency and power output.

1.2 Muscle Activation in Rowing

Understanding muscle activation patterns during the rowing stroke is essential for evaluating the specific physical demands placed on athletes and for informing effective

training practices. The rowing motion involves a coordinated sequence of muscular engagement, with different muscle groups contributing at various phases of the stroke. By analyzing these activation patterns, practitioners can gain valuable insights into the muscular capacities that underpin performance, helping to identify technical inefficiencies, minimize injury risk, and tailor training to reinforce the most critical muscular actions. Throughout the rowing cycle, virtually every major muscle group is recruited in a synergistic pattern of activation. Notably, three main synergies of muscular activation have been identified (Turpin et al., 2011). First, the leg and trunk muscles are predominantly active at the beginning of the drive phase, reaching peak activation during mid-drive. Second, arm and trunk muscles reach peak activation later in the drive, assisting with the completion of force application. Finally, during the recovery phase, activation shifts to muscles such as the tibialis anterior and upper trapezius. Among all muscles involved, the gluteus maximus and long head of the triceps demonstrated the greatest increase in activity across different power outputs (Turpin et al., 2011). However, caution should be used to interpret this finding, as an increase in muscular activation does not indicate increased contribution to rowing performance. Although overall muscle activity tends to increase with power output, this trend is not consistent across all phases. For instance, Turpin et al. (2011) observed minimal activation of the tibialis anterior and a lack of foot stretcher force during recovery, suggesting a period of relative muscular inactivity. More critically, muscle activation is not only dependent on power output but also on stroke rate. As stroke rate increases, muscles such as the tibialis anterior, trapezius medius, biceps brachii, brachialis, triceps surae, biceps femoris, and

semitendinosus display progressively earlier activation timing (Guével et al., 2011; Turpin et al., 2011). This adaptive shift reflects the capacity to synchronize muscular activation to produce force efficiently at higher speeds. In summary, muscle activation in rowing is dynamically influenced by both stroke phase and intensity, highlighting the central roles of lower body extension and upper body flexion in delivering force. Understanding these phase-specific activation patterns is crucial for refining technique, tailoring strength training, and optimizing performance across the full race profile.

1.3 Strength Testing in Rowing

Across sporting domains, five qualities of strength are typically assessed: Heavy maximal dynamic strength (HMDS), the ability to produce maximal force against high external loads; fast maximal dynamic strength (FMDS), the capacity to express maximal force rapidly against little or no additional load; maximal isometric strength (MIS), the greatest amount of force applied to an unyielding object; reactive strength, the ability to produce force in a stretch shortening cycle characterized by ground contact times less than 0.25s; and explosive strength (ES), the ability to generate force very early in the contraction phase, typically within 0.03 to 0.15 seconds (James et al., 2023). For rowing, strength and conditioning practitioners commonly assess explosive, isometric, and both qualities of dynamic strength. HMDS is often evaluated using 1, 3, and 5 repetition maximum (RM) tests. In rowing, exercise derivatives of leg extension and arm flexion tasks such as the leg press and bench pull are widely used (Lawton et al., 2013). Moreover, the bench pull has demonstrated significant correlations with rowing ergometer performance across 1RM (Akça, 2014; Izquierdo-Gabarren et al., 2010; Kramer et al., 1994) and 6RM (Lawton et al.,

2013) conditions. Similarly, the leg press has shown strong correlations with rowing performance for both 1RM (Akça, 2014; Gillies & Bell, 2000; Huang et al., 2007; Kramer et al., 1994) and 5RM tests (Lawton et al., 2013), reinforcing the correlation between HMDS and rowing ergometer performance. Additionally, strength standards for successful U23 male rowers include a back squat and deadlift at 1.3 times body weight and a bench pull at 0.9 times body weight (McNeely et al., 2005). FMDS is typically evaluated using the counter-movement jump (CMJ) or squat jump (SJ). CMJ and SJ height (Huang et al., 2007; Sebastia-Amat et al., 2020) as well as CMJ power output (Sebastia-Amat et al., 2020), have been correlated to rowing ergometer performance. ES is assessed through measures such as time-specific impulse or instantaneous force recorded at predetermined early time points. With greater variable clarity, using measures such as time-specific impulse, instantaneous force, or RFD, tests evaluating countermovement, or squat jumps may be used to assess ES, although limited research has explored this in rowing. Through James et al.'s (2023) definition of ES, little research has examined its correlative value to rowing ergometer performance. RFD at 150ms during an isometric leg press has shown moderate correlations to 2 km rowing performance in club level teenage rowers (Ledergerber et al., 2023). Albeit outside of the 150ms time window indicative of ES, RFD during an isometric leg press at 350ms and Isometric mid-thigh pull at 300ms show strong correlations as well (Ledergerber et al., 2023). Furthermore, it should be noted that ES measures of a longer durations may provide muscular evaluations more akin to MIS (James et al., 2023). Likewise, correlations between the isometric leg press and mid-thigh pull with 2 km rowing

ergometer performance (Ledergerber et al., 2023) are likely demonstrative of this overlap in strength qualities.

In conclusion, evaluating strength in rowing athletes remains a complex undertaking with each of the five strength qualities requiring its own specialized test, equipment, and data-analysis. This fragmented approach is informative but logistically heavy, often demanding multiple sessions, lengthy warm-ups, and repeated maximal efforts that can interfere with regular training. The practical burden exposes a clear gap in our assessment toolkit: coaches need a more refined, time-efficient method that can characterize several strength qualities at once while still preserving the precision of domain-specific metrics. Developing and validating such an integrated protocol would streamline athlete monitoring, reduce testing fatigue, and allow test data to be captured more frequently throughout the season ultimately giving practitioners a sharper, real-time picture of the exercise adaptations that underpin rowing performance.

1.4 Force-Velocity Profiling

Underpinned by Hill's muscle model, which describes how slower shortening velocities allow for greater actin-myosin cross bridge formation and thus increased force production (Fenwick et al., 2017), a FVP serves as a biomechanical assessment method that characterizes an athlete's performance by quantifying the inverse relationship between force production and movement velocity during a specific movement or exercise (Samozino et al., 2012). More specifically, a FVP provides insight into the athlete's neuromuscular function by capturing the mechanical limits of performance, as reflected through the mechanical, morphological, and neural determinants of power production

(Samozino et al., 2012). Mechanically, this reflects muscle properties such as the rate of force development, length-tension, and force-velocity relationships, which govern how efficiently muscles can generate force across varying loads and joint angles (Samozino et al., 2012). Morphological influences including muscle cross-sectional area, fascicle length, pennation angle, and tendon stiffness directly affect the contractile and elastic potential of the muscle-tendon unit (Samozino et al., 2012). Neural mechanisms such as motor unit recruitment strategies, firing frequency, synchronization, and intermuscular coordination contribute significantly to the expression of force and velocity during movement (Samozino et al., 2012). Collectively, these components form a mechanical basis by which neuromuscular adaptations are grossly described by FVP metrics, making it a valuable tool to track and optimize performance.

1.4.1 Development of a FVP

A FVP is developed by measuring an athlete's force and velocity outputs across a range of external loads during a specific movement, such as jumping (Jiménez-Reyes et al., 2017; Samozino et al., 2008), sprinting (Samozino et al., 2016), or other exercises (Levernier et al., 2020; Rahmani et al., 2018). Regardless of the measurement tool used, be it force plates (Jiménez-Reyes et al., 2017; Samozino et al., 2008), accelerometers (Levernier et al., 2020; Rahmani et al., 2018), a linear position transducer (Muñoz-López et al., 2017), Radar (Jiménez-Reyes et al., 2018; Mendiguchia et al., 2016), optical measurement system (Jiménez-Reyes et al., 2018), or timing gates (Haugen et al., 2020), the essential steps remain the same: examine the task at different velocities, record and calculate the corresponding force and power values, and plot them to produce the force-velocity

relationship (Jiménez-Reyes et al., 2017; Samozino et al., 2012, 2016). A linear regression is then applied to force and velocity values to derive theoretical maximal force (F_0), corresponding to the force axis intercept; theoretical maximal velocity (V_0), the velocity axis intercept; and theoretical maximal power (P_{max}), the apex of the parabolic F-V relationship (Samozino et al., 2012). Collectively, these variables characterize the mechanical capacities of the lower limb neuromuscular system that underpin an athlete's ability to generate maximal power output. Furthermore, the ratio/slope of the theoretically maximal F-V relationship (S_{FV}), is representative of the relative force to velocity output achieved by the athlete, wherein a steeper, more negative slope indicates a higher force output relative to velocity (Samozino et al., 2012). Thus, it is possible for two athletes to display the same P_{max} , yet achieve it through different means, thereby resulting in different performance outcomes. Those demonstrating a more force biased S_{FV} (steeper slope) typically perform better under circumstances that require lower velocity and higher force outputs, whereas athletes with more velocity biased S_{FV} perform better in opposing circumstances (higher velocity, lower force) (Samozino et al., 2012). To optimize the force-velocity relationship, an athlete's profile can be compared to the optimal, allowing for identification of force- or velocity-dominant imbalances and enabling the prescription of targeted strength training interventions (Morin & Samozino, 2016). Imbalances oriented towards velocity are given heavy strength training to improve force capabilities; imbalances towards force are prescribed maximal efforts under low loads to improve velocity capabilities. By implementing targeted exercise prescription to optimize the force-velocity relationship, P_{max} can theoretically be enhanced through neuromuscular

adaptations, leading to improved ballistic push-off performance. In rowing, optimizing the force–velocity relationship of the lower limbs could theoretically produce similar performance benefits, highlighting its relevance and value for further study.

1.4.3 Force-Velocity Profiling in Sports

Vertical force-velocity profiling has been utilized and contrasted to athletic performances in a collective of sports; Basketball (Baena-Raya et al., 2021; Jiménez-Daza et al., 2023), soccer (Fernández-Galván et al., 2021; Hervéou et al., 2018; Manson et al., 2021), handball (Jiménez-Reyes et al., 2018; Petridis et al., 2021), rugby (Alonso-Aubin et al., 2021; Nicholson et al., 2021; Watkins et al., 2021), and volleyball (Akinci & İnce, 2025; Petridis et al., 2021), among others. To our knowledge, (Giroux et al., 2017) is the only study sought to characterize lower limb FVP's in elite teenage rowing athletes. However, since its publication, researchers have examined the influence of maturation on FVP metrics, potentially affecting the generalizability of findings to other populations.

Examination of youth male basketball athletes (Jiménez-Daza et al., 2023) and youth female volleyball athletes (Akinci & İnce, 2025) have demonstrated important maturity-related effects on CMJ FVP metrics. With maturation, male basketball athletes demonstrated consistent relative force output and steady increases in V_0 , yielding higher force-velocity imbalances and P_{max} values (Jiménez-Daza et al., 2023). Opposingly, maturing female volleyball athletes demonstrated lower V_0 and higher relative F_0 scores, resulting in force-velocity imbalances more akin to mature males than immature females (Akinci & İnce, 2025). The contrasting force–velocity adaptations between male basketball and female volleyball athletes could be driven by a combination of biological sex

differences, maturation timing, and sport-specific neuromuscular demands. While maturation enhances V_0 and P_{\max} in males, likely due to hormonal and training synergy, females often develop higher relative F_0 without corresponding V_0 gains, leading to the same force-dominant imbalances despite overall performance improvements. The findings of Giroux et al. (2017) which identified significant relationships between rowing ergometer performance and F_0 and P_{\max} , but not V_0 or S_{FV} and must be interpreted in the context of the youth and biological immaturity of their sample. It is possible that participants were in mid-peak height velocity, a stage where key neuromuscular traits and coordination with recently developed limb length are still developing (Malina et al., 2024). Given that both V_0 and S_{FV} are likely influenced by maturation-dependent traits, this may help explain their limited variability and lack of statistical significance in this group. Similarly, P_{\max} , which depends on both F_0 and V_0 , may have been underrepresented in its full potential due to consistently low V_0 values across the cohort. In contrast, F_0 in males tends to scale with body mass during adolescence, likely due to increases in muscle mass and neural adaptations (Jiménez-Daza et al., 2023). This likely explains its stronger predictive relationship with ergometer performance in youth rowers. Furthermore, S_{FV} which reflects the imbalance between F_0 and V_0 , is difficult to meaningfully interpret in this age group due to limited variability in velocity. As athletes mature, their profiles typically flatten (less steep S_{FV}), as V_0 increase and becomes more influential. Therefore, the limited relevance of S_{FV} and V_0 observed in this study may reflect the developmental stage of the athletes rather than their long-term importance to rowing performance.

1.5 Conclusions

Requiring both high muscular power and aerobic endurance, the development of rowing athletes must be taken with great care to mitigate conflicting adaptive processes.

Precisely monitoring and assessing neuromuscular adaptations over time is crucial to longitudinal performance enhancement. By theoretically yielding insight into multiple strength qualities, SJ-based FVPs provide a reliable and time efficient method of quantifying lower-body mechanical output through metrics of F_0 , V_0 , and P_{max} .

Furthermore, as athletes reach biological maturity, key neuromuscular traits, such as motor unit recruitment, tendon stiffness, and contraction velocity, become more fully developed, making mature varsity-level athletes' ideal candidates for accurate FVP assessment. Ultimately, vertical FVPs offer a practical, non-invasive tool to monitor mechanical readiness and tailor concurrent training strategies, ensuring that rowers can balance strength and endurance capacities for maximal rowing efficiency and race-day output. Therefore, the aim of the study in Chapter 2 is to investigate the relationship between vertical FVP metrics and rowing performance in varsity-level athletes.

Specifically, this study seeks to examine the relationship between squat jump-derived force-velocity metrics (e.g., F_0 , V_0 , S_{FV} , P_{max}) and 250 m split performance during a 2 km rowing ergometer test in male varsity rowers. By evaluating how the predictive strength of these metrics changes across race segments, the study aims to identify which traits are most relevant at different phases of the race. This approach may reveal phase-specific relationships between mechanical traits and rowing output, enabling coaches to monitor mechanical readiness in a time-efficient manner, while also providing insights into

performance monitoring, targeted training prescription, and athlete development within a high-performance environment.

2 The Relationship Between Squat Jump Force-Velocity Profiles and 2,000m Rowing Ergometer Performance Across Split Intervals

2.1 Abstract

Force-velocity profiling (FVP) provides a practical assessment of neuromuscular capabilities, yet its application to rowing performance remains underexplored. This study investigated the relationship between squat jump-derived FVP metrics and 250 m split performance during a 2 km rowing ergometer test in male varsity rowers. Sixteen athletes (age = 21.12 ± 1.68 y; height = 1.88 ± 0.07 m; body mass = 86.58 ± 9.47 kg) completed a 2 km ergometer trial followed by loaded squat jumps to determine maximal force (F_0), maximal velocity (V_0), maximal power (P_{max}), and the slope of the force-velocity relationship (S_{FV}). Linear regression analyses revealed that S_{FV} significantly predicted power output across all race segments ($r = -0.54$ to -0.82), while F_0 significantly predicted all but the first segment ($r = 0.51-0.83$). P_{max} and V_0 showed no significant relationships with any segments. Across the race profile, the predictive strength of F_0 increased in later stages, suggesting that force production becomes more critical as fatigue accumulates. These findings highlight the utility of FVP, particularly F_0 and S_{FV} , for monitoring mechanical capabilities relevant to sustained rowing performance and for informing strength-oriented training interventions.

Key Words: Rowing performance, performance testing, Strength Training, Velocity Training

2.2 Introduction

Performance testing is a cornerstone of strength and conditioning practice, supporting talent identification, team selection, and monitoring of training adaptations. In rowing, a sport that uniquely combines aerobic endurance, muscular strength, and muscular power, effective performance assessments are critical. Rowing demands high force outputs at the start (Hartmann et al., 1993) and sustained aerobic energy contributions of 70-85% across a standard 2 km race (Lawton et al., 2011). Consequently, average power output during a 2 km rowing ergometer test is widely used performance benchmark that correlates with $VO_2\text{max}$ (Jensen et al., 2021; Mazza et al., 2023). In addition to understanding the average outcome of the whole race, evidence suggests that the determinants of rowing performance may vary across different phases of a 2 km race, as physiological and mechanical demands evolve throughout the effort (Gee et al., 2023; Oshikawa et al., 2022; Sekine et al., 2021). This would support the inclusion of performance test measurements related to both aerobic and strength/power ability of rowing athletes as well as research into their unique contributions to different segments of a rowing race effort.

To understand the strength qualities that underpin rowing performance, various assessments have been used, including maximal strength (Akça, 2014; Huang et al., 2007; Kramer et al., 1994; Lawton et al., 2013; Ledergerber et al., 2023), rate of force development (Ledergerber et al., 2023), and vertical jump testing (Huang et al., 2007; Maciejewski et al., 2019; Sebastia-Amat et al., 2020). However, taken together, these methods can be time-consuming and may interfere with regular training. In contrast,

force-velocity profiling (FVP) offers a more efficient and holistic evaluation of muscular capabilities. Derived from loaded jump (Jiménez-Reyes et al., 2017; Samozino et al., 2008) or sprinting (Samozino et al., 2016) tasks, FVP's quantify key mechanical outputs including maximal force (F_0), maximal velocity (V_0), maximal power (P_{max}), and the slope of the force-velocity relationship (S_{FV}), which taken together, reflect the morphological and neural determinants of athletic power (Samozino et al., 2012).

Recent work has advanced understanding in this area as it relates to rowing. For instance, Giroux et al. (2017) demonstrated strong correlations between squat-jump derived F_0 and P_{max} , and 1500 m ergometer performance in junior rowers. Reflecting similar trends in findings, more recent research examining FVP's derived from on-water and rowing ergometer performance found significant correlations between F_0 and P_{max} (Nordez et al., 2025). Another study examined load-velocity metrics derived from squat jumps in relation to 2 km rowing ergometer performance, reporting comparable findings and confirming high test-retest reliability, thereby supporting their practicality for field-based monitoring (Pérez-Castilla et al., 2023). In sum, these studies reinforce that FVP metrics are feasible and relevant for rowing research and practice.

However, to date, no studies have evaluated individual FV metrics as separate predictors of performance across distinct race segments in rowing. Prior research has primarily examined these metrics in relation to overall 2 km or 1500 m performance (Giroux et al., 2017; Pérez-Castilla et al., 2023), leaving how each mechanical trait contributes to performances throughout the race largely unexplored. In contrast, segment-specific analysis using FVP-derived characteristics has shown utility in other sports. In

sprinting, (Morin et al., 2012) demonstrated that FVP variables such as horizontal force production better predicted performance during the acceleration phase, while velocity-oriented variables became more relevant in later segments. Given the complex and evolving neuromuscular demands of a 2 km rowing race, different segments may require different muscular strategies (Gee et al., 2023; Li et al., 2023; Oshikawa et al., 2022), meaning a deeper temporal analysis using FVP metrics in rowing is both novel and warranted.

Therefore, the purpose of this study was to investigate the temporal profile of explained variance across a 2 km rowing ergometer test to assess how the predictive strength of individual force–velocity profile metrics (F_0 , S_{FV} , P_{max} , V_0) evolve over the course of a race. This approach may reveal phase-specific relationships between mechanical traits and rowing output, offering insights for performance monitoring, individualized training, and athlete development.

2.3 Methods

2.3.1 Approach to the Problem

To examine the relationship between lower-body FVP characteristics and 2 km rowing ergometer performance in male varsity-level rowing athletes, a cross-sectional study design was used. The 2 km rowing ergometer test was selected due to its status as the standard competitive distance and its association with VO_{2Max} (Akça, 2014; Cerasola et al., 2020; Jensen et al., 2021; Mazza et al., 2023; Turnes et al., 2020). Average power across 250 m splits served as the primary outcomes to assess the phase-specific influence of FVP characteristics. Squat jumps were used under loaded conditions to generate individual

FVPs, as this movement minimizes stretch-shortening cycle contributions and more closely resembles the concentric nature of the rowing stroke (Rawley-Singh & Wolf, 2023). To assess how FVP characteristics relate to rowing ergometer performance over time, individual linear regression models were used to predict power at each 250 m stage from key FVP metrics (F_0 , S_{FV} , P_{max} , V_0). This allowed for a temporal profile of explained variance across the full 2 km, highlighting how the predictive strength of each metric evolves through the different stages of a race. This structure enabled a multifaceted assessment of how lower-body mechanical qualities contribute to performance dynamics over the course of a maximal rowing effort.

2.3.2 Subjects

Seventeen heavyweight (age: 20.48 ± 1.78 years; height: 1.91 ± 0.06 m; body mass: 90.55 ± 7.17 kg) and four lightweight (age: 21.27 ± 1.97 years; height: 1.80 ± 0.03 m; body mass: 74.14 ± 2.01 kg) highly trained athletes (McKay et al., 2022) from the University of Victoria men's rowing team volunteered for this study. Informed consent was obtained, and the study received ethical approval from the University of Victoria Human Research Ethics Board and complied with the principles outlined in the Declaration of Helsinki.

2.3.3 Procedures

In the week prior to testing, the rowing team completed 330 minutes of ergometer training at 135-150 bpm across three sessions, one 90-minute session at 150-165 bpm, and three on-water sessions. In addition, the athletes completed two weights sessions focusing on Olympic and compound lifts, including power cleans, deadlifts, squats, barbell rows, and bench press. One weight session occurred <48hrs prior to the first round of testing and

was de-loaded to approximately 40% of typical volume load to mitigate any fatigue incurred. Two testing sessions were conducted 48 hours apart. Participants were asked to refrain from physical activity between testing sessions. Session one aligned with regular team testing and included a 2km rowing ergometer trial. Session two consisted of vertical FVP and anthropometric testing.

2.3.3.1 2000 m Rowing Ergometer Testing

Participants performed self-directed warm-ups for approximately 15-minutes consisting of self-selected intervals of varying intensities and durations on their rowing ergometer to best prepare themselves for their 2km test. This was followed by a 5-minute rest before they began the 2 km time trial. All participants used a Concept2 rowing ergometer (Model D, Morrisville, VT, USA) with the drag factor set to 120. Verbal encouragement was provided by training staff and other team members. Performance data were recorded using the PM5 monitor (Concept 2, PM-5, Morrisville, VT, USA), including average power (watts), completion time (seconds), average stroke rate (strokes per minute), and split time for each 250 m segment. Split times were then converted to watts using Concept2's pace-to-power calculator (Concept2, n.d.).

2.3.3.2 Vertical Force-Velocity Profiling

Participants performed a standardized 20-minute warm-up consisting of 10 minutes of general activity through multiple planes to elevate the body temperature and a 10-minute specific warm-up comprised of low amplitude hops and squat jumps. They then performed squat jumps at five external loads: 0.5 kg, 20 kg, 40 kg, 50 kg, and 60 kg. Three repetitions per load were recorded, with 10–15 seconds of rest between jumps and >3 minutes between loads. Squat depth was set to 0.5 m, marked by a rubber band

positioned over the posterior edge of the force plates to standardize push-off distance between trials and loads (Agar-Newman et al., 2025). The squat depth was held for three seconds, counted aloud by the tester prior to jumping as high as possible. After completing three repetitions for the given load, data collection was stopped, then the athlete was instructed to rack the weight. Trials were excluded if any movement or technique errors occurred (e.g., countermovement, improper depth, or force plate landing errors). Jumps exceeding 2% body mass in unweighting amplitude were excluded (Agar-Newman et al., 2025). Squat jump technique was evaluated by a National Strength and Conditioning Association, Certified Strength and Conditioning Specialist. Data was collected at 1,000 Hz and analyzed using a custom LabView script (National Instruments; LabVIEW 2015, Austin, TX, USA). Force-time data were filtered with a fourth-order Butterworth filter with a low-pass cutoff of 50 Hz. The unweighting phase and relative countermovement during this phase were identified and calculated using the same methods outlined by Agar-Newman et al. (2025). Net force was calculated by subtracting system mass from total ground reaction force. Take-off velocity was calculated using the impulse-momentum method (Linthorne, 2001), and push-off height was determined by integrating velocity during the push-off phase. In our laboratory, previous research examining test-retest reliability for squat jump height showed an intraclass correlation coefficient of 0.98 (95% CI: 0.93–0.99) and a typical error of measurement of 0.02 m (Agar-Newman et al., 2025). Mean force and velocity were estimated using the three-factor model (Samozino et al., 2008), and a linear regression was used to determine F_0 (y-intercept), V_0 (x-intercept), and slope (S_{FV}) (Samozino et al., 2012). P_{\max} was computed

using standard parabolic power equations (Morin & Samozino, 2016). FVPs with an R^2 below 0.95 were excluded. The mean R^2 for included profiles was 0.99 ± 0.01 .

2.3.3.3 Anthropometric Protocols

Body mass was measured using dual force plates (AMTI; OR6-7, Watertown, MA, USA) prior to each jump. Plates were zeroed prior to each trial, and system mass (body mass + external load) was calculated using the average force output divided by $9.81 \text{ m}\cdot\text{s}^{-2}$ over the quiet stationary period. The external load was then subtracted from the system mass to determine body mass.

2.3.4 Statistical Analysis

Participants who were unable to complete four or more loads due to technical errors, countermovement $> 2\%$ body weight, or a force velocity relationship $R^2 < 0.95$, were removed from analysis. In addition, FVP metrics existing outside of 1.5 times their respective interquartile range were identified as outliers and subsequently removed. Normality of the force-velocity and rowing ergometer metrics were evaluated using a Shapiro-Wilk's normality test. Multiple linear regressions were conducted for each FVP variable to predict each split performance. To account for the increased risk of Type I error due to multiple comparisons, a Bonferroni correction was applied to adjust the significance threshold across regressions. Regression assumptions were evaluated by inspecting scatterplots of standardized residuals versus fitted values to assess constant variance and linearity, and Q-Q plots of residuals to assess normality. All statistics were conducted in JASP (version 0.17.1; Amsterdam, Netherlands).

2.5 Results

Of the 21 participants who completed testing, five were excluded: three were beyond the countermovement threshold ($>2\%$ bodyweight), one was below the R^2 cutoff ($R^2 < 0.95$), and one participant produced values beyond 1.5 times the interquartile range and was removed as an outlier. The final sample consisted of 16 male varsity-level rowers (mean \pm SD: age = 21.12 ± 1.68 years; height = 1.88 ± 0.07 m; body mass = 86.58 ± 9.47 kg).

Shapiro-Wilk tests confirmed normality for all variables. Descriptive statistics for rowing ergometer performance are presented in Table 1, and FVP results are summarized in Table 2.

Table 1 - Rowing Ergometer Descriptives

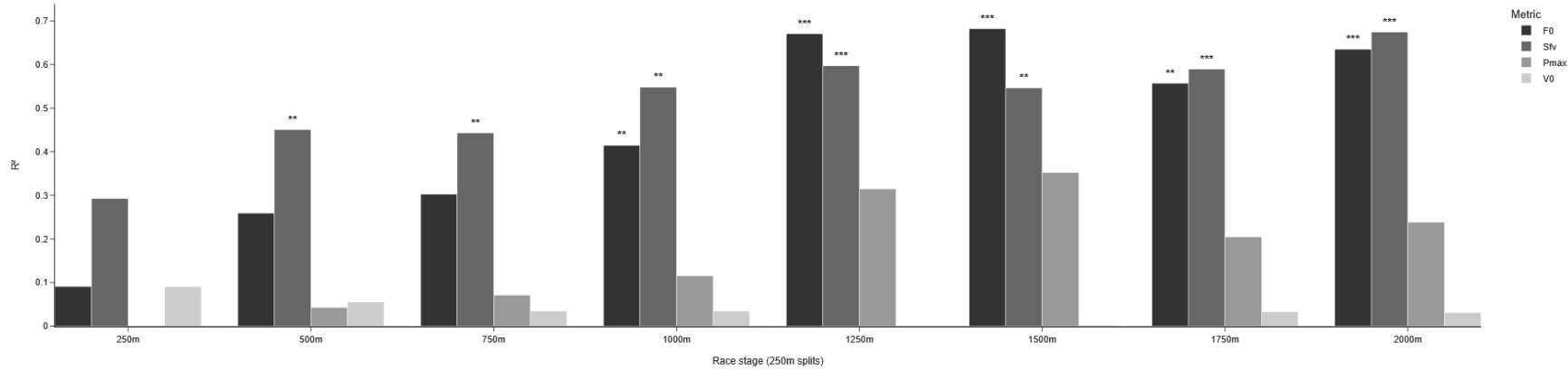
Variable	Mean	SD
2 km Avg Power (W)	390.25	39.88
Avg Split Power (W)	378.14	39.44
Stroke Rate (strokes/min)	34.48	2.22
1st 250m (W)	451.38	56.38
2nd 250m (W)	394.73	46.52
3rd 250m (W)	382.13	42.58
4th 250m (W)	373.04	44.06
5th 250m (W)	373.64	42.97
6th 250m (W)	370.67	37.74
7th 250m (W)	379.97	41.45
8th 250m (W)	419.45	49.7

Table 2 - FVP Descriptives

Variable	Mean	SD
F_0	2360.41	292.37
V_0	2.75	0.31
S_{FV}	-886.81	172.45
P_{max}	1593.48	272.04

Linear regression models using S_{FV} significantly predicted all but the first split. Models using F_0 significantly predicted all splits from 1000m onwards. No models using V_0 or P_{max} were able to significantly predict any split performance. Figure 1 presents the linear regression results, including the corresponding R^2 values and significance levels.

Figure 1 - Split Performance Linear Regression Bar Graph



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

2.5 Discussion

This study examined whether force-velocity profile metrics derived from progressively loaded squat jumps could predict segment-specific rowing ergometer performance in male university-level rowers. The findings demonstrated that the predictive strength of FVP variables was highly stage-dependent, highlighting the importance of temporal dynamics across the 2 km effort. Among the primary metrics, F_0 demonstrated strong predictive value, particularly from 1000 m onwards, indicating that force production becomes increasingly vital as fatigue accumulates. By contrast, V_0 showed no meaningful predictive power at any segment, aligning with previous findings by Giroux et al. (2017). This likely reflects rowing's mechanically constrained stroke, which involves little true high-velocity movement. Moreover, because rowers typically train at relatively low stroke rates (McArthur, 1997), their training inherently prioritizes force production at lower velocities. It remains unclear whether sustained training at higher stroke rates could meaningfully enhance V_0 , as empirical evidence on this specific adaptation in rowing is lacking. Among the secondary, composite metrics, S_{FV} consistently explained the most variance across most stages, particularly in the second half of the race, when stroke velocity remains relatively stable but sustaining force becomes increasingly difficult under fatigue. Conversely, P_{max} , while conceptually a key output variable, underperformed. Examination of the mathematical derivation and underlying components of these composite measures may help to further clarify the important role of force production during 2 km erg performance. Ultimately, squat jump derived FVP offers a time-efficient and informative

strategy for monitoring strength qualities relevant to rowing and tailoring training interventions to phase-specific demands.

Results showed that predictive strength varied substantially across race segments, reinforcing previous research that biomechanical and physiological demands are dynamic throughout the 2 km effort (McGregor et al., 2004; Oshikawa et al., 2022; Pollock et al., 2010; Sekine et al., 2021). Biomechanical research on the rowing stroke has shown that contributions from the trunk, upper, and lower limbs, shift over the course of a race, with increased reliance on the lower limbs and trunk during later stages when fatigue is more pronounced (McGregor et al., 2004; Pollock et al., 2010). Similarly, recent research has found that muscle activation shifts across race splits, indicating that rowers adjust neuromuscular recruitment to maintain power output as fatigue accumulates (Oshikawa et al., 2022; Sekine et al., 2021). The findings of the present study indicate that F_0 grows in importance from mid-race onward, reflecting the increasing difficulty of sustaining force under accumulating fatigue. In contrast, V_0 showed no meaningful relationship with segment performance, aligning with the mechanically constrained nature of rowing, where propulsion occurs under high resistance and low movement velocity (Sanderson & Martindale, 1986). This finding mirrors previous work in elite rowers, showing that peak stroke rates are not limited by maximal movement velocity (Ettema et al., 2022). In sprinting (Morin et al., 2012), high-velocity capabilities strongly influence short acceleration phases, whereas our findings provisionally indicate that sustaining steady force output may be more decisive in rowing. Future research should pair FVP with direct technical measures like stroke length, drive and recovery timing, and power-curve

characteristics, to determine whether sustained force genuinely preserves stroke effectiveness across the race. The present comparison between S_{FV} and P_{max} underscores distinct conceptual and practical implications for profiling rowers. Although both variables are computed from the same primary metrics, they capture different aspects of neuromuscular function. S_{FV} quantifies the relative orientation of an athlete's FVP; a steeper (more negative) slope indicating force-orientation, whereas a shallower slope reflects a velocity orientated profile. In contrast, P_{max} denotes the theoretical maximum mechanical power that can be generated at an athlete's optimal combination of force and velocity. In the present study, S_{FV} explained substantially more variance in 2 km rowing ergometer performance than P_{max} , suggesting that an orientation towards higher force capability may be more consequential for performance than maximizing theoretical peak power. This interpretation should be tempered by the cohort's lack of diversity. All participants exhibited velocity-biased FVP's, restricting between-subject variance in V_0 . Because both S_{FV} and P_{max} are mathematical composites of F_0 and V_0 , this range restriction likely weakened the association of P_{max} . With V_0 nearly constant, differences between athletes were likely driven by F_0 , which is highly relevant to 2 km performance. Notably, (Giroux et al., 2017) reported a different pattern in a force-biased cohort, where P_{max} showed a very large association with 1500 m ergometer performance, while S_{FV} was only moderately related. Taken together, this suggests that the relative importance of composite FVP metrics may be influenced by an athlete's position along the force-velocity spectrum.

From an applied standpoint, FVP can inform phase-specific training priorities. Classifying athletes as force- or velocity-oriented enables targeted emphasis (e.g., maximal-strength work to bolster late-race F_0 , or mixed loading to rebalance S_{FV}). Coupling FVP with simple stroke mechanics, examining stroke length and drive time to derive drive speed, would allow practitioners to infer whether segment power is driven primarily by force, length, or speed and to set priorities accordingly. The present data showed that segment-specific race power mirrored the behavior of force variables, albeit to a smaller extent, reinforcing the primacy of force-dominant qualities in rowing. Accordingly, whole-race averages should be supplemented with segment-level mechanical profiling to align physical qualities with the distinct demands of each race phase. This integrated approach clarifies emphasis without becoming overly prescriptive and aligns with recent work identifying phase-specific strength determinants of rowing ergometer performance (Ledergerber et al., 2023).

Several technical and methodological factors may have influenced the observed relationships between FVP metrics and segment-specific performance. The rowing ergometers used in this study (Concept 2, Model D, Morrisville, VT, USA) may inherently limit the expression of power output in the earliest strokes, when intensity and stroke rate fluctuate the most (Boyas et al., 2006; Holt et al., 2021). During this period, high stroke-to-stroke variability can reduce measurement accuracy, underestimating power values and attenuating early-segment associations (Boyas et al., 2006). Further, power output measured by the Concept2 has been shown to be ~10% lower than performed by the rower (Holt et al., 2021). Research by (Nordez et al., 2025), which examined FVP's from

both rowing ergometers and on-water performance, found that ergometer FVP's tend to be skewed towards higher force and lower velocity compared to on-water profiles. These differences in velocity characteristics may partly explain the limited associations observed with velocity-related metrics in the present study. Therefore, while our findings indicate that squat jump FVP metrics are relevant to rowing ergometer performance, their transferability to on-water performance has not been examined and remains uncertain.

In summary, this study demonstrates that the relevance of FVP metrics to rowing ergometer performance is not static but varies meaningfully across the race profile, with force-oriented and balanced FV characteristics emerging as the most important determinants of sustained performance. Integrating segment-specific mechanical profiling with targeted training interventions has the potential to enhance performance outcomes and offers a promising direction for applied rowing science.

2.6 Practical Applications

Practitioners working with varsity-level rowers may consider incorporating squat jump-based FVP as a tool to monitor split performance. Emphasis should be placed on tracking F_0 , as it appears to drive changes in related metrics such as P_{max} and S_{FV} . While S_{FV} showed strong predictive value in this study, its utility may be limited to athletes who already exhibit velocity-biased profiles. Overall, these findings support the integration of heavy strength training aimed at increasing lower limb force production to enhance rowing performance, particularly in the latter stages of a 2 km effort where fatigue resistance is critical.

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