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UNIVERSITY OF CALGARY

The Effects of Force-Velocity Test Specificity on On-ice Acceleration Performance Prediction in Elite Speed Skaters

by

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Abstract

This primary purpose of this thesis was to investigate the influence of off-ice force-velocity test specificity on the prediction of on-ice acceleration performance in elite long track speed skaters. We assessed a functional force-velocity relationship using three loaded jump protocols. In the first study, we established the intra-day reliability of two novel unilateral loaded jump protocols, the single leg horizontal ($Jump_{Horz}$) and lateral ($Jump_{Lat}$) jumps. These protocols were shown to be reliable, displaying significant interrelationships with on-ice sprint race split times at distances of 100 m, 400 m, and 500 m. The second study validated an exponential function model to evaluate velocity changes during an on-ice sprint start that provided a more detailed assessment of on-ice acceleration capacity compared to the convention of split times. The exponential model allowed for the calculation of performance parameters, which demonstrated strong reliability, and differentiation between elite and sub-elite athletes. In the final study, we compared the $Jump_{Lat}$, $Jump_{Horz}$ and CMJ loaded jump tests for the prediction of on-ice acceleration performance obtained from our exponential model. Using a regularized regression model, we found that the loading condition is more significant than movement specificity for predicting on-ice acceleration performance. In summary, these studies provide practitioners in skating sports with novel off and on-ice testing methodology that may be used to better monitor performance during the running and gliding phases on-ice, and to inform individualized training prescription.

Preface

The following four chapters are based on published manuscripts:

Chapter 2	Zukowski, M., Herzog, W., & Jordan, MJ. Single Leg Lateral and Horizontal Loaded Jump Testing: Reliability and Correlation with Long Track Sprint Speed Skating Performance. *The Journal of Strength & Conditioning Research*, *37(11):p 2251-2259*
Chapter 3	Zukowski, M., Herzog, W., & Jordan, M. J. (2023). Modeling the Early and Late Acceleration Phases of the Sprint Start in Elite Long Track Speed Skaters. *The Journal of Strength & Conditioning Research*, 10-1519.
Chapter 4	Zukowski M, Herzog W, Jordan MJ. Velocity-Load Jump Testing Predicts Acceleration Performance in Elite Speed Skaters: But Does Movement Specificity Matter? *International Journal of Sports Physiology and Performance* [In Revision]
Appendix 1	Zukowski, M., Herzog, W., & Jordan, M. J. (2023). Multi-Planar Jump Performance in Speed Skating Athletes: Investigating Interlimb Differences in an Asymmetrical Sport. *Symmetry*, *15*(5), 1007.

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

AI	Asymmetry index
CMJ_{BW}	Countermovement jump (bodyweight)
CMJ_{Con}	Countermovement jump concentric impulse
CMJ_{Ecc}	Countermovement jump eccentric deceleration impulse
CMJ_{30}	Countermovement jump (30% of body mass in external load)
CMJ_{60}	Countermovement jump (60% of body mass in external load)
CV	Coefficient of variation
ES	Effect size
F_0	Theoretical maximum force
FV	Force velocity
FVP	Force-velocity profile
ICC	Intraclass correlation coefficient
$Jump_{Lat}$	Single leg lateral jump
$Jump_{Horz}$	Single leg horizontal jump
LOA	Limits of agreement
LVP	Load velocity profile
MAC	Maximal acceleration capacity
MSE	Mean standard error
MSS	Maximal skating speed at 50 m
P_{Max}	Maximum net relative horizontal mechanical power
PV	Peak velocity
SD	Standard deviation
S_{FV}	Force velocity linear line slope
τ	Acceleration-time constant
TOV	Takeoff velocity
V_0	Theoretical maximum velocity
WR	World record

Chapter 1: Introduction and Literature Review

1.1 The Long Track Speed Skating Sprint Start

Long track speed skating, an Olympic sport, challenges athletes to cover set distances on a 400 m oval ice surface in the shortest time possible (Konings et al., 2015). Each race begins from a stationary position at the starting line, where athletes hold for an auditory signal from a start gun that initiates the race. In sprint distances, particularly the 500 m event, the ability accelerate over the initial 100 m into the first turn is critical to final placing (de Koning, de Groot, & van Ingen Schenau, 1989; de Koning, Thomas, Berger, de Groot, & van Ingen Schenau, 1995; Song, Lee, & Moon, 2017). Data from the 1988 Olympic Games serves as evidence, with observations that 80% of the variation in total 500-meter times was attributable to performances in the initial 100-meter segment (de Koning, de Groot, & van Ingen Schenau, 1989). The importance of the initial 100 m was further confirmed via published data from the 2022 Olympic trials, where U.S. speed skaters' 100-meter split times accounted for 95% of the variability in their final 500-meter times (McKeever, Stuart, Tufano, & Suchomel, 2023).

In speed skating, the initial on-ice acceleration phase is divided into two unique movement phases: running and gliding. The running phase is crucial for optimal acceleration off the start line as skaters push off a fixed point on the ice for their initial 5-6 strides (Song et al., 2017). This phase is characterized by brief ice contact times and shallow hip and knee angles, akin to the kinematics of overground sprinting (de Koning, Thomas, Berger, de Groot, & van Ingen Schenau, 1995). The running phase typically covers the first 1.6-2.2 s of a 500-meter race (Song et al., 2017). According to modeling studies, the relative mechanical power exerted during the running phase significantly surpasses the estimated outputs during peak velocity skating (de Koning et al., 1989).

Once speed skaters reach a certain speed threshold—estimated to be around 6.7 m/s (de Koning et al., 1995)—it becomes disadvantageous to push in a rearward direction off a fixed point on the ice. This necessitates a transition into the glide phase to continue accelerating, which is characterized by a more flexed knee and hip position and extended push-off durations. During this phase, athletes produce force via a powerful extension of the lower limb which spans approximately 200 ms (de Boer et al., 1987). It has been suggested that gliding consists of alternating isometric and concentric muscle actions as skaters transition between the support and push-off phases (de Groot, Hollander, Sargeant, van Ingen Schenau, & de Boer, 1987). Moreover, small pre-extension knee angles during this phase in the sprint events have been shown to differentiate between elite athletes and their lesser counterparts (van Ingen Schenau & de Groot, 1983).

1.2 Assessment of Neuromuscular Power in Speed Skaters

Maximal muscle power capacity is a crucial determinant of athletic performance across various sports (Cronin & Sleivert, 2005). In long track speed skating, the highest power outputs are thought to occur during the on-ice acceleration phase (de Koning et al., 1989). Therefore, it is critical for practitioners and coaches to identify the most reliable and predictively valid off-ice tests of mechanical power.

Traditionally, the Wingate cycle ergometer protocol has been the preferred method for evaluating speed skaters' maximal power capabilities (van Ingen Schenau, de Koning, Bakker, & de Groot, 1996). Despite the strong correlation between 5 s Wingate peak power and overall 500 m times (r=0.81) (Smith & Roberts, 1991), the protocol fails to match the movement specificity inherent to speed skating kinematics due to the incomplete knee extension in cycling. Other studies have attempted to overcome these limitations with knee extension dynamometry, observing strong associations with sprint distance performance (r=0.61-0.75) (Liebermann, Maitland, & Katz, 2002; Smith & Roberts, 1991). Interestingly, stronger relationships were observed at higher absolute knee extension velocities, suggesting an adaptation to the force velocity capacities of the knee extensors in sprint distance skaters.

Though dynamometer testing effectively simulates the powerful knee extension observed during speed skating, the external power generated by athletes also depends on the work performed by muscles acting at the hip and ankle joints (de Boer et al., 1987). This complexity is potentially best accounted for by vertical and horizontal jump tests. These assessments are widely regarded as some of the most valid and reliable indicators of lower body mechanical power (Markovic, Dizdar, Jukic, & Cardinale, 2004; Pazin, Berjan, Nedeljkovic, Markovic, & Jaric, 2013; Rittweger, Schiessl, Felsenberg, & Runge, 2004).

Despite the kinematic similarities between speed skating and jumping (Bobbert, Houdijk, de Koning, & de Groot, 2002), research exploring the relationship between vertical jump capacity and on-ice skating performance is sparse. Only two studies exist to date, both of which have reported strong correlations (r= -0.62 to -0.76) between countermovement jump (CMJ) performance and on-ice split times (de Greeff, Elferink-Gemser, Sierksma, & Visscher, 2011; Liebermann et al., 2002). However, neuromuscular testing that assesses basic muscle properties that influence force production and enhance the mechanical capacity of the lower limb may provide additional insight beyond standard vertical jump testing – this includes the multi-joint force velocity properties of the lower body agonist muscles (Samozino, Rejc, Di Prampero, Belli, & Morin, 2012). The functional force velocity relationship in jumping has been assessed with incremental loaded jump protocols and provides a practical approach for advanced analyses of an athlete's neuromuscular capacities in a sport performance setting (Sheppard, Cormack, Taylor, Mcguigan, & Newton, 2008). However, the value of loaded jump protocols for evaluating skating athletes' functional force velocity relationship and the influence of movement specificity (i.e., vertical vs. horizontal frontal plane jumping) with respect to the predictive validity for on-ice acceleration performance is unexplored. On this front, the emergence of robotic resistance training systems which can accommodate multi-planar loaded movement while measuring kinematic data provides promise for new test methodologies for skating athletes (Eriksrud, Ahlbeck, Harper, & Gløersen, 2022).

1.3 The Force Velocity Relationship of Skeletal Muscle

In a landmark series of experiments on frog muscle, AV Hill was able to successfully identify and model the force velocity relationship of isolated skeletal muscle (1938). Hill observed that the slower a muscle shortens, the more force it can generate, and vice versa. This relationship was best fit by a hyperbolic equation and was fundamental in the development of the sliding filament theory of muscle contraction (Huxley & Hanson, 1954). To reproduce this relationship, measurements must be made during maximal, steady-state contractions performed at optimal muscle or fiber lengths (Hill, 1938).

The earliest work on the force velocity relationship was performed in vivo, with data best fit by a linear relationship (Hansen & Lindhard, 1923; Hill, 1922; Lupton, 1922). However, post-hoc analysis suggests this may be a consequence of assessing a relatively narrow range of conditions that fall in the middle of the force velocity spectrum (Alcazar, Csapo, Ara, & Alegre, 2019). Subsequently, as advances in dynamometry allowed for broader experimental data ranges, it was demonstrated that in vivo data during knee extension and plantar flexion best fit Hill's hyperbolic model (Hauraix, Dorel, Rabita, Guilhem, & Nordez, 2017; Hauraix, Nordez, & Dorel, 2013; Hauraix, Nordez, Guilhem, Rabita, & Dorel, 2015). Inconsistencies might also stem from the inability to meet Hill’s carefully controlled experimental conditions with in vivo testing in humans and additional factors such as neural activation level, in-series elastic components, lateral muscle force transmission, muscle architecture, and muscle tendon moment arms that are challenging to account for (Alcazar et al., 2019). Furthermore, changes in rate of shortening at the muscle tendon unit (MTU) level are not necessarily indicative of the fascicles themselves (de Brito Fontana, Roesler, & Herzog, 2014).

During multi-joint movements, further degrees of freedom allow for other factors such as intermuscular coordination and segmental dynamics to confound force velocity relations. As such, it has been posited that the force velocity relationship is quasi-linear during multi-joint movements (Bobbert, 2012). In contrast, Hahn et al. (2014) demonstrated that with a sufficient range of data points along the force velocity spectrum, Hill's model offered the superior fit during a leg press task. Therefore, it could be argued that the frequently observed linear force velocity relationship in applied literature results from the limited range over which the force velocity relationship is assessed and the challenges in ensuring all of Hill's original conditions are met across all muscles during functional movement. This is particularly true in applied research using movements like sprinting and jumping, where excessive loading or unloading can alter movement kinematics. These complexities cause the in vivo force velocity relationship measured during multi-joint movements such as the vertical jump to differ from the force velocity relationship measured in whole muscle. Thus, practitioners must employ specific experimental controls and analysis procedures to ensure sufficient test reliability and validity when employing this testing technique in a sports performance setting.

1.4 Force velocity vs. load-velocity profiling

The application of multi-joint force velocity testing, often referred to as force velocity profiling (FVP), in sports performance research has increased in recent years (Cross et al., 2021; Cuk et al., 2014; de Lacey et al., 2014; Jiménez-Reyes et al., 2019; Marcote-Pequeño et al., 2019; Stavridis, Smilios, Tsopanidou, Economou, & Paradisis, 2019). FVP assumes that the linearity observed in the middle of the multi-joint force velocity relationship will hold near its intercepts, enabling the calculation of theoretical maximal force (F_0), velocity (V_0), and maximal mechanical power (P_{Max}) during functional movements like sprinting and jumping (Samozino, Morin, Hintzy, & Belli, 2008). FVPs offer more resolution than raw outputs such as jump height or split times, and the slope of these relationships has been proposed to indicate whether an athlete is force or velocity dominant (Morin, Jiménez-Reyes, Brughelli, & Samozino, 2019; Samozino et al., 2014; Samozino, 2018; Samozino, Morin, Hintzy, & Belli, 2010). These profiles have shown promise as a basis for individual training prescription and appear to differ between sports (Giroux et al., 2016; Pedro Jiménez-Reyes, Samozino, Brughelli, & Morin, 2017; Lahti et al., 2020; Morin & Samozino, 2016).

Despite the benefits, FVP comes with certain limitations. One of these is the inherent challenge of testing high force or velocity conditions during a movement such as a vertical jump. Without a sufficient range of experimental data, the assumption of linearity fundamental to the FVP cannot be confirmed. The reliability of vertical jump force-velocity profiles is a subject of ongoing debate in the research. Some studies have raised questions about the inter-day reliability of the force-velocity profiling method (Kotani et al., 2021; Lindberg et al., 2021; Valenzuela et al., 2021), as well as the reliability of FVP parameters such as V_0 and S_{FV} (Cuk et al., 2014; Janicijevic, Knezevic, Mirkov, Pérez-Castilla, Petrovic, Samozino, & Garcia-Ramos, 2020; Lindberg et al., 2021). However, other studies suggest sufficient reliability (Cuk et al., 2014; García-Ramos, Jaric, Pérez-Castilla, Padial, & Feriche, 2017; García-Ramos, Pérez-Castilla, & Jaric, 2018; Rivière, Morin, Bowen, Messonnier, & Samozino, 2021). Moreover, reliability work to date has focused on the reliability of FVP parameters, rather than the direct measures being used to create the model, such as the vertical takeoff velocity (TOV) or jump height across different loads.

Regardless of the profiling approach selected, minimizing variability in jump performance during loaded jump testing would seem critical. Modelling research has demonstrated that loading with 60% of additional mass relative to bodyweight causes a smaller decrease in the TOV than has been reported in applied literature (Bobbert, 2014). Moreover, performance across loading conditions in simulated jumps could only be partly attributed to the intrinsic force velocity relationship of skeletal muscle, with factors such as reduced countermovement depth and sub-optimal neuromuscular control strategies being proposed as other contributors (Bobbert, 2014). Similarly, initial joint angle and range of motion have been shown to confound the FVP during jumping (Janicijevic, Knezevic, Mirkov, Pérez-Castilla, Petrovic, Samozino, & García-Ramos, 2020) and the in vivo force velocity relationship during multi-joint movements (Hahn et al., 2014).

Jump type also influences outcomes of force-velocity testing. During the CMJ, jump performance and FVP parameters have been shown to be higher than the squat jump (SJ) or non-countermovement jump using a static squat start position (Jiménez-Reyes et al., 2014). This may be attributed to increases in the active state or decreases in muscle slack achieved with a countermovement (Van Hooren & Zolotarjova, 2017). Likewise, the number of loading conditions and the external loads themselves may influence an FVP protocol. While multiple loading conditions approaching the individual's maximal muscle strength may improve the estimate of intercepts, this could also impair vertical jump technique and cause acute neuromuscular fatigue (Garcia-Ramos & Jaric, 2018). Recent data suggests that the two-load and three-load method with a load of 60% of the estimated 1RM are sufficient for an FVP or a load velocity profile (LVP) test (García-Ramos et al., 2018; Jordan et al., 2020)

A LVP with incremental external loads applied during vertical jumping may be a suitable alternative to the three-component vertical jump FVP, whereby a stable outcome of interest (typically a measure of movement velocity) is measured across a range of loading conditions. In fact, this approach has been used in cross country skiers (Herzog, Killick, & Boldt, 2015), for monitoring neuromuscular recovery after ACL injury in elite alpine ski racers (Jordan et al., 2020), and for the estimation of 1 repetition maximum (RM) in exercises such as the squat and bench press (Banyard, Nosaka, Vernon, & Haff, 2018). During jumping, external load could be plotted against the velocity of an athlete's centre of mass (CoM) (Jordan et al., 2020; Kotani et al., 2021), thus relying on more robust, direct measures to establish overall profiles.

Correspondingly, Kotani et al. (2021) found the vertical TOV measured with force platforms to be reliable across conditions ranging from 10-100% of external load relative to body mass. Similar findings have been reported by García-Ramos et al. (2017) and Sheppard et al. (2008). However, when it comes to the day-to-day absolute reliability of force-velocity profiles, the results have been moderate to poor (Kotani et al., 2021; Lindberg et al., 2021). Collectively, these findings suggest that the calculated parameters associated with linear force-velocity profiles (F_0,V_0, S_{FV}) do not provide an advantage for assessing neuromuscular capacities over and above directly measured vertical jump performance measures such as the vertical takeoff velocity, peak velocity or mean propulsive velocity achieved against a range of external loads. Future research is required to compare the predictive validity of these two methodologies.

1.5 Training and Test Specificity

To achieve transfer between strength training and sporting environments, Sale & McDougall (1981) advocated for the selection of movements with greater specificity that replicate the postures, contraction types, velocities, and forces observed in sport. Accordingly, training and testing studies using dynamometry and single joint movements have indicated that specificity in terms of joint angle and angular velocity is an important consideration when seeking to maximize the transfer between the tested and trained movement (Aagaard, Simonsen, Trolle, Bangsbo, & Klausen, 1996; Kanehisa & Miyashita, 1983; Kitai & Sale, 1989; Wilson, 1996). Carroll et. al (2001) stated that the transfer of training can occur in both the negative and positive directions, particularly during movements involving complex coordination of agonist, antagonist, and synergist muscles. For instance, Bobbert (1994) showed that increased muscle force does not equate directly with increased vertical jump performance unless accompanied by concomitant adaptations in neuromuscular control, including the timing and control of muscle activation. Collectively, these findings suggest that to predict performance, movement specificity might be a crucial factor when designing test protocols.

Aligned with this thinking, the bilateral vertical CMJ test is non-specific relative to the single leg lateral application of force in the gliding phase and the rearward, horizontal application of force in the running phase of speed skating acceleration. To address this gap, unilateral jump testing in the lateral and horizontal plane may improve off-ice testing methodology for sprint speed skaters by testing movement patterns that more closely resemble the distinct phases of on-ice acceleration. In accordance, unilateral jump testing in different planes may measure independent power capacities of the lower limb (Meylan, Nosaka, Green, & Cronin, 2010; Meylan et al., 2009; Murtagh et al., 2017), while changes in jump angle have previously shown to alter coordinative strategies and EMG recruitment (Fukashiro et al., 2005; Jones & Caldwell, 2003).

1.6 Summary and purpose

Despite its long history in the Olympic Winter Games, the neuromuscular capacities that predict acceleration performance during the initial 100 m of the speed skating sprint events including the initial gliding phase and running phase are not fully understood. Previous research in this field has relied on competition timing splits, which do not provide information on the distinct performance phases of on-ice acceleration: running and gliding. As such, there is a need for reliable and valid performance summaries for each phase, which could be used as benchmarks for off-ice training and testing interventions.

The performance during each movement phase of a 100 m on-ice acceleration might differ according to the individual skater's neuromuscular control of their lower limbs, their maximal muscle power capacity, and their multi-joint force velocity relationships. Understanding the underlying factors that contribute to on-ice acceleration performance, including fundamental muscle properties like the force velocity relationship, could assist coaches in tailoring resistance training programs to individual athletes, monitoring adaptations to training, and predicting on-ice acceleration performance.

Loaded jump velocity profiling with incremental external loads is a practical method to assess neuromuscular capacities related to the basic properties of skeletal muscle, notably the force velocity relationship. Loaded jump protocols have gained popularity in assessing the lower body LVP in athletes. LVP jump profiles have been created for soccer players, track & field sprinters, and athletes with ACL injuries (Haugen, Breitschädel, & Seiler, 2019; Jiménez-Reyes et al., 2019; Jordan et al., 2020; Marcote-Pequeño et al., 2019). Resultant profiles and parameters have also shown promise in differentiating between athletes of different sports (Giroux, Rabita, Chollet, & Guilhem, 2016) and individualizing the prescription of strength training (Morin & Samozino, 2016). Resultant profiles are unique to the movement tested, highlighting a need for test protocols high in specificity with the sport of interest.

The aim of this thesis was to assess the reliability and predictive validity of loaded jump profiles generated from three exercises: the bilateral vertical CMJ (non-specific movement), the lateral single-leg jump (Jump_{Lat}), and the horizontal single-leg jump ($\text{Jump}_{\text{Horz}}$) (collectively specific movements), in predicting on-ice acceleration in elite long track speed skaters. A secondary goal was to evaluate the utility of monoexponential modelling to predict velocity during the speed skating sprint start, and to assess the reliability and discriminant validity of model parameters, which may offer additional diagnostic insight into performance during the independent on-ice acceleration phases. We hypothesized that monoexponential modeling would offer a valid and reliable overview of on-ice acceleration performance. Furthermore, we posited that the $\text{Jump}_{\text{Horz}}$ would be the superior predictor of running phase performance, in contrast to the Jump_{Lat}, which we expected to predict glide phase performance more effectively.

Chapter 2: Single Leg Lateral and Horizontal Loaded Jump Testing: Reliability and Correlation with Long Track Sprint Speed Skating Performance

2.1 Introduction

Maximal muscle power capacity is a key performance indicator in many cyclic sports like sprinting (Cronin & Sleivert, 2005), and in long track sprint speed skating, during which the largest mechanical power outputs can be observed during the acceleration phase which is initiated from a static start position similar to the sprint events in track and field (de Koning, de Groot, & Schenau, 1989). In the 500 m sprint event, the opening 100 m acceleration accounts for a large proportion of the explained variance in the overall race time (de Koning et al., 1989). Here, skaters transition between a running phase and a gliding phase that require two distinct techniques (de Koning, Thomas, Berger, de Groot, & van Ingen Schenau, 1995). The running phase is characterized by short ice contact times and typically spans the initial 1.6-2.2s of the race (Song et al., 2017). Thereafter, skaters transition to gliding, utilizing longer push-offs to maintain acceleration for the remaining 60-70 m in preparation for the first turn (de Koning et al., 1995). The gliding technique has been shown to share intermuscular coordination and kinematics with the vertical jump, even being likened to a single legged jump in the frontal plane (de Boer et al., 1987). Leveraging these two movement strategies, elite long-track speed skaters can achieve skating velocities up to 15 m/s (de Koning, de Groot, & van Ingen Schenau, 1992).

As such, the assessment of maximal neuromuscular power capacity in sprint speed skaters can provide coaches with crucial information to individualize programs, monitor training adaptations, and predict on-ice acceleration performance. Historically, the Wingate protocol on a cycle ergometer has been a key test to evaluate lower body maximal muscle power capacity in speed skaters (Foster, Thompson, & Snyder, 1993; de Greeff, Elferink-Gemser, Sierksma, & Visscher, 2011; Smith & Roberts, 1991). While the peak external mechanical power in the Wingate correlates strongly with on-ice sprint performance (Smith & Roberts, 1991), it has been shown to lack sensitivity to track longitudinal training changes and differentiate sprint skating performance in homogenous subsets of elite athletes (Foster et al., 1993; van Ingen Schenau, Bakker, de Groot, & de Koning, 1992). These limitations may be attributed to a lack of movement specificity between skating and cycling. While both involve the leg extensor musculature, the time to produce force, line of action for force application, intermuscular coordination, and motor unit recruitment patterns are different between skating and the cycling test (Kandou et al., 1987). To this end, tests with a higher degree of movement specificity with respect to the velocity, range of motion, joint angles, line of action for force application, and contraction type may enhance the transfer between a test and the competitive exercise (Atha, 1981; Behm & Sale, 1993; Morrissey, Harman, & Johnson, 1995). As such, the capacity of a given laboratory or field test to accurately predict sport-specific performance in high level athletes may be dependent on the degree to which the testing procedure itself can assess movement strategies that are specific to the competition skill or movement.

The gliding phase in speed skating has been shown to share intermuscular coordination and kinematics with the vertical jump (Bobbert, Houdijk, de Koning, & de Groot, 2002; de Boer et al., 1987). Two existing studies have established strong relationships (r=0.62 to 0.76) between countermovement jump (CMJ) performance and on-ice sprint performance (de Greeff et al., 2011; Liebermann, Maitland, & Katz, 2002), but the vertical CMJ test does not align with the lateral application of force in the gliding phase and the rearward, horizontal application of force in the running phase of skating acceleration. This notion has been discussed with respect to elite ice hockey players where the standing horizontal long jump was found to be a significant predictor of performance for forwards and defence players (Burr et al., 2008), but this has yet to be investigated with sprint distance speed skaters.

Unilateral jump testing in the lateral and horizontal plane may further improve off-ice testing methodology for sprint speed skaters by testing movement patterns that more closely resemble the distinct phases of on-ice acceleration. In accordance, unilateral jump testing in different planes may measure independent power capacities of the lower limb (Meylan et al., 2010; Meylan et al., 2009; Murtagh et al., 2017), while changes in jump angle have previously been shown to induce changes in muscle activation measured via surface electromyography (EMG), which may reflect the motor unit recruitment strategy (Fukashiro et al., 2005; Jones & Caldwell, 2003). The value of jump testing for sport performance diagnosis and prediction may be further augmented by applying incremental external loads to the jumping athlete (Pierre Samozino et al., 2012). Commonly, linear models are used to quantify the relationship between the external load and movement velocity during loaded jump protocols, with intercept values and line slope being reported as parameters (Kotani et al., 2021). This method is referred to as load-velocity (LV) profiling, and the viability of such approaches during unilateral jumping in the horizontal plane has not been reported.

Thus far, unloaded vertical jump outcomes have only been reported as predictors of sprint speed skating performance. Recently, robotic resistance devices have become commercially accessible, with the capability to apply precise loads during horizontal movements via a cable fixed to a waist harness worn by the athlete. Kinematic and kinetic variables measured by these devices have demonstrated acceptable reliability during cyclical movements such as running (Rakovic, Paulsen, Helland, Haugen, & Eriksrud, 2020), but the feasibility of such devices during multiplanar unilateral jumps has yet to be determined . If proved reliable, the combination of a single leg horizontal loaded jump test ($\text{Jump}_{\text{Horz}}$) and single leg lateral loaded jump test (Jump_{Lat}) appears warranted for long track sprint speed skating performance analysis.

The purpose of this research was to: (1) establish the intra-day reliability of peak velocity (PV) measurements obtained during a single leg lateral jump (Jump_{Lat}) test and a single leg horizontal jump ($\text{Jump}_{\text{Horz}}$) test with three external loading conditions; (2) assess the relationship between single leg jump PV and 500 m long track speed skating performance in highly trained long track speed skaters; and (3) examine the feasibility of a linear modelling approach by determining the intra-day reliability of load-velocity (LV) parameters for each loaded jump protocol.

2.2 Methods

2.2.1 Experimental Approach to the Problem

This study utilized an intra-day design to determine the test-retest reliability of the peak velocity (PV) as measured by a robotic resistance device during both the Jump_{Lat} and $\text{Jump}_{\text{Horz}}$ across three separate loading conditions. Participants attended three total test sessions. The first session served to familiarize participants with the Jump_{Lat} and $\text{Jump}_{\text{Horz}}$ protocols. Following familiarization, participants attended two subsequent sessions, one for each jump protocol. During these sessions, participants completed two consecutive test protocols with the same jump type to evaluate intra-day reliability. All data were collected during the competitive season and within a 75-day period. Three local competitions at the University of Calgary Olympic Oval coincided with reliability testing, allowing the use of correlational analysis to examine relationships between unilateral jump performance and on-ice 500m split times.

2.2.3 Participants

Highly trained, national level speed skaters (age=18-27 yrs.) from both the long track (n=22, males: n=12; females: n=10) and short track (n=4, males: n=4) disciplines volunteered to participate in this study, which was approved by the Conjoint Health Research Ethics Board of (CHREB: 20-1751). Participants were informed of possible risks and benefits associated with participation and provided written informed consent before participating. For inclusion, participants were required to have amassed ≥ 2 years participating in sport specific training and strength & conditioning. Participants were excluded from the present study in the event of any injury preventing full exertion at the time of testing, or any injury in the month prior to testing that sidelined the athlete for > 7 days from full participation in training.

2.2.4 Procedures

Prior to testing, each subject's age and body mass were recorded. Participants were asked to attend three testing sessions. Participants were instructed to use their typical pre-ice training warm-up prior to each test session, keeping the routine consistent for each testing session. The leg used to complete the initial push-off in an on-ice start (i.e., the rear leg that initiates the first step in the start) was determined (i.e., the dominant limb) and tested throughout the study. The first session served to familiarize participants with the Jump_{Lat} and $\text{Jump}_{\text{Horz}}$ protocols. Following familiarization, participants attended two subsequent sessions, one for each jump protocol.

During these sessions, participants completed two consecutive test protocols of the same jump type to evaluate intra-day reliability. Participants were given 20 minutes of rest between each trial, with 10 minutes spent cycling at a self-selected cadence to mitigate losses in muscle temperature. All data were prior to any other training scheduled the same day.

A commercial robotic resistance device (1080 Sprint device, 1080 Motion, Lidingö, Sweden) that uses a servo motor (2000 RPM OMRON G5 Series Motor; OMRON Corporation, Kyoto, Japan) was used to conduct the multi-planar loaded jump testing protocol (sampling frequency = 333 Hz). Measurement errors obtained from the manufacturer were: velocity error = ± 0.5%, distance error = ± 5 mm, force error = ± 4.8 N) (Bergkvist, Svensson, & Eriksrud, 2015). Participants attached a waist-borne harness to the cable of the robotic resistance device.

Three loading conditions including 10 N (i.e., the minimum load required to maintain proper flywheel function), an external load equal to 7.5% of body weight (BW) and a load equal to 15% BW were applied during the jump test. For Jump_{Lat}, participants initiated each of the 3 jumps for each loading condition with their dominant limb, starting on a 30-degree angled plate set 5 m away from the robotic device (Figure 2.1). Participants initiated the jump from a self-determined skating position and were permitted to use an arm swing. A strong verbal cue was used, and participants were instructed to “jump laterally as far as possible, landing on both legs”.

Figure 2.1 Experimental setup and starting position for the Jump$_{\text{Lat}}$ test.

The Jump$_{\text{Horz}}$ testing was conducted in the same manner as the Jump$_{\text{Lat}}$, except the participants projected their body centre of mass forward (Figure 2.2) and were instructed to "jump horizontally as far as possible, landing on both legs". Position-time data of the jumping athlete was measured by a linear encoder within the robotic resistance device and integrated by the "TrainitTest" software (1080 Motion) to calculate the mean and peak velocity (PV) of each jump. The jump trial resulting in the highest PV value was exported for further analysis. In addition, a three-point peak velocity vs. external load profile was derived for both the Jump$_{\text{Lat}}$ and the Jump$_{\text{Horz}}$, with a linear regression and line of best fit to determine the slope and extrapolated maximum load intercept (L_0). Trial 1 and 2 were included in the reliability analysis, and the results from trial 1 were used for correlation analysis with on-ice data.

Figure 2.2 Experimental setup and starting position for the $\text{Jump}_{\text{Horz}}$ test.

2.2.5 On-ice Performance Data

The present study coincided with the 2021-2022 competitive speed skating season. Three long tack competitions were held within the 75-day testing period on the same indoor ice surface. The 100 m split time, 400 m split time, and 500 m finish time from each participant's best race were obtained and normalized to the percent of the current sex-specific world record (WR) time.

2.2.6 Statistical Analysis

Intrasession reliability was assessed using the coefficient of variation (CV), intraclass correlation coefficient using a two-way mixed effects model (ICC 3,1) and Bland-Altman analysis to determine the 95% limits of agreement (LOA) (Table 2.1). ICC ≥ 0.70, CV ≤ 10% and ICC ≥ 0.80, CV ≤ 5% were set as the thresholds for acceptable and good reliability, respectively. All statistical analyses were conducted in R Studio Version 2021.09.2 (R Version 4.1,3). The "agRee" package was used for reliability analysis. The normality of dependent variables was assessed using the Kolmogorov-Smirnov test. Pearson correlation coefficients were used to examine relationships between jump outcomes and on-ice split times (Table 2.2), with an alpha level of < .05 set as the threshold for statistical significance. Descriptive statistics for peak velocity across all loads and jump types, as well as on-ice split times are presented as means and one standard deviation (SD).

2.3 Results

Descriptive statistics are presented in Table 2.1.

Table 2.1 Jump results of male and female highly trained speed skaters compared with on-ice 500 m performance (mean ± SD).

		Male	Female
Subject Characteristics			
	Age (yrs)	21.1 ± 3.0	21.4 ± 2.1
	Body Mass (kg)	78.8 ± 10.2	64.5 ± 4.8
Jump Peak Velocity			
	Jump_{Lat} 10 N (m/s)	3.0 ± 0.2	2.80 ± 0.2
	Jump_{Lat} 7.5 % BW (m/s)	2.8 ± 0.1	2.5 ± 0.1
	Jump_{Lat}: 15 % BW (m/s)	2.7 ± 0.2	2.4 ± 0.1
	$\text{Jump}_{\text{Horz}}$: 10 N (m/s)	3.9 ± 0.3	3.4 ± 0.3
	$\text{Jump}_{\text{Horz}}$: 7.5% BW (m/s)	3.4 ± 0.3	3.0 ± 0.3
	$\text{Jump}_{\text{Horz}}$: 15% BW (m/s)	3.2 ± 0.2	2.8 ± 0.3
On-ice Competition Splits			
	100 m (s)	10.4 ± 0.2	11.8 ± 0.3
	400 m (s)	26.4 ± 0.6	30.3 ± 0.7
	500 m (s)	36.8 ± 0.7	42.3 ± 0.9

Note. On-ice statistics representative of long track skating participants only (n=22)

PV across each jump type and loading condition exhibited good reliability (ICC > 0.8, CV < 5%) (Table 2.2, Figures 2.3-2.4). LV parameters (slope, L_0) did not meet the threshold for acceptable reliability in either of the Jump_{Lat} or $\text{Jump}_{\text{Horz}}$ (Table 2.3). Positive correlations were observed between the Jump_{Lat}, $\text{Jump}_{\text{Horz}}$ and on-ice performance (Table 2.4, Figures 2.4-2.6).

Table 2.2 Test-retest reliability of the peak velocity (m/s) recorded from different jumps and load conditions (n=26).

Jump Type	*ICC (95% CI)*	*CV*	LOA (m/s)
Jump$_{\text{Lat}}$ *(10N)*	0.82 (0.68-0.9)	3.0%	-0.03 ± 0.24
Jump$_{\text{Lat}}$ *(7.5%BW)*	0.84 (0.71-0.92)	2.7%	0.03 ± 0.19
Jump$_{\text{Lat}}$ *(15% BW)*	0.90 (0.81-0.94)	2.6%	0.00 ± 0.19
Jump$_{\text{Horz}}$ *(10N)*	0.90 (0.82-0.95)	3.5%	-0.04 ± 0.34
Jump$_{\text{Horz}}$ *(7.5%BW)*	0.91 (0.83-0.95)	3.4%	0.04 ± 0.29
Jump *(15%BW)*	0.92 (0.82-0.96)	3.1%	0.03 ± 0.23

Note. Jump$_{\text{Horz}}$, single leg horizontal jump; Jump$_{\text{Lat}}$, single leg lateral jump; ICC, intraclass correlation coefficient; CV, coefficient of variation; LOA, 95% limits of agreement.

The strongest correlations with skating performance in the Jump$_{\text{Horz}}$ were recorded for the 10 N condition ($r=0.72-0.8$, $p<0.01$). In contrast, for the Jump$_{\text{Lat}}$, the strongest correlation with the 100 m split time was observed with the 7.5% BW load condition ($r=0.73$, $p<0.01$), whereas the 400 m ($r=0.69$, $p<0.01$) and 500 m ($r=0.71$, $p<0.01$) times correlated strongest with the 15% BW condition. The weakest relationships with all on-ice split distances were observed for the 10 N Jump$_{\text{Lat}}$ ($r=0.5-0.52$, $p<0.05$).

Table 2.3 Test-retest reliability of load-velocity parameters recorded from different jumps and load conditions (n=26).

LV Parameter	*M ± SD*	*ICC (95% CI)*	*CV%*
L$_0$ (Jump$_{\text{Horz}}$)	61.46 ± 8.46	0.44 (0.07-0.70)	15%
Slope (Jump$_{\text{Horz}}$)	-0.06 ± 0.01	0.44 (0.06-0.70)	15%
L$_0$ (Jump$_{\text{Lat}}$)	103.65 ± 28.9	0.47 (0.11-0.72)	40%
Slope (Jump$_{\text{Lat}}$)	-0.04 ± 0.01	0.50 (0.15-0.74)	20%

Note. L$_0$, theoretical maximum load intercept; Slope, slope of linear regression line; Jump$_{\text{Horz}}$, single leg horizontal jump; Jump$_{\text{Lat}}$, single leg lateral jump.

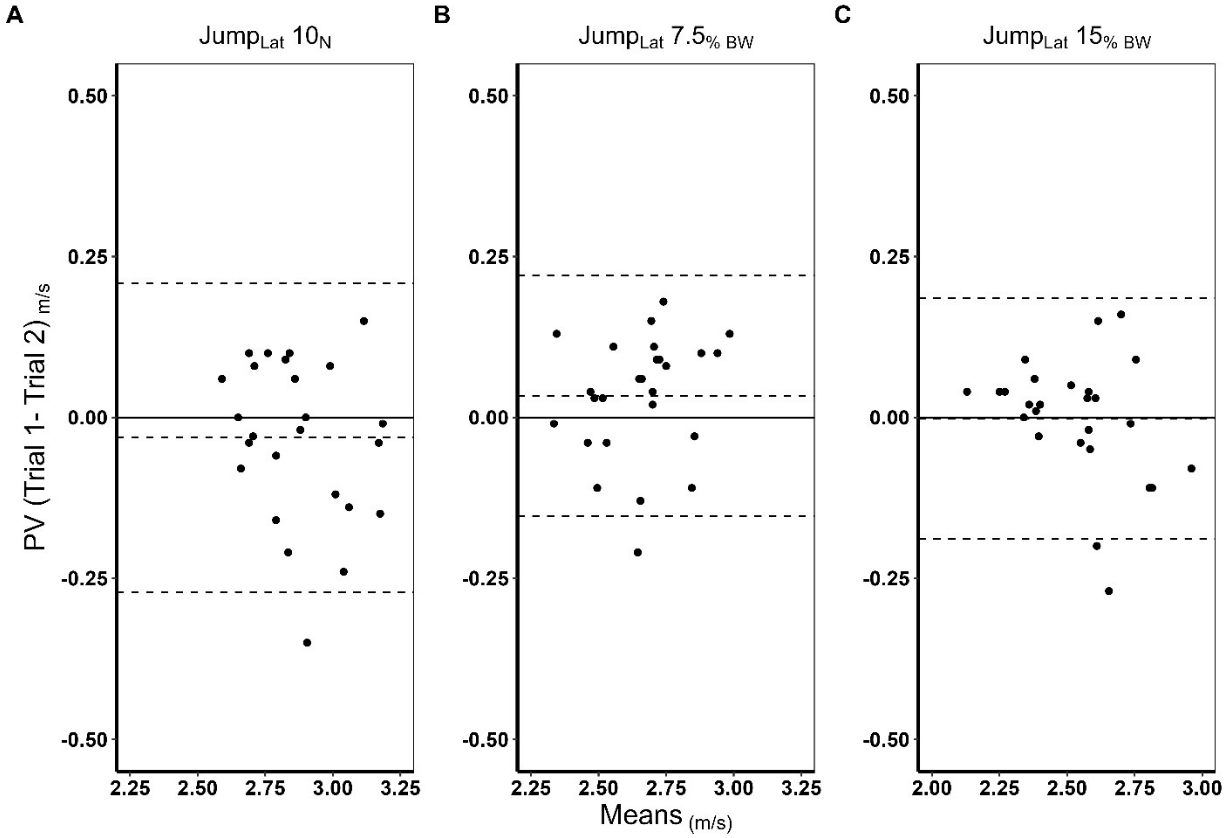

Figure 2. 3 Jump_{Lat} peak velocity (PV) mean vs. difference in means (trial 1-trial 2), dashed lines indicate bias and 95% limits of agreement (LOA). **A)** Jump_{Lat} with 10N of external resistance. **B)** Jump_{Lat} with 7.5% of bodyweight in external resistance. **C)** Jump_{Lat} with 15% of bodyweight in external resistance (n=26).

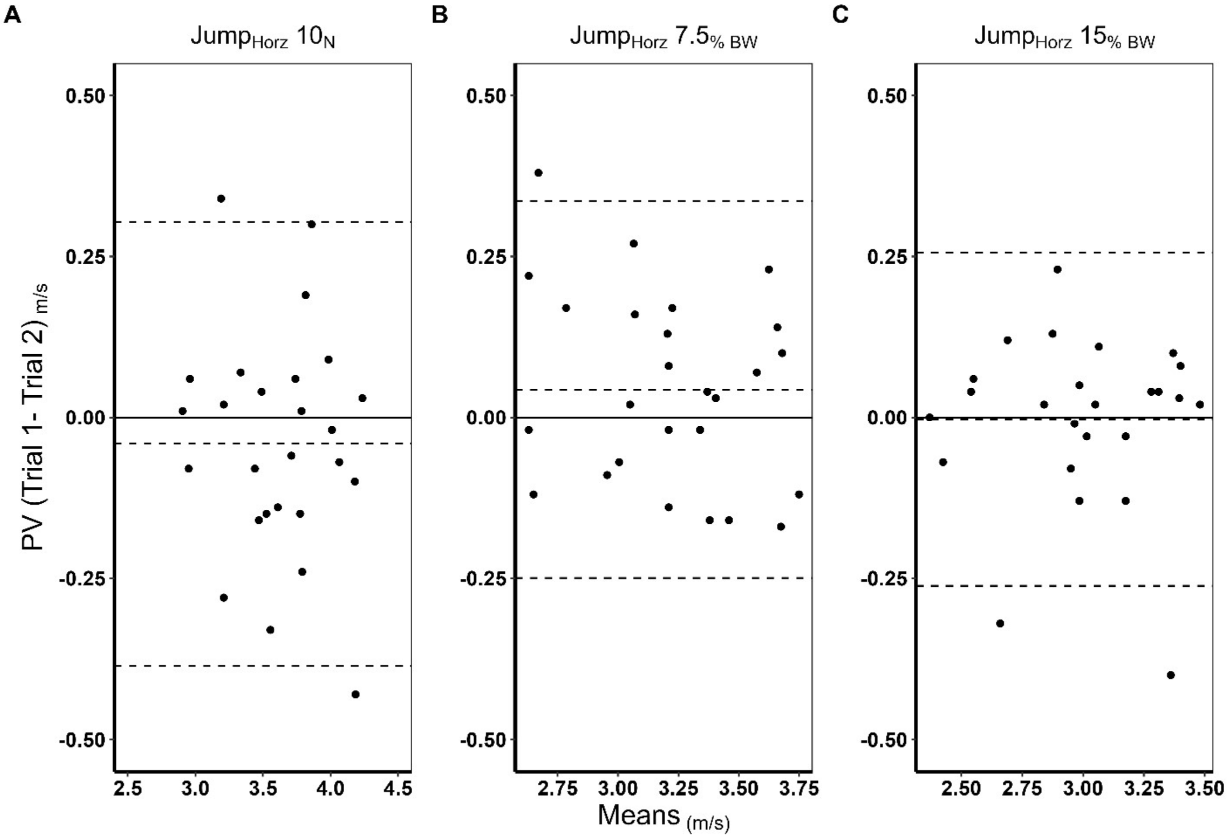

Figure 2.4 Jump$_{\text{Horz}}$ peak velocity (PV) mean vs. difference in means (trial 1-trial 2), dashed lines indicate bias and 95% limits of agreement (LOA). **A)** Jump$_{\text{Horz}}$ with 10N of external resistance. **B)** Jump$_{\text{Horz}}$ with 7.5% of bodyweight in external resistance. **C)** Jump$_{\text{Horz}}$ with 15% of bodyweight in external resistance (n=26).

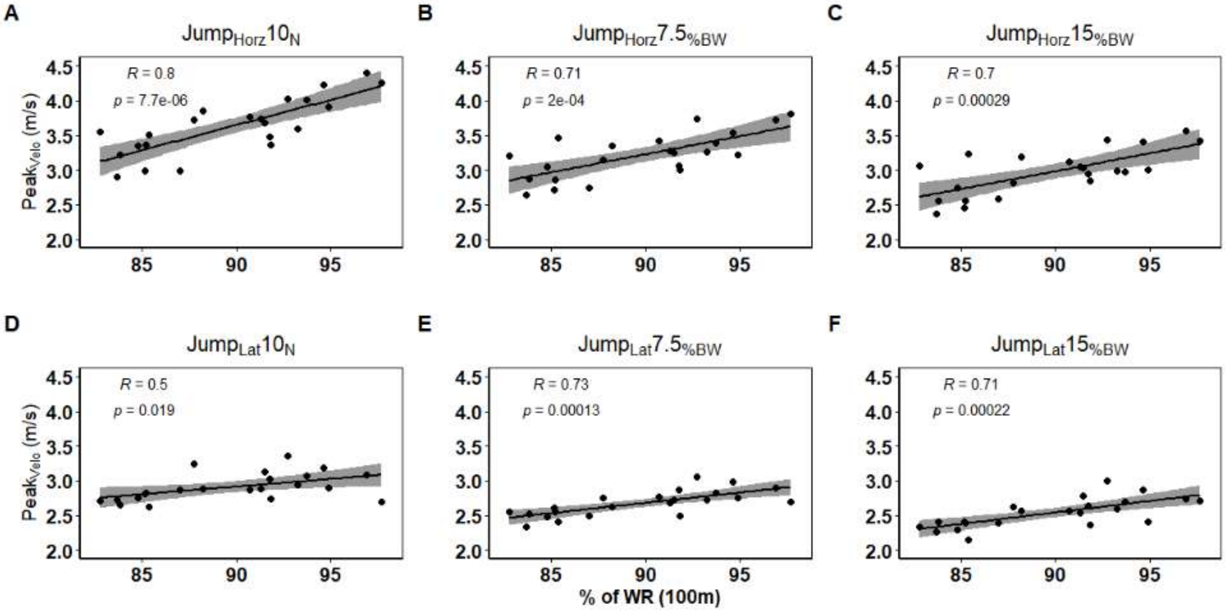

Figure 2.5 Relationship between Jump$_{Lat}$ and Jump$_{Horz}$ PV (m/s) and 100-m race split time performance (%WR) (n=22). **A)** Jump$_{Horz}$ with 10N of external resistance. **B)** Jump$_{Horz}$ with 7.5% of bodyweight in external resistance. **C)** Jump$_{Horz}$ with 15% of bodyweight in external resistance. **D)** Jump$_{Lat}$ with 10N of external resistance. **E)** Jump$_{Lat}$ with 7.5% of bodyweight in external resistance. **F)** Jump$_{Lat}$ with 15% of bodyweight in external resistance. PV = peak velocity; WR = world record.

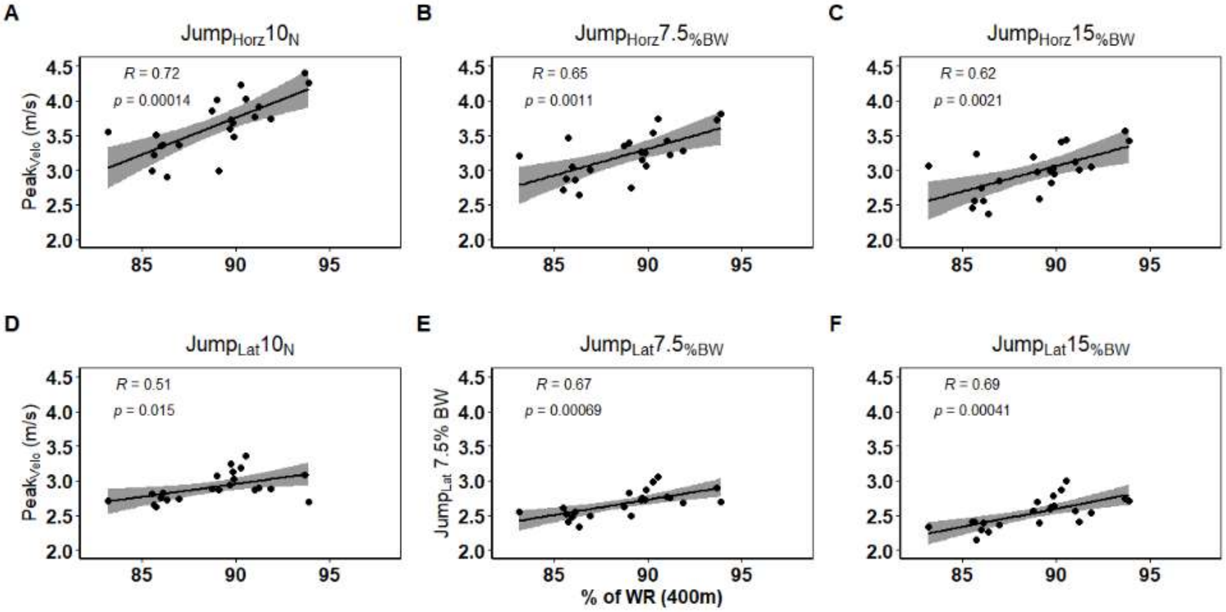

Figure 2.6 Relationship between Jump$_{Lat}$ and Jump$_{Horz}$ PV (m/s) and 400-m race split time performance (%WR) (n=22). **A)** Jump$_{Horz}$ with 10N of external resistance. **B)** Jump$_{Horz}$ with 7.5% of bodyweight in external resistance. **C)** Jump$_{Horz}$ with 15% of bodyweight in external

resistance. **D)** Jump$_{\mathrm{Lat}}$ with 10N of external resistance. **E)** Jump$_{\mathrm{Lat}}$ with 7.5% of bodyweight in external resistance. **F)** Jump$_{\mathrm{Lat}}$ with 15% of bodyweight in external resistance. PV = peak velocity; WR = world record.

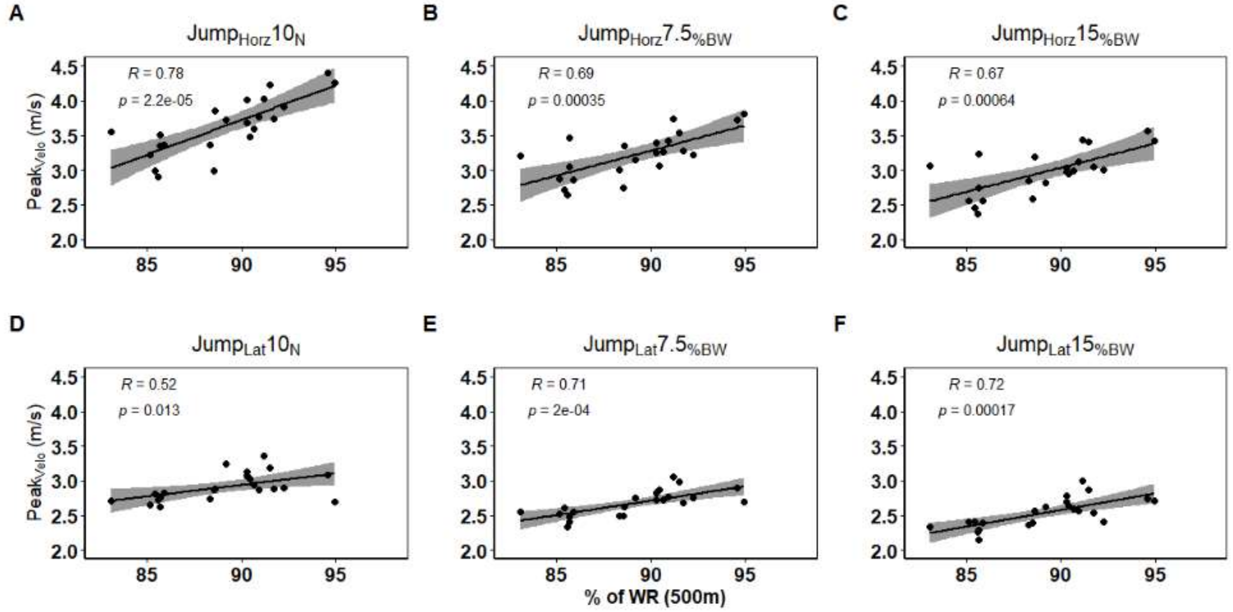

Figure 2.7 Relationship between Jump$_{\mathrm{Lat}}$ and Jump$_{\mathrm{Horz}}$ PV (m/s) and 500-m race split time performance (%WR) (n=22). **A)** Jump$_{\mathrm{Horz}}$ with 10N of external resistance. **B)** Jump$_{\mathrm{Horz}}$ with 7.5% of bodyweight in external resistance. **C)** Jump$_{\mathrm{Horz}}$ with 15% of bodyweight in external resistance. **D)** Jump$_{\mathrm{Lat}}$ with 10N of external resistance. **E)** Jump$_{\mathrm{Lat}}$ with 7.5% of bodyweight in external resistance. **F)** Jump$_{\mathrm{Lat}}$ with 15% of bodyweight in external resistance. PV = peak velocity; WR = world record.

2.4 Discussion

In the present study, we investigated the reliability of two sport-specific, unilateral, lower body loaded jump tests for sprint speed skating athletes using a commercially available robotic resistance device, and we assessed the relationship with 500 m sprint speed skating performance in highly trained athletes. We established good reliability for PV measured in the Jump$_{\mathrm{Lat}}$ and Jump$_{\mathrm{Horz}}$ for routine off-ice testing with elite speed skaters, and a positive relationship between performance in the jump tests across loading conditions and on-ice performance. Notably, the strongest correlations to on-ice performance were observed during the 10 N single leg horizontal jump (i.e., the condition with the least external resistance). These results could inform future off-ice testing protocols for long track speed skaters and lead to more targeted off-ice training methods to enhance on-ice performance.

While the validity and reliability of this commercially available robotic resistance device to measure continuous velocity and time has previously been established during resisted cyclical movements such as running (Feser et al., 2022; Rakovic et al., 2020), this is the first study to investigate the intra-day reliability of peak velocity during unilateral jumping in skating athletes. The primary finding was that PV of the Jump_{Lat} and $\text{Jump}_{\text{Horz}}$ exhibited good reliability (ICC > 0.8, CV < 5%) across all three load conditions evaluated. Kotani et al. (2021) observed a similar reliability in PV during incrementally loaded squat jumps (SJ) on force platforms, while Hansen, Cronin & Newton (2011) reported high reliability of PV measured with linear position transducers (LPTs) using a similar protocol (ICC = 0.89, CV = 3.7%). Reliability of single leg jumps performed in the lateral and horizontal directions was examined by Meylan et al. (2009) , with distance jumped (cm) of both jump types exhibiting high reliability (ICC = 0.97-0.98, CV =3.1-4.6%). Collectively, our findings fall in line with previous articles, and suggest that PV as measured during the loaded Jump_{Lat} and $\text{Jump}_{\text{Horz}}$ force velocity protocol is a reliable measure in well-trained skating athletes.

In addition to being reliable, a performance test should also demonstrate strong predictive validity, often assessed by the association between the test and competitive skill or exercise (Currell & Jeukendrup, 2008). This notion highlights the limitation with the current practice of cycle ergometer testing in long track speed skating athletes, which may lack the sensitivity to detect longitudinal training changes or predict the performance of elite athletes despite strong cross-sectional relationships with on-ice performance (Foster et al., 1993; van Ingen Schenau et al., 1992). Thus, a secondary goal of the present study was to establish a relationship between Jump_{Lat} and $\text{Jump}_{\text{Horz}}$ outcomes and on-ice performance. Significant positive correlations between peak velocity and on-ice split times were observed across all load conditions and split distance times (r=0.5-0.8). Despite the similarity between jumping and gliding technique in speed skating, there is a limited number of peer-reviewed studies examining the relationship between performance during the two movements. Liebermann & Katz (2002), observed a strong relationship (r= -0.76) between body mass normalized peak external mechanical power measured during the CMJ with force platforms and opening 100 m on-ice split performance with similar participants to those in the present study.

Notably, correlation coefficients with on-ice performance differed between $\text{Jump}_{\text{Horz}}$ and Jump_{Lat}, with trends toward stronger relationships for the lesser resistance conditions for $\text{Jump}_{\text{Horz}}$ and greater resistance load conditions for the Jump_{Lat}. These patterns may be representative of adaptations to on-ice training and seem to align with the mechanics of on-ice acceleration, during which skaters transition between short push off times in the initial start phase to long push-off times in the latter start phase of speed skate sprinting (de Koning et al., 1995). The rearward application of force during the $\text{Jump}_{\text{Horz}}$, may have best simulated the on-ice demands during the running phase at 10 N of external resistance (i.e., the least resistance condition), with heavier external loads slowing the movement velocity and thus reducing specificity. Likewise, the shift to stronger relationships with the moderate-heavy load conditions during the Jump_{Lat} may indicate that these test conditions were more representative of the push-off velocity and time to produce force observed while gliding.

Counterintuitively, the $\text{Jump}_{\text{Horz}}$ was found to have a stronger correlations with sprint distance race performance compared to the Jump_{Lat}, which would seem to be a more specific movement pattern for maximum velocity speed skating that involves a laterally directed push off. This finding may suggest that in sprint distance speed skaters, the ability to displace the center of mass horizontally at the onset of the race is critical for performance during the start. Accordingly, it has been reported that a substantial proportion of final performance could be explained by acceleration over the initial three strides of a 500 m race (van Ingen Schenau, de Koning, & de Groot, 1990). This segment of the race would be comprised of predominantly running vs. gliding, and the $\text{Jump}_{\text{Horz}}$ might represent a more specific performance test of this capacity. Alternatively, given the small negative slope (Table 2.3) observed in the Jump_{Lat} LV profile, indicating minimal drops in PV under increasing load conditions, the loads selected may have been insufficient for speed skating athletes to discriminate performance between participants.

Jumping and sprinting as methods to assess the multi-joint force velocity relationship have become widely used in sport performance settings. but this relationship has been known for more than 80 years and is typically modelled as a hyperbolic equation (Hill, 1938). The force velocity relationship obtained in multi-joint movements such as sprinting and jumping is typically modeled with linear relationships to quantify the inverse relationship between force or load and external movement velocity (Cross et al., 2021; Jaric, 2015; Jiménez-Reyes, Pareja-Blanco, Rodríguez-Rosell, Marques, & González-Badillo, 2016; Kotani et al., 2021). These linear force velocity profiles (LVP) obtained for different movements are often reported with parameters such as the intercept (L_0, V_0, F_0) and the slope (S_{FV}) of the corresponding regression line (Kotani et al., 2021; Lindberg et al., 2021). During multi-joint movements, further degrees of freedom allow for other factors, such as intermuscular coordination and segmental dynamics, to confound the otherwise hyperbolic FV relations obtained for single muscles. As such, it has been posited that the FV relationship is quasi-linear during multi-joint movements (Bobbert, 2012). In contrast, Hahn et al. (2014) demonstrated that with a sufficient range of data points along the FV spectrum, Hill's model offered the superior fit during a leg press task. The observation of a linear FV relationship found in the scientific literature may stem from the narrow range over which the FV relationship is assessed, as well as difficulties ensuring all of Hill's original conditions are met across all muscles during functional movement. In accordance, recent work examining the inter-day reliability of FVP parameters during the vertical jump has highlighted concerns (Kotani et al., 2021; Lindberg et al., 2021).

However, force velocity (FV) or load velocity (LV) sprint and jump profiles appear to offer more resolution into the mechanical capacity of the lower limb than single variable outputs such as jump height and split times (Morin, Jiménez-Reyes, et al., 2019; Samozino et al., 2016; Samozino et al., 2012). In addition, profiles seem to differ between sports and performance level (Giroux et al., 2016; Jiménez-Reyes et al., 2019; Stavridis et al., 2019), showing promise as a means for individualizing training prescription in athletic populations (Jiménez-Reyes et al., 2017; Jean Benoît Morin & Samozino, 2016). During the unilateral jump tasks in the present study, a narrow range of external loads was used to ensure that the participants could readily perform the jumping movement, and the fact that we did not use the entire possible range of external resistances is a limitation of this work. Though PV at each jump condition exhibited good reliability, the traditional LV outcomes measures (slope, L_0) exhibited poor reliability (Table 2.3). For these reasons, we elected to focus on the PV achieved under each individual load condition for the computation of intra-day reliability and associations with skating performance.

Despite the narrow loading range, each loading condition in both the $\text{Jump}_{\text{Horz}}$ and Jump_{Lat} test protocols appeared to demonstrate varying correlations with the measured segments of on-ice performance (i.e., 100 m split, 400 m split, 500 m finish time). This result may be indicative of training induced adaptations to the multi-joint force velocity relationships of skating athletes. Recent work corroborates this idea. Thompson et al. (Thompson, Safadie, Ford, & Burr, 2020), concluded that on-ice speed in collegiate ice hockey players was best predicted by off-ice resisted vs. bodyweight sprinting. Similarly, Smith & Roberts (1991) demonstrated that the relationship between peak isokinetic knee extension torque and 500 m performance was greater at 180 $\text{rad}\cdot\text{s}^{-1}$ vs. 30 $\text{rad}\cdot\text{s}^{-1}$ in elite sprint distance male speed skaters. Thus, while loaded jump protocols have demonstrated utility in a wide range of populations (Giroux et al., 2016; Jiménez-Reyes et al., 2017), the unique mechanics of on-ice acceleration may render them particularly useful in skating athletes.

Unfortunately, the use of competition timing systems in the present study left only 100 m, 400 m, and 500 m splits available as markers of on-ice performance. Given that the running phase only spans the initial 1.6-2.2s of the 500 m event (Song et al., 2017), we could not examine the running and gliding phase of the skate start discretely but this is certainly an area for future research. While the correlations in the present study agree well with previous work examining jump and on-ice outcomes in long track speed skating athletes, it is likely that the relationships would have differed had we been able to examine each movement phase independently, especially considering the specificity of the Jump_{Lat} and $\text{Jump}_{\text{Horz}}$.

Due to the realities of conducting a study during the competitive season, the study design was not without limitations. As a result of training demands, the number of days between familiarization, Jump_{Lat} testing, and $\text{Jump}_{\text{Horz}}$ testing could not be controlled. Consequently, some participants completed testing more than 2 months after the initial familiarization session. Similarly, time of day for testing, and any chronic neuromuscular fatigue from the present block of training could not be carefully controlled across participants.

2.5 Practical Applications

The results of this study suggest that both the Jump_{Lat} and $\text{Jump}_{\text{Horz}}$ loaded jump protocols used in the present study were reliable and showed a strong correlation with long track speed skating performance. Practitioners seeking to use linear modelling approaches during resisted unilateral jumping must determine how to sufficiently load the jump without degrading movement kinematics or focus on PV across load conditions as an outcome measure rather than relying on LV parameters. Directions of future research may be to implement these tests in other skating populations, compare results with standard bilateral jump assessments, and move towards on-ice measurement tools that allow running and gliding performance to be assessed separately.

Chapter 3: Modelling the Early and Late Acceleration Phases of the Sprint Start in Elite Long Track Speed Skaters

3.1 Introduction

The 500 m event in long track speed skating is the shortest and fastest event, with world records of 33.61 s and 36.36 s for males and females respectively (International Skating Union, 2023). To initiate the race, athletes begin in a static start position, react to a starting gun, and accelerate over 100 m prior to the first turn (de Koning et al., 1989). This initial 100 m time split is crucial for overall race performance, accounting for a large proportion of observed variance in the final 500 m race time(de Koning et al., 1989, 1995; Song et al., 2017). Elite 100 m split times are comparable to the 100 m track & field world record times ranging from < 9.5 s for males and <10.5 s for females. At the 2022 Olympic Winter Games, the gold and silver medallists were separated by only a few hundredths of a second for both the males (0.07 s) and females (0.08 s), which could be accounted for by small but worthwhile changes in the initial acceleration phase of the race (International Skating Union). Given the potential for the acceleration phase of the 500 m event to determine overall medal performance, practitioners require valid and reliable methods to assess acceleration capacity in elite speed skaters.

The acceleration phase in long track speed skating is characterized by a running phase and a gliding phase (de Koning et al., 1995). During the running phase, skaters use a rearward push against a fixed point on the ice and jump from one skate to the other, projecting themselves horizontally down the track (de Koning et al., 1989; Mossink, Kiel, Geraets, Veeger, & Beek, 2018). This phase is characterized by a higher stride frequency, shorter ice contact times, and shallower joint angles than the gliding phase, often drawing comparisons to track and field sprinting for these reasons (de Koning et al., 1995; Song et al., 2017). After approximately 20 m, the forward velocity of the athlete's center of mass exceeds the threshold needed to continue using a rearward push, necessitating the transition to gliding (de Koning et al., 1989; Song et al., 2017). Gliding is characterized by a perpendicular push-off to the direction of travel, along with a lowering of the center of mass allowing the skater to use a larger range of motion at the hip and knee joints (de Koning et al., 1995). This change in position coincides with longer ice contact times that are approximately 200 ms in duration (de Groot, Hollander, Sargeant, van Ingen Schenau, & de Boer, 1987; de Koning, de Groot, & van Ingen Schenau, 1991; Mossink et al., 2018).

The initial 100 m time split is crucial to 500 m race performance, yet the variation explained by the initial 50 m, which involves the run-to-glide transition, has not yet been quantified. Given the kinematic differences in running and gliding, reliable methods of measuring performance outcomes specific to each movement phase using continuous on-ice measurements of power and velocity are needed. This can contribute to a better understanding of the key performance indicators of each acceleration phase, along with a new testing method to inform training interventions designed to improve skating acceleration performance. Exponential modeling may be a viable approach to analyze speed skating acceleration profiles, which fits a curve to data points that exhibit an exponential decay, such as the velocity-time profile of the speed skating sprint start. This approach has previously been used to assess acceleration sprinting capacity in overground running, extracting parameters such as the calculated maximal sprint speed (MSS), the maximal acceleration capacity (MAC) and horizontal power (P_{Max}) (Clark, Rieger, Bruno, &

Stearne, 2019; Healy, Kenny, & Harrison, 2022; Jovanović & Vescovi, 2022; Morin, Samozino, Murata, Cross, & Nagahara, 2019; Souhaiel & Denis, 2001).

Long track speed skating includes a prolonged acceleration phase in comparison with other sports, providing a strong rationale to develop sport-specific, valid, and reliable testing methods to model performance. The main objective of this study was to test the validity of monoexponential modelling of the speed skating sprint start. Specifically, our study examined concurrent validity, or the alignment between model predictions and actual measured performance characteristics. Furthermore, the intra-day reliability of model parameters (MSS, τ, MAC, P_{Max}) was examined. Finally, the construct validity (i.e., the ability to discriminate performance level) was established by comparing the model outputs in elite (internationally ranked) and sub-elite (nationally ranked) long track speed skaters.

3.2 Methods

3.2.1 Experimental Approach to the Problem

This study utilized a cross-sectional design to assess the monoexponential fit during maximal effort 50m on-ice sprint start and an intra-day design to determine the test-retest reliability of model performance parameters (MSS, τ, MAC, P_{Max}). Position, time, and velocity were measured continuously during 50 m starts on an indoor long track speed skating ice surface using a linear encoder embedded in a robotic resistance device (1080 Sprint device, 1080 Motion, Lidingö, Sweden). The robotic resistance device uses a servo motor (2000 RPM OMRON G5 Series Motor; OMRON Corporation, Kyoto, Japan) and a linear encoder sampling at 333 Hz to apply an external load with simultaneous recording of position and velocity data. Measurement errors obtained from the manufacturer were: velocity error = ± 0.5%, distance error = ± 5 mm, force error = ± 4.8 N) (Bergkvist et al., 2015). The split times from the device were validated against timing gates during overground 30 m sprinting (Rakovic, Paulsen, Helland, Haugen, & Eriksrud, 2022), and continuous velocity was validated against three-dimensional kinematic data during the 5-0-5 change of direction test (Eriksrud, Ahlbeck, Harper, & Gløersen, 2022).

Data collection was conducted during a weekly on-Ice start training sessions held between 10:45-11:45 am the day following a rest day. Participants performed 1-2 x 50m on-Ice standing starts while tethered to the robotic resistance device with 5-10 minutes of rest between each trial. Data from participants that completed two trials (n=31) was used to establish the intra-day reliability of model parameters. Data collection took place over an 8-week period during the fall of the 2022-2023 competitive speed skating season, on the same temperature-controlled indoor ice surface, immediately after an ice resurfacing. This test interval coincided with three local competitions held at the same location, from which the fastest 100 m opening split was obtained to examine construct validity of the model parameters relative to competition performance.

3.2.2 Participants

Long track speed skaters (n=38, males: n=24, females: n=14) volunteered to participate in this study, which was approved by the Conjoint Health Research Ethics Board of the University of Calgary (CHREB 20-1751). Participants provided written informed consent before participating. Participant characteristics are presented in Table 3.1. The competitive level of the participants ranged from highly trained sub-elites competing at the national level within Canada (n=24) to elite athletes competing at International Skating Union (ISU) World Cup level and participants from the 2022 Olympic Winter Games (n=12). National level skaters participated in a centralized high performance speed skating training program for 3-6 years whereas international level athletes participated in the same program for between 4-15 years. Participants with an injury that limited a maximal effort for on-ice sprinting were excluded.

3.2.3 On-ice Start Testing

Prior to testing, each participant's age and body mass were recorded. Participants were instructed to use their individual competition warm up routine, which commonly included off-ice exercises such as dynamic stretching, multi-direction jumps, and running sprints along with on-ice exercises including low intensity warm up laps and sub-maximal on-ice accelerations from a gliding (rolling) start. Participants lined up at the 500 m start line and were provided with a familiarization trial, followed by the test trial (s). All trials were separated by a rest period of 5-10 minutes. Ice availability and training schedule constraints resulted in seven participants being unable to partake in the intraday reliability study. Consequently, a subset of the original participants (n=31) was able to complete a second test trial using the same procedure.

A waist-borne harness attached to the cable of the robotic resistance device was secured to participants. Participants then performed a maximal standing sprint start that was initiated without reaction to an external stimulus (i.e., no voice command, light, sound or starting gun was used). A cone was placed 60 m away from the start line that cued the participant to disengage the harness using a release lever on the front of the harness. To ensure that the data collection was not affected by a potential deceleration, only the initial 50 m of each start was used for the data analysis.

The robotic resistance device was placed 5 m behind the start line with 10 N of external load applied to each athlete. The 10 N external load was determined to be the minimum load required to limit unwanted sinusoidal vibration in the cable of the robotic resistance device. Position and time were collected and processed using the robotic resistance device software (*TrainitTest* software – 1080 Motion) to obtain the instantaneous velocity. In order to assess the construct validity of the testing method relative to the on-ice competition data, the fastest of the two trials was used for the analysis for the participants who performed two trials (n=31). Using the data obtained from the robotic sprint device, the 20 m interval from the testing data set was obtained as a benchmark comparison for the modeled parameters. Finally, a competition benchmark comparison was also obtained, notably the fastest 100 m opening split time from three on-ice 500 m competition races that were conducted during the same 8-week time period. These benchmarks were used in the statistical analysis and to objectively differentiate the sub-elite speed skaters from the elite speed skaters.

3.2.4 On-ice Acceleration Modelling

Modelling was performed in R Studio Version 2022.07.2 (R Version 4.2) using the "shorts" package (Jovanović, 2022; Jovanović & Vescovi, 2022) and the "nlsLM" function. Nonlinear least square regression was used to model the raw 50 m velocity-time data and derive model parameters in accordance with previous research (Clark et al., 2019; Feser et al., 2022; Healy et al., 2022; Jovanović & Vescovi, 2022; Souhaiel & Denis, 2001). The maximal skating speed (MSS) over 50m and τ (defined as the time (s) to achieve 63.2% of MSS) were then obtained using the following equation: $v(t) = MSS\left(1 - \mathrm{e}^{\frac{-t}{\tau}}\right)$. Using these values, the maximal acceleration capacity (MAC) was calculated as: $MAC = \frac{MSS}{\tau}$. Finally, the theoretical maximal instantaneous horizontal mechanical power was obtained from the model outputs. Here, the horizontal acceleration was obtained by time differentiation of the modelled velocity-time curve.

Neglecting the ice and air friction, and assuming that $a = \frac{F_H}{m}$, instantaneous acceleration was used as an estimate of the body mass normalized net horizontal force (N/kg) and integrated with velocity (m/s) to calculate the horizontal mechanical power (W/kg) throughout the on-ice start. Assuming a linear relationship to exist between acceleration and velocity, along with parabolic power-velocity and power-force relationships, the values corresponding to maximal power were 0.5 MSS and 0.5 MAC respectively (Vandewalle, Peres, Heller, Panel, & Monod, 1987). This was calculated in the 'shorts' package using the following equation: $P_{Max} = \frac{MSS\ x\ MAC}{4}$. The maximal instantaneous horizontal power value achieved by each athlete was then obtained (P_{Max-}). An illustration of the model parameters is presented in Figures 3.1-3.2.

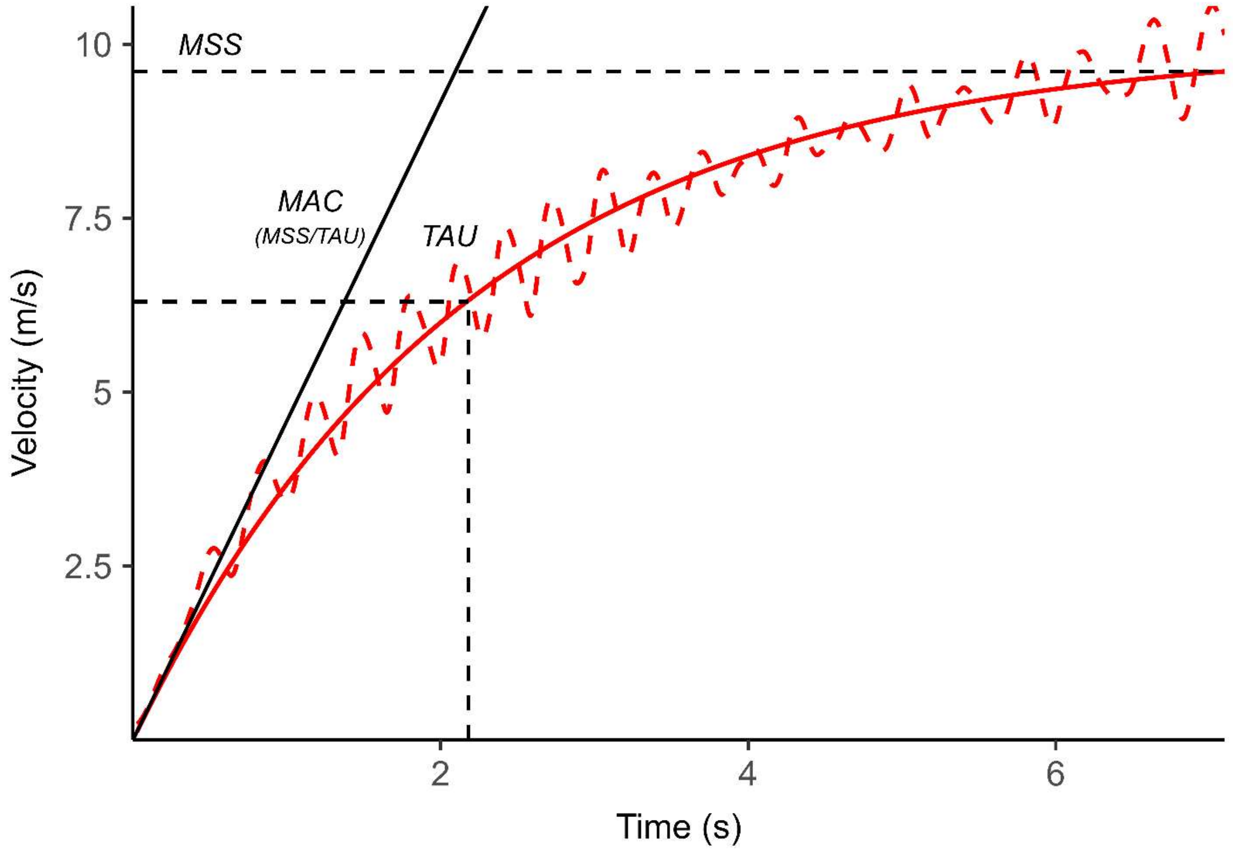

Figure 3.1 Representative measured vs. modelled on-ice 50m sprint start velocity-time graph (n=1). MSS, maximal skating speed at 50 m; MAC, maximal acceleration, TAU; acceleration-time constant.

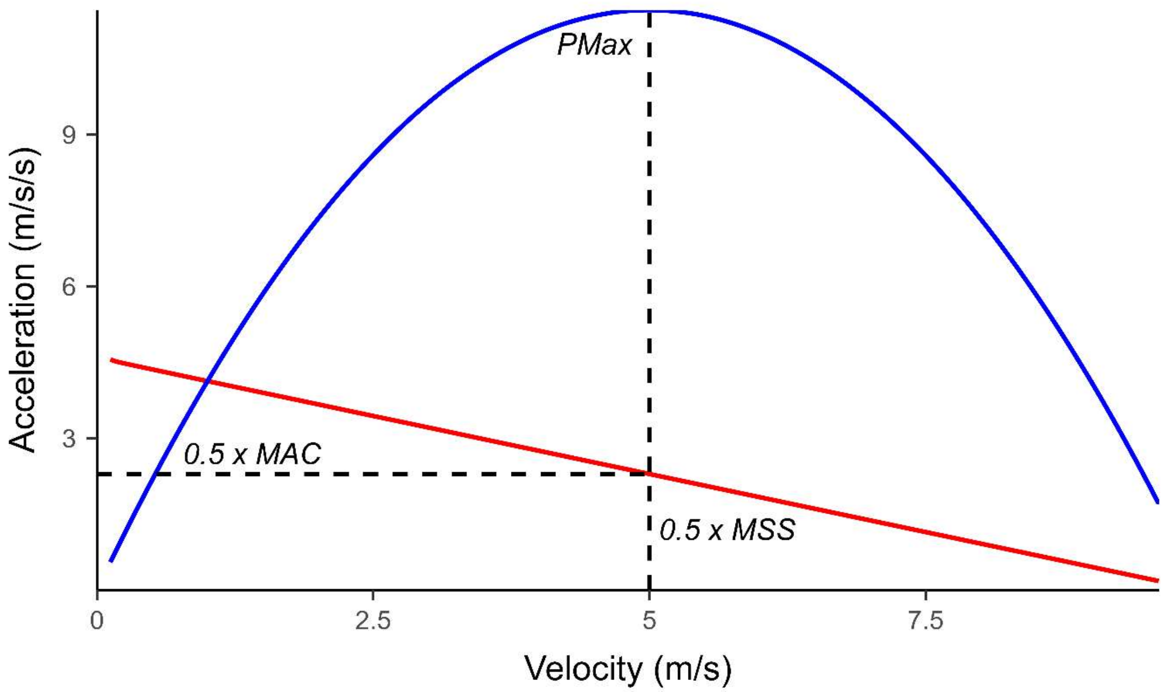

Figure 3.2 Representative modelled on-ice 50m sprint start acceleration-velocity-power graph (n=1). MSS, maximal skating speed at 50 m; MAC, maximal acceleration, PMax; net body mass normalized maximal horizontal mechanical power.

3.2.5 Between Group Comparisons

To examine the construct validity of the testing methodology, a group comparison was used to compare the model parameters between the faster and slower speed skaters using on-ice split times measured during the start testing for this study and actual race data obtained during the same time period. Two sets of groups were defined for both males and females based on the 20 m time (measured with the robotic resistance device) and the 100 m competition time for the purposes of direct comparisons. Based on the data distribution and the sample size, the on-ice data of the male participants (n=24) were split into tertiles. The bottom tertile and the top tertile were defined as the slower and faster groups respectively and used for the between-group comparison (the middle group was not used for this analysis). Due to the smaller sample of female participants, data was divided based on the median value, with those falling above and below classified as faster and slower skaters respectively.

3.2.6 Statistical Analysis

All statistical analyses were conducted in R Studio Version 2022.07.2 (R Version 4.2). Intrasession reliability of model parameters for 31 paired samples (MSS, MAC*,* τ*,* P_{Max}) was assessed using the coefficient of variation (CV), intraclass correlation coefficient using a two-way mixed effects model (ICC 3,1) and Bland-Altman analysis to determine the 95% limits of agreement (LOA) (Hopkins, Marshall, Batterham, & Hanin, 2009). ICC $\geq$ 0.70, CV $\leq$ 10% and ICC $\geq$ 0.80, CV $\leq$ 5% were set as the thresholds for acceptable and good reliability, respectively.

To evaluate the concurrent validity of the monoexponential modelling approach, mean model R-squared (R^2) was used, as well as direct comparisons between measured and modelled mean velocities at 5-10 m, 15-20 m, 25-30 m, 35-40 m and 45-50 m. Bland-Altman 95% agreement analysis, single measure intraclass correlation coefficients (ICC 2,1) with 95% confidence intervals (95% CIs) were used to compare measured and modelled data.

The normality of the data was assessed through visual inspection of plots and histograms for all variables and by using the Kolmogorov-Smirnov test with the α level set to <0.05. Pearson correlation coefficients were used to examine sex specific relationships between on-ice start parameters and split times with α level set to <0.05 as the threshold for statistical significance. Finally, independent samples *t* tests were used to assess differences in all model parameters between faster vs. slower skaters to the 20m and 100m on-ice intervals. Cohen *d* effect sizes (ES) were calculated and interpreted as trivial (<0.2), small (0.2 ≥ to <0.6), moderate (0.6 ≥ to<1.2), large (1.2 ≥ to <2), very large (2 ≥ to<4), or extremely large (≥ 4) as proposed by Hopkins et. al (2009).

3.3 Results

Descriptive statistics (mean ± SD) for participant characteristics, on-ice start parameters and on-ice split times are presented in Table 3.1. The intra-session reliability of MSS, MAC and P_{Max} satisfied the criteria for good reliability, while τ presented with acceptable reliability (Table 3.2). The mean R^2 for the models that were fitted using raw data from 72 total on-ice start repetitions across 38 total participants was 0.97, with all models >0.94. Examples of models for participants of different speeds are presented in Figure 3.3. Measured and modelled velocities presented with excellent agreement, with single measure ICCs ranging from 0.97-0.99 and mean bias between -1.7% to 1.7% (Table 3.3).

Table 3.1 Participant characteristics, model parameters, and male vs. female on-ice performance characteristics (mean ± SD).

		Males	Females
Participant Characteristics			
	Age (years)	22.2 ± 2.5	23.8 ± 3.4
	Body Mass (kg)	80.4 ± 8.4	65.0 ± 5.2
Model Parameters			
	MSS (m/s)	10.9 ± 0.4	9.2 ± 0.6
	MAC (m/s^2)	4.6 ± 0.3	3.9 ± 0.3
	P_{Max} (W/kg)	12.5 ± 0.9	8.9 ± 1.1
	τ (s)	2.4 ± 0.1	2.4 ± 0.2
On-ice Split Time (s)			
	10 m	2.2 ± 0.1	2.4 ± 0.1
	20 m	3.49 ± 0.1	3.88 ± 0.2
	100 m	10.26 ± 0.3	11.53 ± 0.5

Note. On-ice 100m split time represents the season best times for each athlete during the early 2022-2023 season (n=35). 10m and 20m time measured with linear encoder during on-ice testing.

Table 3.2 Intra-day reliability results of on-ice start parameters derived from the monexponential model (n=35).

Parameter	*ICC (95% CI)*	*CV*	LOA
MSS (m/s)	0.98 (0.95-0.99)	1.4%	0.03 ± 0.41
MAC (m/s^2)	0.90 (0.81-0.95)	3.2%	-0.01 ± 0.38
P_{Max} (W/kg)	0.98 (0.95-0.99)	2.6%	0.00 ± 0.79
τ (s)	0.76 (0.56-0.88)	4.1%	0.02 ± 0.29

Note. ICC, intraclass correlation coefficient; CV, within participant coefficient of variation; 95% CI, 95% confidence interval; LOA, 95% limits of agreement (Bias ± LOA).

Table 3.3 Mean ± SD, mean bias ± SD with 95% limits of agreement (LoA), and single measure interclass correlation coefficients (ICC) for measured vs. modelled 5 m mean velocity intervals.

	Measured	Modelled	Mean Bias ± SD (95% LoA)	ICC (95% CI)
Mean Velocity (m/s)				
5-10 m	6.01 ± 0.34	5.98 ± 0.34	0.02 ± 0.08 (-0.13 to 0.17)	0.97 (0.95-0.99)
15-20 m	7.75 ± 0.51	7.89 ± 0.5	-0.13 ± 0.06 (-0.25 to -0.02)	0.98 (0.98-1)
25-30 m	8.72 ± 0.62	8.81 ± 0.61	-0.09 ± 0.11 (-0.22 to 0.04)	0.99 (0.99-1)
35-40 m	9.39 ± 0.68	9.34 ± 0.68	0.05 ± 0.09 (-0.12 to 0.22)	0.99 (0.98-1)
45-50 m	9.81 ± 0.74	9.66 ± 0.73	0.14 ± 0.11 (-0.07 to 0.35)	0.99 (0.98-0.99)

Note. n=38.

Pearson correlation coefficient results are presented in Table 3.4. Significant correlations between *MSS* and P_{Max} were observed across all on-ice split times (10 m, 20 m, 100 m competition time). Statistically significant relationships were only found between MAC and the 10 m and 20 m intervals, while no statistical relationship was found between τ and all of the on-ice split times. Strong negative relationships were observed between MSS and all on-ice split times for males ($r = -0.82$ to -0.85, $p<0.001$) and between MSS and the 100 m split time for the females ($r = -0.84$, $p = 0.01$) indicating the higher the MSS, the faster the split time. P_{Max} displayed very strong negative relationships across all distances in females ($r = -0.89$ to -0.96, $p<0.001$) and with the 10 m and 20 m time splits in males ($r = -0.82$ to -0.90, $p<0.001$) indicating the higher the P_{max}, the faster the skater. Relationships between MAC and 10m time ranged from moderate ($r = -0.58$, $p=0.005$) in males to strong ($r = -0.78$, $p=0.001$) in females, indicating the higher the MAC, the faster the split time. Likewise, correlations with 20 m time ranged from very strong ($r = -0.81$, $p<0.001$) in females to strong ($r = -0.68$, $p<0.001$) in males.

Table 3.4 Sex specific Pearson correlation coefficients between model parameters and on-ice performance data.

Parameter	10 m (s)		20 m (s)		100 m (s)	
	r (95% CI)	*p*	*r* (95% CI)	*p*	*r* (95% CI)	*p*
Males						
MSS (m/s)	-0.82 (-0.92 to -0.59)	<0.001	-0.84 (-0.93 to -0.64)	<0.001	-0.85 (-0.94 to -0.65)	<0.001
MAC (m/s²)	-0.58 (-0.81 to -0.20)	0.005	-0.68 (-0.86 to -0.35)	<0.001	-0.41 (-0.71 to 0.02)	0.06
P_{Max} (W/kg)	-0.82 (-0.92 to -0.60)	<0.001	-0.90 (-0.96 to -0.77)	<0.001	-0.72 (-0.88 to -0.42)	<0.001
$\tau\ (s)$	0.04 (-0.40 to 0.46)	0.871	0.12 (-0.33 to 0.63)	0.60	-0.15 (-0.55 to 0.30)	0.50
Females						
MSS (m/s)	-0.64 (-0.87 to -0.16)	0.01	-0.74 (-0.91 to -0.34)	0.002	-0.84 (-0.95 to -0.55)	<0.001
MAC (m/s²)	-0.78 (-0.92 to -0.42)	0.001	-0.81 (-0.93 to -0.48)	<0.001	-0.69 (-0.89 to -0.26)	0.06
P_{Max} (W/kg)	-0.89 (-0.96 to -0.69)	<0.001	-0.96 (-0.99 to -0.89)	<0.001	-0.93 (-0.98 to -0.78)	<0.001
$\tau\ (s)$	0.30 (-0.27 to 0.72)	0.30	0.25 (-0.31 to 0.69)	0.38	0.07 (-0.48 to 0.58)	0.81

Note. On-ice 100m split time represents the season best times for each athlete during the early 2022-2023 season; 10m and 20m time measured with linear encoder during on-ice testing; 95% CI, 95% Confidence Interval

Descriptive statistics (mean ± SD), mean differences, and ES between the slower and faster groups to 100 m are presented in Table 3.5. Across both sexes, the faster group had a significantly lower opening 100 m competition split time (extremely large effects). Similarly, MSS (moderate to large effects, Figure 4.4) and P_{Max} (large effects, Figure 4.5) were significantly higher in the faster group across males and females.

Table 3.5 *G*roup comparison (mean ± SD), mean difference (95% confidence interval) and Cohen d effect size for model parameters and 100 m split time obtained from in-season 500 m competition for faster vs. slower male (n=15) and female (n=14) skaters.

	Fast Group	Slow Group	Mean Difference (95%CI)	*p*	Cohen *d* (95% CI)
Males					
100 m split (s)	9.98 ± 0.17	10.55 ± 0.09	-0.57 (-0.71 to -0.41)	<0.001	-4.05 (-6 to -2.1)
MSS (m/s)	11.23 ± 0.28	10.45 ± 0.17	0.78 (0.53 to 1.04)	<0.001	3.35 (1.62 to 5.08)
MAC (m/s^2)	4.72 ± 0.22	4.45 ± 0.29	0.27 (-0.02 to 0.57)	0.06	1.18 (-0.11 to 2.28)
P_{Max} (W/kg)	13.27 ± 0.77	11.62 ± 0.66	1.65 (0.85 to 2.45)	<0.001	2.27 (0.84 to 3.71)
$\tau\ (s)$	2.38 ± 0.11	2.36 ± 0.18	0.02 (-0.15 to 0.2)	0.84	0.15 (-0.97 to 1.27)
Females					
100 m split (s)	11.09 ± 0.40	11.97 ± 0.10	-0.88 (-1.24 to -0.51)	<0.001	-3.04 (-4.74 to -1.32)
MSS (m/s)	9.56 ± 0.61	8.86 ± 0.34	0.69 (0.11 to 1.28)	0.02	1.42 (0.12 to 2.72)
MAC (m/s^2)	4.1 ± 0.25	3.62 ± 0.21	0.48 (0.2 to 0.57)	0.002	2.07 (0.63 to 3.52)
P_{Max} (W/kg)	9.78 ± 0.86	8.00 ± 0.30	1.78 (0.98 to 2.59)	<0.001	2.78 (1.15 to 4.41)
$\tau\ (s)$	2.34 ± 0.2	2.46 ± 0.22	-0.12 (-0.37 to 0.13)	0.58	-0.55 (-1.74 to 0.63)

Note. On-ice 100m split time represents the season best times for each athlete during the early 2022-2023 season; 10m and 20m time measured with linear encoder during on-ice testing; 95% CI, 95% Confidence Interval

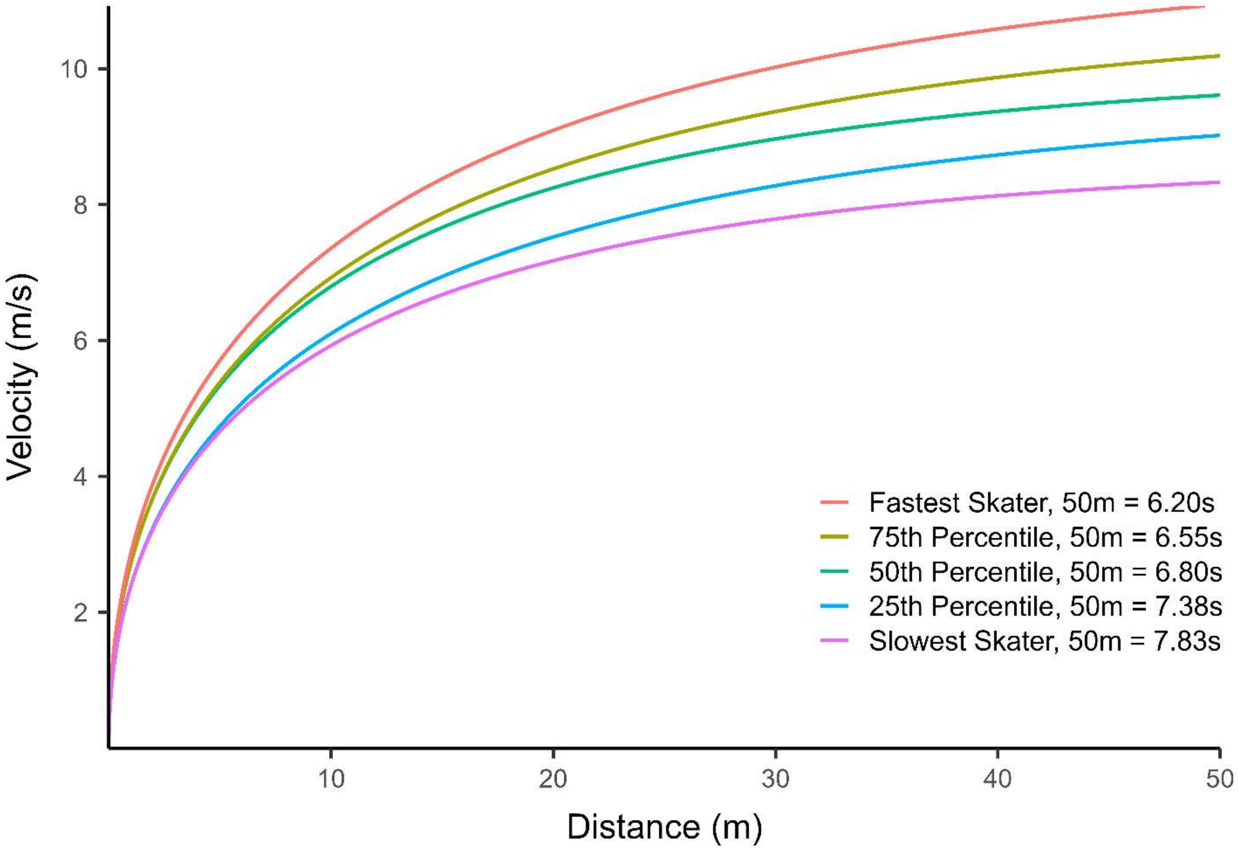

Figure 3.3 A comparison of the distance-velocity relationship obtained from elite speed skaters demonstrating performance differentiation between athletes.

Descriptive statistics (mean ± SD), mean differences, and ES between the slower and faster groups to 20 m are presented in Table 3.6. Large to very large differences between faster and slower groups were observed in 20 m time, MSS and P_{Max} in males and in 20 m time and P_{Max} in females (Table 3.6, Figure 3.4-3.5). Moderate between-group differences were observed for MSS and MAC in females and for MAC in males (Table 4.6).

Table 3.6 Group comparison (mean ± SD), mean difference (95% confidence interval) and Cohen d effect size for model parameters and 20 m split time obtained from the testing data collection for faster vs. slower male (n=15) and female (n=14) skaters.

	Fast Group	Slow group	Mean Difference (95%CI)	*p*	Cohen *d* (95% CI)
Males					
20 m Time (s)	3.39 ± 0.03	3.60 ± 0.06	-0.21 (-0.26 to -0.14)	<0.001	-4.37 (-6.51 to -2.22)
MSS (m/s)	11.26 ± 0.27	10.46 ± 0.17	0.8 (0.53 to 1.07)	<0.001	3.53 (1.67 to 5.4)
MAC (m/s^2)	4.76 ± 0.28	4.40 ± 0.17	0.36 (0.11 to 0.61)	0.008	1.69 (0.34 to 3.05)
P_{Max} (W/kg)	13.40 ± 0.66	11.50 ± 0.52	1.90 (1.2 to 2.59)	<0.001	3.20 (1.44 to 4.96)
τ (s)	2.37 ± 0.1	2.38 ± 0.16	0.01 (-0.17 to 0.14)	0.84	0.11 (-1.27 to 1.05)
Females					
20 m Time (s)	3.74 ± 0.14	4.01 ± 0.04	-0.27 (-0.50 to -0.13)	0.02	-2.56 (-4.14 to -0.99)
MSS (m/s)	9.56 ± 0.28	8.85 ± 0.17	0.71 (0.13 to 1.29)	0.02	1.46 (0.46 to 2.78)
MAC (m/s^2)	4.05 ± 0.25	3.66 ± 0.31	0.39 (0.06 to 0.71)	0.253	1.37 (0.08 to 2.67)
P_{Max} (W/kg)	9.69 ± 0.99	8.10 ± 0.46	1.59 (0.65 to 2.54)	0.004	2.06 (0.62 to 3.51)
τ (s)	2.37 ± 0.16	2.44 ± 0.27	-0.07 (-0.37 to 0.13)	0.58	-0.3 (-1.47 to 0.86)

Note. 20 m time measured during on-ice testing with linear encoder. 95% CI, 95% Confidence Interval

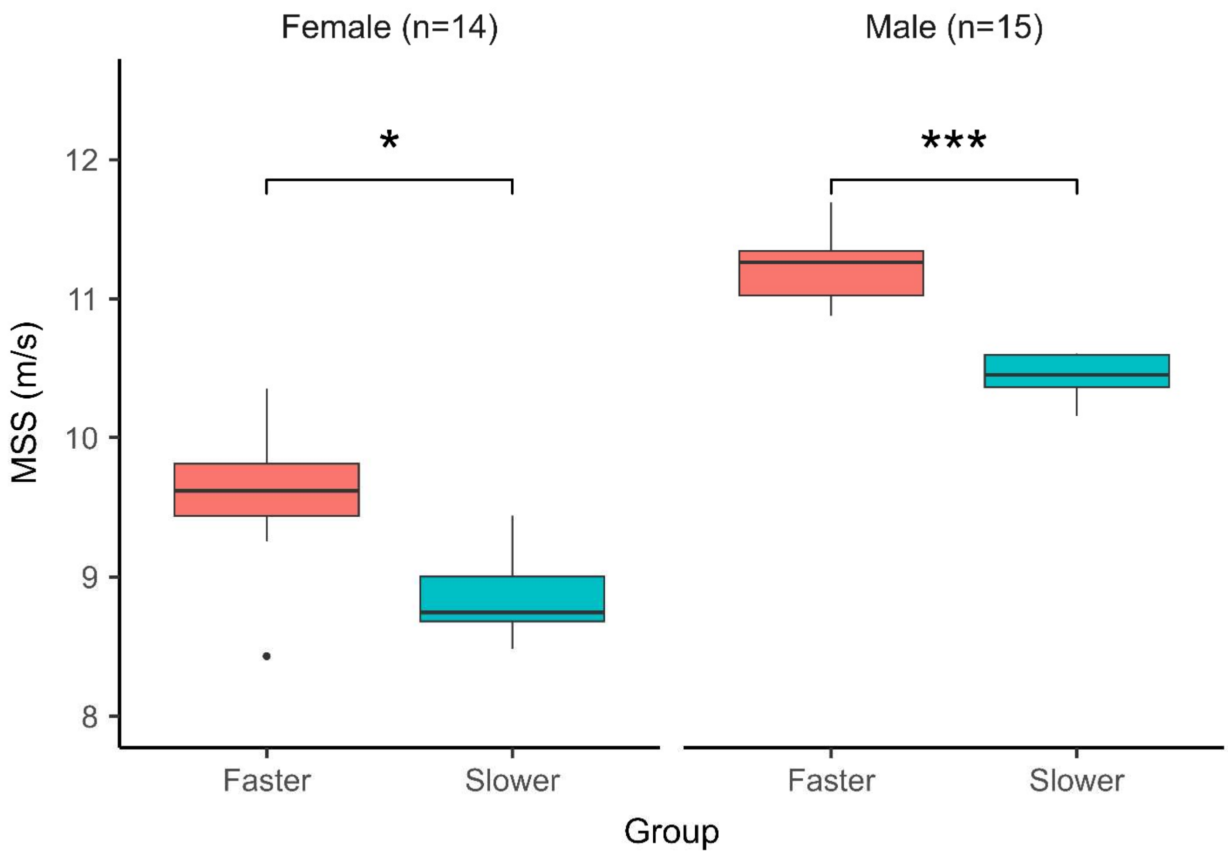

Figure 3.4 Modeled maximal skating speed (MSS) group comparison between fast and slow skaters demarcated using the 100 m split time obtained from in-season 500 m competition. *Note. 100m time represents the season best competition time of each athlete; *, $p<0.05$; **, $p<0.01$; ***, $p<0.001$.*

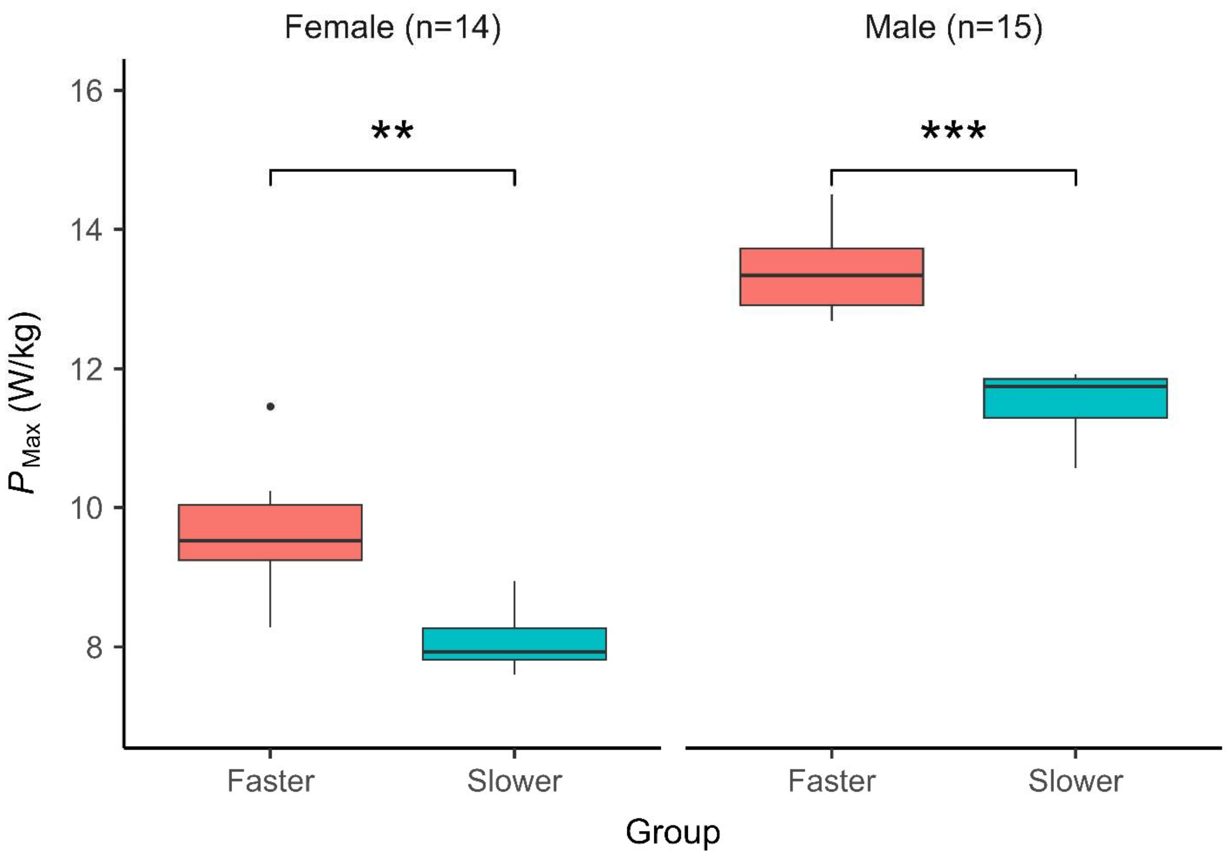

Figure 3.5 Modeled horizontal peak power (P_{Max}) group comparison between fast and slow skaters demarcated using the 20 m split time obtained from test data collection using the robotic sprint device. *Note. 20m time measured during on-ice testing with linear encoder; *, p<0.05; **, p<0.01; ***, p<0.001.*

3.4 Discussion

This study established high agreement between continuously measured and monoexponentially modelled velocity during the initial acceleration phase of the sprint start in elite level long track speed skaters. The model parameters MSS, MAC, and P_{Max} also satisfied the criteria for good reliability (ICC ≥ 0.80, CV ≤ 5%). These results align closely with previous research applying monoexponential modelling to overground running acceleration (Buchheit et al., 2014; Clark et al., 2019; de Lacey et al., 2014; Greene, 1986; Jiménez-Reyes et al., 2019).

In order to assess the utility of a performance test, Currell & Jeukendreup (2008) recommend that two types of validity should be examined: criterion and construct. The present study evaluated the criterion (concurrent) validity between measured and modelled velocity-time data during a 50 m on-ice sprint start in elite and sub-elite speed skaters using a monoexponential model. The study found high concurrent validity with mean R^2 values for all constructed models of 0.97. Moreover, low mean velocity error was observed throughout the 50 m on-ice start, with the highest percent bias observed at the 15-20 m (-1.7%) and 45-50 m (1.7%) intervals. These values are higher than the -0.1% to 0.2% bias reported by Healy, Kenny, and Harrison (2022) in a similar study with track and field sprinters.

A possible reason for the high bias in comparison to Healy et. al. (2022) may be that the average velocity was obtained over 5 m segments in the present study vs. 20 m segments. Additionally, as it pertains to the 45-50 m segment, speed skaters would typically continue to accelerate under normal race conditions through to 250 m (after the first turn), which is entirely different from over-ground running. While we provided a 10 m buffer zone for participants to detach their harness (i.e., 50-60 m) and instructed them to accelerate maximally through to 50 m, the possibility that an inadvertent deceleration occurred from 45-50 m should be considered in future studies attempting to replicate these methods. Consequently, the model assumption of an exponential decay in on-ice acceleration for speed skaters can be questioned. Regarding the increased error observed at the 15-20 m interval, this may be attributed to the transition from the running to gliding phase. According to Song et al. (2017), this transition typically occurs during the initial 1.6-2.2 s of the race corresponding to the fifth or sixth push-off. This coincides with the 10 m split times found in our study (Table 3.1). Nonetheless, the observed error seems acceptable for routine performance monitoring of elite speed skaters.

The intra-day study design along with the relatively large sample of elite athletes (n=31) allowed us to determine the repetition-by-repetition reliability of model outputs in participants with stable expert-level skating technique, accelerating in a controlled indoor ice surface facility while minimizing the effects of acute neuromuscular fatigue (Currell & Jeukendrup, 2008). This protocol and the research outcomes are crucial for informing athlete monitoring practices. Our primary finding was that MSS, MAC, and P_{Max} all exhibited good reliability (ICC: 0.92-0.98, CV $\leq$ 3.2%) while the reliability of τ was acceptable (ICC: 0.76, CV: 4.6%). Similar work has been performed in hockey players using radar or timing splits to model velocity using the same monoexponential approach as used in the present study (Perez, Guilhem, & Brocherie, 2019; Stenroth, Vartiainen, & Karjalainen, 2020). Inverse dynamics and modeling have also been used to estimate the horizontal component of the ground reaction force contributing to propulsion during on-ice acceleration using a mathematical approach to predict the horizontal force velocity profile (Morin, Samozino, et al., 2019). Though the model parameters differed slightly from the approach used in the present study, we observed similar or better reliability across variables such as the modelled velocity (V_{Max}) and relative maximal horizontal power (P_{Max}) (Perez et al., 2019; Stenroth et al., 2020). For example, the present study found ICC values of 0.98 for MSS and P_{Max}, while Perez et al. (2019), reported ICC values of 0.91 and 0.87 for V_{Max} and P_{Max}, respectively.

Although the mathematically derived force velocity profile has been used for running sprint testing in field sport athletes (Cahill et al., 2020; Haugen et al., 2019; Jiménez-Reyes et al., 2019), it has not been extensively explored in elite sprint speed skaters. This may be attributed to the unique mechanical aspects of skating as compared to running, including the reduced friction and a glide phase push-off which predominantly occurs in the frontal plane. These considerations may reduce the utility of common running based force velocity profile outcome measures such as the theoretical maximum force (F_0), ratio of horizontal force (D_{RF}), or theoretical maximum velocity (V_0) (Samozino et al., 2016). Consequently, a velocity-based model of acceleration performance in skating athletes using the methods described in this study may be a reasonable substitute for the force velocity profile method used in overground running and provide more relevant information for coaches and practitioners wanting to individualize and monitor the training response. The protocol described in this study was also practical for a high performance sport environment and had the advantage that additional participant characteristics required for the running based force velocity profile method (e.g., participant height, body mass) were not required in the model computation (Cahill et al., 2020; Haugen et al., 2019; Jiménez-Reyes et al., 2019).

Predictive validity, the final component of criterion validity, denotes the extent to which the outcome of a test correlates with competition performance (Currell & Jeukendrup, 2008). In the long track sprint distances, skaters attempt to skate each segment of the race in the shortest time possible (i.e., the 500 m sprint event is typically not paced) (de Koning et al., 1992). To assess the utility of different model parameters to predict performance during both the running and gliding phases of on-ice acceleration, correlational analysis was performed using the 10 m, 20 m, and 100 m as outcome measures. For both males and females, MSS had significant negative relationships with all split times, with a trend towards greater predictive validity as the distance interval increased. In males, MSS was the single best predictor of competition 100m time. This is consistent with work in football and track & field which indicates that maximal velocity is the single greatest predictor of performance during short sprints (Clark et al., 2019; Healy et al., 2022).

The relationships between MAC, P_{Max}, and 20 m split time were analyzed for both male and female skaters, with P_{Max} showing a stronger correlation compared to MAC. The present study estimated the relative net horizontal power by integrating velocity and acceleration throughout the sprint. Given that P_{Max} occurs early during the overground running acceleration (Jean Benoit Morin, Samozino, et al., 2019), along with modelling which indicates a similar occurrence during the speed skating start, our results highlight the potential utility of P_{Max} for describing early acceleration performance. Monitoring P_{Max} over time may assist practitioners and coaches to detect important adaptations in response to technical or training interventions.

Characteristics of a good laboratory or field test include a strong association with sport performance or the competitive skill, and the ability to distinguish between athletes of different performance levels, which has been termed construct or discriminant validity (Currell & Jeukendrup, 2008). In our study, model parameters demonstrated the ability to discriminate between performance level of highly trained skaters over a 20 m testing interval and a 100 m on-ice competition split intervals obtained from maximal effort races, further supporting the utility of this approach with skating athletes (*c.f.* Tables 3.5-3.6, Figures 3.4-3.5). Given these findings and the good intra-day reliability, monoexponential start parameters may be a feasible method of making direct comparisons between skaters to guide individualized training prescription. As an illustrative example, if an athlete had a relatively lower P_{Max} and MAC but a higher MSS, interventions to target early acceleration capacity or the run-phase transition could be applied. Typical training strategies to address this capacity include technical interventions, performing resisted starts on-ice, or targeted off-ice training including the use of plyometrics, strength training and sprinting (Hedrick, 1994; Stuart & Cochrane-Snyman, 2022). Given the good reliability, model parameters could be used as a component of routine athlete monitoring to track progression over time.

Given the importance of test feasibility (Bishop, Turner, et al., 2022), future work should consider comparing the outcomes obtained with the robotic sprint device used in the present study with more affordable technologies such as video or timing gates. Additionally, the use of the robotic sprint device with a maximal cable length of 90m limited the distance we could measure safely whilst still allowing time to release the harness. This limited the extension of our methods to the entire acceleration phase of the first 100 m interval and the remaining 400 m of the 500 m sprint event. Due to the limitations of the testing system, we were also unable to account for the potential effect of the 10 N of resistance on reducing overall acceleration performance. These limitations should be considered in future studies attempting to replicate the methods or results described in this study.

3.5 Practical Applications

This study explored the utility of a new on-ice testing method to quantify acceleration capacity in elite speed skaters using a robotic resistance device and monoexponential modeling. Importantly, given that on-ice acceleration is characterized by an initial running phase followed by a gliding phase, this method allows practitioners to quantify performance in each phase with metrics that display high intra-day reliability and concurrent validity. Notably, three metrics were obtained from the model including the initial acceleration capacity (MAC), the peak horizontal power (P_{Max}) that was highly correlated with 100 m start performance, and the maximal skating speed at 50 m (MSS). The high intra-day reliability of these parameters highlights the utility of these parameters for practitioners who are interested in monitoring performance changes in elite skating athletes. This method may also allow practitioners to better target off-ice strength and speed training to maximize transfer to on-ice acceleration capacity. Practitioners seeking to apply these methods may also consider the applicability of these methods for other skating athletes (e.g., ice hockey players) and assessing the utility of other measurement devices to obtain velocity profiles such as radar guns and timing lights.

Chapter 4: Velocity-Load Jump Testing Predicts Acceleration Performance in Elite Speed Skaters: But Does Movement Specificity Matter?

4.1 Introduction

The principle of specificity is a widely held training concept that suggests a training adaptation is closely coupled with the parameters of the training stress (Young, 2006). This principle has been shown in strength testing where performance in trained and tested exercises decouple if the movements diverge in terms of the kinetic and kinematic requirements (Aagaard et al., 1996; Behm & Sale, 1993; Harris, Cronin, & Keogh, 2007). While neuromuscular specificity in terms of terms of the mode, joint angle, contraction type, and movement velocity (Aagaard et al., 1996; Baker, Wilson, & Carlyon, 1994) has been examined previously, the influence of movement specificity remains ambiguous. Specifically, it is unclear how closely the kinematics of a lower body mechanical power tests should mimic the actual sport in order to effectively predict performance.

Long track speed skating provides a novel model to study this aspect of strength testing given the constraints of on-ice acceleration, which includes divergent techniques known as the running phase and the gliding phase in the sprint start (de Koning et al., 1995). The running phase spans the initial 1.6-2.2s of a race and resembles overground sprinting by nature of the shallow joint angles, short contact times, and rearward application of force (Song et al., 2017). To maintain acceleration over the remaining 80 m of the start phase of a race, prior to the first turn, skaters transition to gliding, characterized by longer push-off times, larger knee and hip flexion angles, and an application of force perpendicular to the direction of travel (de Koning et al., 1995).

Effective on-ice acceleration capacity is a crucial determinant of 500 m sprint performance in long track speed skating (de Koning et al., 1995). The 100 m split time of elite long track speed skaters is comparable to elite track and field sprinters with times ranging from less than 9.5 s for men to less than 10.5 s for women (International Skating Union). Overground sprinting is also characterized by an acceleration phase and maximum velocity phase (Colyer, Nagahara, & Salo, 2018; von Lieres Und Wilkau et al., 2020), and previous research has shown that the neuromuscular determinants of performance during each sprint phase may differ (Douglas, Pearson, Ross, & McGuigan, 2020). Similarly, performance assessments predicting initial acceleration capacity may not correlate with performance in the maximum velocity phase (Young, McLean, & Ardagna, 1995). However, research on the determinants of acceleration capacity in elite speed skaters typically focuses on overall 100 m performance (de Greeff, Elferink-Gemser, Sierksma, & Visscher, 2011; Zukowski et al., 2023b). Recently, a new method was introduced to measure the running and gliding phase of on-ice acceleration and quantify acceleration capacity in elite speed skaters using monoexponential modeling (Zukowski, Herzog, & Jordan, 2023a).

Traditional test methods for speed skaters such as the Wingate protocol and vertical countermovement jump (CMJ) exhibit mechanical and neuromuscular differences when compared to speed skating (Foster et al., 1993; Kandou et al., 1987). For example, while the bilateral vertical CMJ has been used to assess muscle power in elite speed skaters (de Greeff et al., 2011), skating is a unilateral movement with rearward and lateral force application (de Koning et al., 1995). Similarly, to optimize performance during the start, speed skaters must produce force throughout varied contact times and postures (de Koning et al., 1995; Song et al., 2017), and muscle properties such as the force velocity and force length relationships are known to contribute to sport performance (Herzog, 1996).

Consequently, functional force velocity testing may offer practitioners and coaches better information and improved methods to monitor training adaptations compared to those traditionally used. However, functional force velocity protocols often use linear modelling to report parameters such as maximum theoretical force (F_0), velocity (V_0) and line slope (S_{FV}) (Samozino et al., 2010). Concerns have been raised regarding the reliability of these parameters, despite performance across loads demonstrating good reliability (Kotani et al., 2021). Therefore, monitoring jump performance across individual loads may be preferred for assessing the relationship between effective work and movement velocity.

Techniques such as regularized regression can be used in these cases to handle correlated predictors (e.g., performance in the same test across different loads). Regularized regression applies penalties to less influential variables, facilitating elimination from models (Kipp & Warmenhoven, 2022; Krzyszkowski & Kipp, 2021). This is useful in scenarios often encountered in applied sports biomechanics research, characterized by a high number of predictor variables and relatively few observations (Kipp & Warmenhoven, 2022). Regularized regression can enhance model robustness by reducing sensitivity to noise and decreasing the risk of overfitting (Kipp & Warmenhoven, 2022; Krzyszkowski & Kipp, 2021).

The purpose of this study was to compare differences between movement-specific (i.e., lateral and horizontal single leg jumping) and non-specific (i.e., bilateral vertical CMJ) functional load-velocity jump testing to predict on-ice acceleration performance in elite speed skaters. This research extends previous research examining the reliability of a velocity-load jump protocol using the horizontal ($\text{Jump}_{\text{Horz}}$), lateral ($\text{Jump}_{\text{Lat}}$) (Zukowski et al., 2023b). Further, 50 m on-ice acceleration capacity was quantified using an established exponential modeling method (Zukowski et al., 2023a). We hypothesized that the $\text{Jump}_{\text{Horz}}$ is a better predictor of running phase performance, whereas the Jump_{Lat} is a better predictor of glide phase performance, and that both tests have a stronger association with acceleration performance than the bilateral vertical CMJ test.

4.2 Methods

4.2.1 Design

A cross-sectional design was used to examine the relationship between velocity-load jump performance and on-ice acceleration performance quantified with monoexponential modelling. Participants were recruited from the Calgary high-performance training centre, and testing was embedded within a typical training week. Each participant underwent three testing sessions over an 8-week data collection period. Testing for specific movements (Jump_{Lat} and $\text{Jump}_{\text{Horz}}$), non-specific movement (CMJ), and on-ice starts were on separate days, in a randomized order. All participants were familiarized with the testing procedures prior to data collection. Participants were instructed to use the same self-determined competition warmup prior to each session. The data collection period aligned with three 500 m races held at the Calgary Olympic Oval, from which the fastest 100 m time was recorded for each participant.

4.2.2 Participants

Twenty-seven long track speed skaters (14 males, 13 females) took part in this study, approved by the University of Calgary's Conjoint Health Research Ethics Board (CHREB 20-1751). All provided written consent. Participants had a training age of > 5 years within the Calgary high-performance centre and ranged from highly trained national level athletes to internationally ranked athletes competing in International Skating Union (ISU) World Cups and the 2022 Olympic Winter Games. Individuals with injuries that limited maximal effort jump testing were excluded. Subject characteristics and descriptive statistics are presented in Table 4.1.

Table 4.1 Subject characteristics and descriptive statistics for off-ice jump and on-ice acceleration performance (mean ± SD) for female vs. male speed skaters

	Females	Males
Subject Characteristics		
n	13	14
Age (years)	23.2 ± 2.4	22.5 ± 2.7
Body Mass (kg)	65.7 ± 4.7	82.7 ± 9.7
CMJ Takeoff Velocity		
BW (m/s)	2.6 ± 0.3	2.9 ± 0.2
30% BW (m/s)	2.2 ± 0.2	2.6 ± 0.2
60% BW (m/s)	1.8 ± 0.2	2.2 ± 0.2
Unilateral Jump Peak Velocity		
Jump_{Lat} 10 N (m/s)	2.7 ± 0.2	3.0 ± 0.2
Jump_{Lat} 7.5% BW (m/s)	2.5 ± 0.2	2.7 ± 0.1
Jump_{Lat} 15% BW (m/s)	2.4 ± 0.2	2.6 ± 0.2
$\text{Jump}_{\text{Horz}}$ 10 N (m/s)	3.3 ± 0.4	3.8 ± 0.3
$\text{Jump}_{\text{Horz}}$ 7.5% BW (m/s)	3.0 ± 0.3	3.4 ± 0.2
$\text{Jump}_{\text{Horz}}$ 15% BW (m/s)	2.8 ± 0.4	3.1 ± 0.2
On-ice Acceleration Performance		
100 m (s)	11.6 ± 0.5	10.2 ± 0.3
MAC (m/s^2)	3.8 ± 0.3	4.6 ± 0.3
P_{Max} (W/kg)	8.8 ± 1.1	12.5 ± 1.0
MSS (m/s)	9.2 ± 0.6	11.0 ± 0.4

Note. Jump_{Lat}, single leg lateral jump; $\text{Jump}_{\text{Horz}}$, single leg horizontal jump; MAC, maximal modelled acceleration capacity; P_{Max}, maximal modelled net relative horizontal power; MSS, maximal modelled skating speed at 50 m; 100 m, competition 100 m split time.

4.2.3 Jump_{Lat} and $\text{Jump}_{\text{Horz}}$ Protocols

Procedures are outlined in detail by Zukowski et al. (2023a). In summary, a commercially available robotic resistance device (1080 Sprint device, 1080 Motion) was used to measure single leg jump peak velocity (PV) in horizontal and lateral directions with loads of 10 N, 7.5%, and 15% body mass. The leg used to initiate the initial push-off from an on-ice start was identified as the testing limb and used for the unilateral jump tests. Participants attached a waist-borne harness to the cable of the robotic resistance device, and all jumps were initiated from a static position 5 meters away from the device. The participants were instructed to jump "as far as possible, landing on both legs" in both the horizontal ($\text{Jump}_{\text{Horz}}$) and lateral ($\text{Jump}_{\text{Lat}}$) directions. For each load and jump condition, three trials were performed, and the *TrainitTest* software (1080 Motion) was used to collect and process the position and time data to determine the maximum velocity (PV) of each jump. A minimum of three-minutes of rest was provided between each load and jump condition. The best trial (i.e., highest PV) for each load and jump condition was exported for further analysis.

4.2.4 Loaded CMJ Protocols

Participants performed three maximal CMJ trials to a self-selected depth, with no external load and external loads corresponding to 30% and 60% of their body mass (CMJ_{BW}, CMJ_{30}, CMJ_{60}). They were instructed to jump "as high as possible" and received a countdown of "3, 2, 1, Jump!" prior to each trial. Dual force plates (ACP-O Force Platform, AMTI) measured vertical ground reaction forces (Fz) from both limbs at 1000 Hz, recorded using MyoResearch 3.20 (Noraxon). Kinetic impulses for both limbs were analyzed using custom software (Matlab R 2022a, Mathworks). The total kinetic impulses for the left and right limb during each respective phase were exported and analyzed using a custom-built computer program (Matlab R 2022a, Mathworks). The velocity of the body center of mass (BCM) was obtained as described by Jordan et al. (2015), and it was used to determine the takeoff velocity (TOV) of each jump. A minimum rest interval of three minutes was provided between load conditions. The repetition with the highest TOV for each load condition was exported for further analysis.

4.2.5 On-ice Start Testing

On-ice start procedures are described in Zukowski et al. (2023b). Participants performed two all-out sprint starts from the 500 m start line, wearing a waist-borne harness attached to a robotic resistance device placed 5 m behind the line. The device provided 10 N of external resistance (i.e., the minimum load required to maintain proper flywheel function) and sampled position-time data at 333 Hz. Instantaneous velocity was derived by time-position data using the device software. A marker placed 60 m away cued participants to disengage the harness, and only the initial 50 m were analyzed to control for unconscious deceleration. The trial with the fastest time was selected for modelling. No external stimulus was used to initiate the start.

(2023)

4.2.6 On-ice Acceleration Modelling

Modelling and the reliability of outcome measures used in this study are described further in Zukowski et al. (2023b). In brief, modelling was performed in R Studio Version 2022.07.2 (R Version 4.2) using the "shorts" package (Jovanović & Vescovi, 2022) and the "nlsLM" function. Raw velocity-time data were fit using nonlinear least square regression to estimate maximal modelled skating speed (MSS) corresponding to the gliding phase and an acceleration-time constant (τ, the time to achieve 63.2% of MSS). These parameters were used to determine the maximal acceleration (MAC) corresponding to the initial running phase (equation 1). Neglecting the influence of ice or air friction, instantaneous acceleration was used as an estimate of the body mass normalized net horizontal force (N/kg). Assuming a linear relationship to exist between acceleration and velocity, along with parabolic power-velocity and power-force relationships, the values corresponding to the maximal horizontal mechanical power were 0.5 MSS and 0.5 MAC (equation 2)

$$MAC = \frac{MSS}{\tau} \qquad (1)$$

$$P_{Max} = \frac{MSS\ x\ MAC}{4} \qquad (2)$$

4.2.7 Statistical Analysis

Analysis was performed using R Studio Version 2022.07.2 (R Version 4.2). Relationships between on-ice acceleration and jump performance were assessed using separate regularized regression models for each of the on-ice acceleration outcome measures (i.e., MAC, net relative P_{Max}, maximum skating speed at 50 m – MSS, and the 100 m competition split time). To guarantee uniform application of penalties in these models, all nine outcomes from different jump-load conditions were standardized prior to their inclusion as predictor variables in the models. The 'glmnet' package was employed to build these regularized regression models, utilizing an elastic net penalty with an alpha (α) parameter of 0.5. The optimal regularization parameter λ, which minimizes mean square error (MSE), was ascertained through a 10-fold cross-validation process. To attain a more parsimonious model, we selected the λ value that was one standard error away from the model with the least MSE. This method effectively accomplished variable selection by nullifying the coefficients of some predictors (Kipp & Warmenhoven, 2022). Following regularized regression, coefficients were de-standardized and are presented throughout the manuscript in original scale. Lastly, Pearson's correlation coefficients (*r*) were computed for all variables retained by each regularized regression model to present interrelationships between individual predictors and on-ice performance measures.

4.3 Results

The CMJ_{BW}, CMJ_{30} and $Jump_{Horz}$ at all load conditions were included in the regularized regression model for MAC (Table 4.2). The $Jump_{Horz}$ conditions with higher external loads presented with stronger relative relationships (r = 0.83, p<0.001). In the model developed for P_{Max}, the CMJ_{Bw}, CMJ_{30}, $Jump_{Lat}$ at 10 N and the $Jump_{Horz}$ across all three loads were retained (Table 5.2). Out of these variables, the CMJ_{BW} and CMJ_{30} displayed had higher Pearson correlation coefficients (r = 0.80-0.86, p<0.001).

The $Jump_{Lat}$ at 10 N and all three CMJ conditions were retained by the model developed for MSS (Table 5.22). Correlation coefficients with jump performance during the CMJ trended highest (r = 0.80-0.84, p<0.001). In the regularized model developed to predict 100 m competition time, six out of nine predictors were retained. The $Jump_{Lat}$ and $Jump_{Horz}$ at 7.5% of bodyweight along with the CMJ_{60} were eliminated. All retained variables were statistically significant based on correlation analysis (p<0.05), with CMJ_{BW} and CMJ_{30} showing the strongest relationships (r = -0.85 to -0.87). Given the high relative regularized regression coefficients for CMJ_{30} and each of the on-ice acceleration measures, relationships are presented in Figure 4.1.

Table 4.2 Regularized regression model coefficients and Pearson correlation coefficients for on-ice acceleration measures vs. off-ice jump performance in highly trained speed skaters (n=27).

	MAC		**P_{Max}**		**MSS**		**100m Time**	
CMJ Takeoff Velocity	**RRC**	*r*	**RRC**	*r*	**RRC**	*r*	**RRC**	**r**
BW (m/s)	0.04	0.72^{***}	0.94	0.80^{***}	0.98	0.82^{***}	-0.99	-0.85^{**}
30% BW (m/s)	0.57	0.79^{***}	3.74	0.86^{***}	1.60	0.84^{***}	-1.28	-0.87^{**}
60% BW (m/s)	-	-	-	-	0.04	0.8^{***}	-	-
Unilateral Jump Peak Velocity								
Jump$_{Lat}$ 10 N (m/s)	-	-	0.37	0.53^{***}	0.40	0.49^{**}	-0.73	-0.47^{*}
Jump$_{Lat}$ 7.5% BW (m/s)	-	-	-	-	-	-	-	-
Jump$_{Lat}$ 15% BW (m/s)	-	-	-	-	-	-	-0.09	-0.45^{*}
Jump$_{Horz}$ 10 N (m/s)	0.11	0.78^{***}	1.08	0.73^{***}	-	-	-0.37	-0.68^{**}
Jump$_{Horz}$ 7.5% BW (m/s)	0.31	0.83^{***}	0.48	0.76^{***}	-	-	-	-
Jump$_{Horz}$ 15% BW (m/s)	0.52	0.83^{***}	0.45	0.75^{***}	-	-	-0.12	-0.47^{*}

Note. – Indicates variable was removed by regularized regression model; RRC, represents regularized correlation coefficient; *r*, Pearson correlation coefficient; *, indicates $p < .05$; **, indicates $p < .01$; ***, indicates $p < 0.001$.

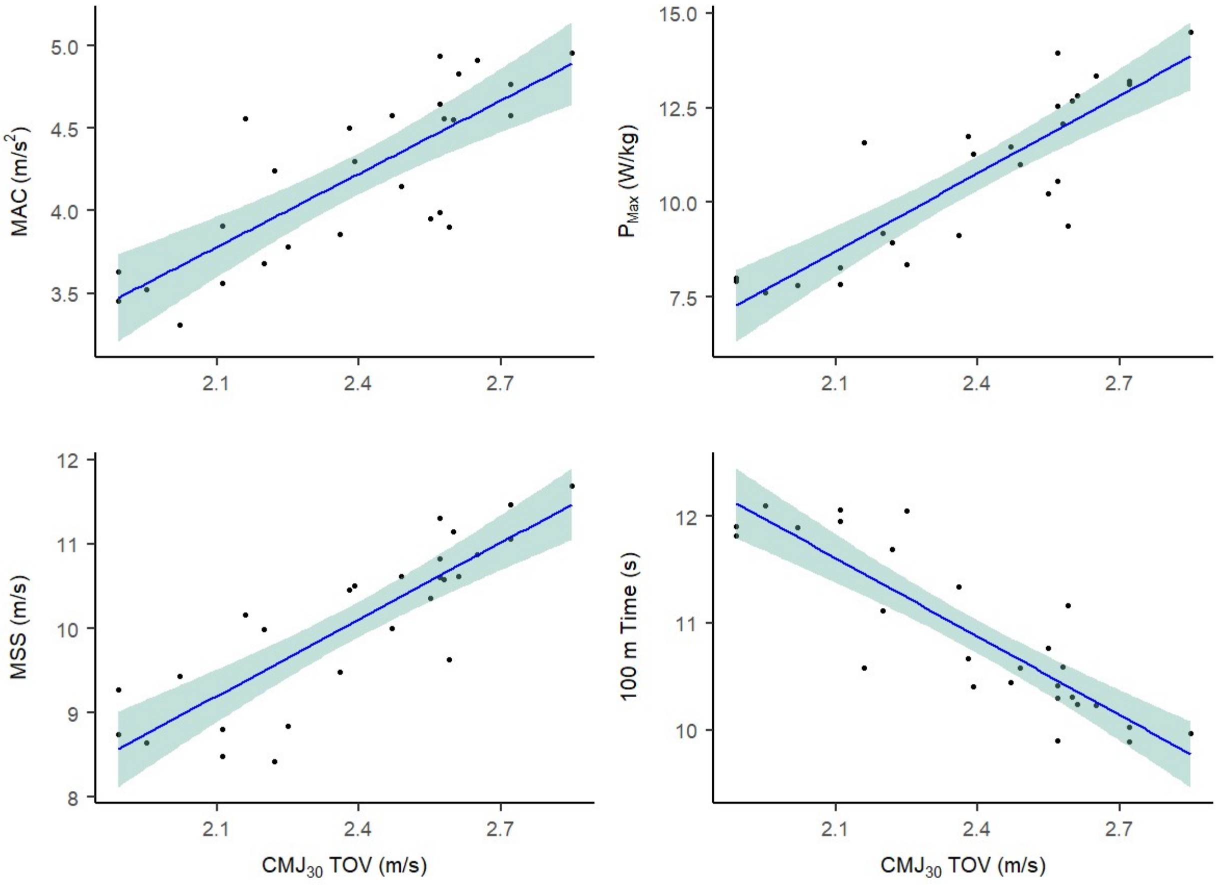

Figure 4.1 Relationship between CMJ_{30} takeoff velocity (m/s) and on-ice acceleration performance (n = 27). CMJ_{30}, countermovement jump with 30% of body weight external load; TOV, vertical takeoff velocity; MSS, maximal skating speed at 50m; 100 m Time, competition 100m time split; MAC, maximal acceleration; P_{Max}, body mass normalized net relative horizontal mechanical power.

4.4 Discussion

In this study, we examined the influence of movement specificity in velocity-load jump testing for predicting on-ice acceleration performance among elite speed skaters. To achieve this, regularized regression was utilized to include all nine jump and load combinations as predictors. Retained variables were then analyzed using correlation analysis to consider individual relationships between off-ice jump performance and on-ice acceleration outcomes. This statistical approach has been used previously to identify biomechanical predictors of javelin throwing distance at the 2017 world championships (Kipp & Warmenhoven, 2022).

Consistent with our initial hypotheses, there was some evidence of the influence of movement specificity in predicting on-ice performance. For example, the Jump_{Lat} was retained by the regularized regression model for gliding phase performance (MSS), but it was not retained for the initial acceleration performance models (MAC, P_{Max}). Conversely, the $\text{Jump}_{\text{Horz}}$ was retained by the regularized regression model for initial acceleration phase performance (P_{Max}). Contrary to our hypotheses, CMJ velocity at all three loading conditions (i.e., the non-specific movement) was also retained by the regularized regression models. Furthermore, CMJ_{30} TOV consistently trended towards higher regularized regression and Pearson coefficients, except for MAC where the $\text{Jump}_{\text{Horz}}$ displayed the strongest associations with performance. Taken together, these results highlight that it was the loading condition, and not movement-specificity, that had the greatest influence on the utility of velocity-load testing to predict on-ice acceleration performance.

Previous research aimed at identifying a correlation between on-ice acceleration performance and off-ice neuromuscular tests has used the 100 m split time measured during competitions, neglecting the disparate movement strategies seen in the running and gliding phases of the start in speed skating (de Greeff et al., 2011; Liebermann, Maitland, & Katz, 2002; Zukowski et al., 2023b). The present study addressed this gap using a robotic resistance device and monoexponential modeling to quantify the early acceleration phase (running phase – quantified by MAC and P_{Max}) and gliding phase (MSS) performance (Jovanović & Vescovi, 2022; Zukowski et al., 2023a). These parameters may provide greater insight into on-ice acceleration performance and have been shown to be reliable and valid for distinguishing between highly trained speed skaters of different ability (Zukowski et al., 2023a). MAC, representing the initial acceleration rate, captures the initial projection from a static stance at the starting line. P_{Max}, or the maximum net relative horizontal power, showed high predictive validity with 10 and 20 m on-ice split times, thereby summarizing performance during the running phase (Zukowski et al., 2023a). Lastly, MSS represents the modelled maximum velocity at 50 m, which corresponds to performance in the gliding phase (Zukowski et al., 2023a). Along with the 100 m competition time, these parameters allowed us to thoroughly quantify on-ice acceleration performance using a novel approach suitable for the routine monitoring of speed skaters.

This study examined the impact of movement specificity in velocity-load testing using a single leg forward horizontal jump ($Jump_{Horz}$) and a single leg lateral jump ($Jump_{Lat}$), mimicking the initial running phase and the lateral push of the gliding phase in skating, respectively. The bilateral vertical CMJ neglected the directionality of the force vector in on-ice acceleration and the unilaterality of skating. Despite this, the bilateral CMJ is a widely used index of lower body external mechanical power (Darmiento, Galpin, & Brown, 2012), and has been used to predict sprint performance in speed skaters (de Greeff et al., 2011; Liebermann et al., 2002). Previous literature in skating also suggests that the relationship between off-ice tests and on-ice performance depends on the external load condition of jump and sprint testing (Thompson, Safadie, Ford, & Burr, 2020; Zukowski et al., 2023b). The present results suggest that the external load condition, and not movement specificity, had a greater influence on predicting skating performance.

CMJ_{30} was retained by all regression models (Table 4.2) and showed higher relative regression coefficients except for with MAC. These results may be because the external load at CMJ_{30} optimized the push-off distance, contraction time, and takeoff velocity relative to skating (Bobbert, 2014; Mundy, Smith, Lauder, & Lake, 2016). Given there is more time for force production during skating compared to overground running (Song et al., 2017), the timeframe for force application in CMJ_{30} may closely align with the mechanical demands placed on the lower limb extensors whilst skating. Further, an increase in load during the jump squat exercise has been shown to increase the proportion of jump duration spent in propulsion (Mundy et al., 2016). This could limit the stretch-shortening cycle (SSC) effect observed during the CMJ (Turner & Jeffreys, 2010), making it more similar to speed skating, where muscles primarily operate isometrically and concentrically (de Groot, Hollander, Sargeant, van Ingen Schenau, & de Boer, 1987). Taken together, these findings underscore that the three-point velocity-load CMJ profile is a superior alternative for speed skaters when compared to common single-load measures of lower body mechanical power, such as the CMJ_{BW} or Wingate ergometer protocol.

There was some evidence of movement specificity but only for $Jump_{Horz}$, which recorded the most robust regression coefficients with MAC (Table 4.2). MAC represents the initial acceleration phase, directly following the reaction to the start gun. This phase requires athletes to initiate movement from a stationary position, overcome inertia, and propel themselves horizontally to begin the running phase. Consistent with the notion of movement specificity, $Jump_{Horz}$ appeared to be a better assessment of this capacity than the CMJ or $Jump_{Lat}$. This finding is consistent with previous work by Zukowski et al. (2023b), who demonstrated that the $Jump_{Horz}$ had the strongest relationships with 100 m, 400 m, and 500 m race performance (r=0.72-0.8, p<0.001). However, their work was constrained by using competition timing splits, which made it challenging to quantify performance in the initial (running) and late (gliding) acceleration phases. The present study addressed these limitations with exponential modeling (Jovanović & Vescovi, 2022), allowing us to quantify the association between the $\text{Jump}_{\text{Horz}}$ and run-phase acceleration performance.

Previous research has shown that performance in vertical and horizontal jumping among team sport athletes differ, indicating that the two assessments may reflect different movement skills or neuromuscular capacities (Dobbs, Gill, Smart, & McGuigan, 2015). Similarly, research by Burr et al. (2008) indicated that horizontal jumps may be a better predictor of hockey potential than vertical jumps in an analysis of NHL combine data. Given the relatively short ice contact times and horizontal projection of the center of mass, the $\text{Jump}_{\text{Horz}}$ assessment would seem highly specific to the running phase of skating acceleration. Fukashiro et al. (2005), previously compared kinematics and electromyographic (EMG) activity during vertical and horizontal jumps, finding that the horizontal jump was characterized by greater trunk flexion and a higher emphasis on power production from the hip joint. These characteristics align closely with the mechanics of skating (de Koning, de Boer, de Groot, & van Ingen Schenau, 1987) and coupled with the present results, would seem to support the use of both horizontal and vertical jump assessments to predict early on-ice acceleration performance in elite speed skaters.

Jump_{Lat} was less strongly associated with on-ice acceleration performance even for the gliding phase than the CMJ or $\text{Jump}_{\text{Horz}}$. Correlation coefficients ranged from 0.47 to 0.53, indicating weaker associations compared to the vertical and horizontal jumps (Table 4.2). Considering the high specificity of Jump_{Lat} with the gliding phase of on-ice acceleration, this outcome was counter to our initial hypothesis. These findings also contradict previous research by Zukowski et al. (2023b), where strong interrelationships between competition performance and the Jump_{Lat} were observed (r= 0.67-0.73). However, previous research did not include elite speed skaters and employed a less robust correlational analysis with multiple comparisons versus the regularized regression modelling methods used in the present study. Therefore, present results suggest that it is more important to consider the external loading condition for the prediction of on-ice acceleration than movement specificity, except for the initial acceleration phase where forward horizontal jumping may provide practitioners with additional information on a skater's performance capacity.

Several limitations must be noted when interpreting the present results. The use of robotic resistance in the Jump_{Lat} protocol restricted our outcome measure to peak velocity during the jump, excluding potential factors such as impulse or jump strategy. These variables may have had stronger associations with speed skating performance. The cable length of the robotic device also restricted data collection between 50 m and 100 m on-ice. In race conditions, long track speed skaters continue to accelerate up to approximately the 250 m mark (van Ingen Schenau, de Koning, & de Groot, 1990). Therefore, it is plausible that changes in velocity between 50-100 m would be important for a full analysis of acceleration during the glide phase. Moreover, on-ice data collection took place early in the season over an 8-week period and results may not represent the peak acceleration capacities of each skater. Future studies might use these tests and models throughout an entire season for performance prediction. Implementing alternative measurement tools like radar guns or local positioning systems to measure velocity across the entire 100 m opener of a 500 m competition race.

4.5 Practical Applications

We suggest that practitioners transition away from general, single-load tests such as bodyweight jump assessments or cycle ergometer protocols. Specifically, the three-point TOV-external load CMJ profile and the unilateral $\text{Jump}_{\text{Horz}}$ demonstrate strong predictive validity with on-ice acceleration performance in skating athletes. Coaches should explore the use of these protocols as both testing and training interventions for predicting and enhancing on-ice skating performance.

4.6 Conclusions

This was the first study to assess the relationship between off-ice neuromuscular tests and on-ice performance in elite long track speed skaters during the independent running and gliding phases of on-ice acceleration. Our results suggest that load rather than movement specificity is an important consideration for the prediction of on-ice acceleration performance. Future work should apply the methodology of the current study to other skating populations.

Chapter 5: Conclusions and Future Directions

The primary aim of this thesis was to evaluate the influence of movement specificity on the predictive validity of off-ice loaded jump tests with on-ice acceleration performance. The thesis addressed several gaps in the current literature, including: (i) a lack of consideration for movement and load specificity whilst assessing neuromuscular strength and power capacities in skating athletes; (ii) limited understanding as to how the inherent asymmetry within the sport of speed skating may contribute to interlimb asymmetries in mechanical muscle testing, and the change in interlimb asymmetries over the course of a typical competitive season (i.e., finding evidence in support of the practice of testing the dominant limb in unilateral testing); (iii) the need for valid and reliable summaries of on-ice acceleration performance during the discrete running and gliding phases of on-ice acceleration; and (iv) the lack of information regarding the degree of test specificity needed whilst designing off-ice neuromuscular testing batteries for skating athletes. On-ice acceleration includes two distinct movement phases (running and gliding) with divergent mechanics in comparison to overground sports (de Koning et al., 1989). In the present thesis, we identified novel methods to summarize on-ice acceleration during each movement phase, as well as off-ice tests that best predict performance. This provides insight into the neuromuscular determinants which underpin effective on-ice acceleration and may help inform off-ice training interventions for skating athletes.

In Chapter 2, highly trained (n=26), national level athletes performed single leg jumps with a horizontal robotic resistance across three external load conditions (10 N, 7.5% of body mass, 15% of body mass) using their dominant limb. The $\text{Jump}_{\text{Horz}}$ and Jump_{Lat} were used to replicate the body position and line of force application observed during the running and gliding phases of on-ice acceleration. Participants completed two consecutive trials of the same jump protocol to examine the intra-day reliability of the peak velocity (PV) achieved for each loading condition. PV across each jump type and loading condition had good reliability (ICC > 0.8, CV < 5%). Within the 75-day time period of data collection, three local 500 m sprint distance races were held at the Calgary Olympic Oval. For 22 of the 26 athletes, allowing competition split times to be used in order to examine interrelationships between jump peak velocity and sprint distance performance. Race results were normalized according to the current sex-specific WR time, and significant positive relationships (r=0.5-0.8, $P < 0.05$; n=22) were observed between all jump conditions and on-ice sprint race split times obtained including 100 m, 400 m and 500m. Results of this chapter indicate that unilateral loaded jump tests are reliable in speed skating athletes and may help practitioners diagnose and monitor lower limb maximal muscle power capacity in a sport-specific manner.

In Chapter 3, the validity and reliability of an exponential function to model velocity during the initial 50 m of the long track sprint start was examined. Elite long track speed skaters (n=38) performed maximal effort 50 m On-ice accelerations from a standing start while tethered to a horizontal robotic resistance device that sampled position and time data continuously. Raw velocity-time data was fit using least squares regression and a monoexponential function, allowing for the computation of various parameters which may be used to summarize acceleration performance (MSS, MAC, P_{Max}). All constructed models provided a sufficient fit of the raw data ($R^2 > 0.95$, mean bias < 2%). Intra-day reliability of all model parameters ranged from good to excellent (ICC > 0.8, CV < 5%). Strong negative correlations (r: -0.72 to -0.96) were observed between MSS and P_{Max} and the 10 m and 20 m split times measured with the robotic resistance and with 100 split times obtained from 500 m races. Moderate to large between-group differences were observed in MSS, MAC, and P_{Max} between the elite vs. sub-elite speed skaters (Cohen d effect sizes: 1.18-3.53). Our results indicate that monoexponential modelling is a valid and reliable method of monitoring initial acceleration performance in elite level long track speed skaters.

In Chapter 4, the methodology developed in previous chapters was integrated in order to address the central objective of this thesis: the impact of movement specificity on the predictive validity of off-ice loaded jump tests in relation to on-ice acceleration performance. Elite long track speed skaters (n=27) performed velocity-load testing with three external loads during unilateral horizontal jumping ($\text{Jump}_{\text{Horz}}$), lateral jumping (JumpLat), and bilateral vertical countermovement jumping (CMJ). On-ice performance measures were obtained during maximal 50 m accelerations from a standing start, including maximal skating speed at 50 m (MSS), maximal acceleration capacity (MAC), and maximum horizontal power (P_{Max}). The 100 m split time from a 500 m race was also obtained. Regularized regression models were used to identify the most important predictors of on-ice acceleration performance. Pearson's correlation coefficients (r) were calculated for all variables retained by the model to further investigate interrelationships between single predictors and on-ice performance measures. CMJ with 30% of body mass demonstrated the strongest association with MSS, P_{Max} and 100 m time ($r = 0.84$-0.97, $p<0.001$). $\text{Jump}_{\text{Horz}}$ with 15% of body mass was the strongest predictor of MAC performance ($r = 0.83$, $p<0.001$). The findings of this chapter suggest that the loading condition was more relevant than movement specificity for predicting on-ice acceleration performance except for the initial acceleration capacity defined by MAC where the forward horizontal jump demonstrated the strongest associations with performance.

The research conducted in this thesis made notable strides in addressing existing gaps in the literature surrounding speed skating acceleration performance. However, certain limitations were universal across each chapter. The primary constraints were the observational nature of each study and the lack of longitudinal data. These factors limited our ability to discern causative relationships and understand the temporal dynamics between off-ice and on-ice performance changes. Furthermore, the predictive models developed in Chapter 4 were constrained in part by the available sample size. Ideally, to ascertain the robustness and generalizability of predictive models, one would split the data into training and test datasets. Without this, the models mainly provide insights into the relative importance of different load and jump conditions rather than genuinely predicting on-ice start performance.

Future research could implement the methods of this thesis with larger samples and a longitudinal design to address this gap and predict changes in acceleration performance throughout a competitive long track season. Further, while the loaded jump protocols used were designed to assess the in vivo force velocity relationship of the lower limb extensors in movements specific to speed skating, this mechanical muscle property is unlikely to be the only factor which influenced jump performance (Bobbert et al., 2023). Consequently, one might contend that multi-joint isokinetic testing, potentially using a device like a leg press, would offer a more specific assessment of the in vivo force velocity relationship for speed skating athletes. This would be in contrast to a jump where velocity consistently rises throughout the push-off phase and is certainly an area of future research. Lastly, while there are undoubtedly subtle variations in on-ice acceleration mechanics between different sports, the methods developed in this thesis deserve exploration in team-based sports like hockey and ringette. This thesis was the first to link off-ice neuromuscular testing to on-ice acceleration performance during the distinct running and gliding movement phases. The author aspires that the findings of this thesis may be valuable to coaches and practitioners in creating more effective and individualized training programs on and off the ice.

5.1 Practical Applications for Coaches and Practitioners

This thesis indicates that when assessing neuromuscular strength and power capacities off-ice, the distinct mechanical demands of skating must be considered. This is especially vital if the objective is to enhance predictive validity for on-ice acceleration. Skating is characterized by longer contact times, differential directions of force application, and propulsion which is initiated from a quasi-isometric position (de Groot et al., 1987; de Koning, de Groot, & Ingen Schenau, 1991; de Koning et al., 1995). Given these characteristics, adding external load to ballistic actions like sprints and jumps can prolong contact times. This may also diminish stretch shorten cycle (SSC) influence on mechanical power output, thereby increasing specificity and transfer between off-ice test results and on-ice acceleration (Turner & Jeffreys, 2010).

Similarly, our results also highlight that load specificity is a more important factor for the prediction of on-ice acceleration than movement specificity for skating athletes. Skating acceleration is comprised of two distinct phases: running and gliding. Running is characterized by shorter contact times, shallower joint angles, and horizontal application of force while gliding involves longer contacts, deeper joint angles, and lateral force application. To simulate each phase, specific unilateral jump assessments in the horizontal and lateral directions were contrasted with a standard bilateral countermovement jump. Despite high movement specificity, the loaded three point (BW, $30\%_{BW}$, $60\%_{BW}$) CMJ vs. TOV protocol consistently displayed the highest associations with on-ice acceleration during both the running and gliding phases, particularly for the loaded conditions (CMJ_{30},CMJ_{60}).

For practitioners working with skating athletes, this protocol would seem to be a pragmatic starting place for the assessment of off-ice strength and power. Establishing benchmarks for performance at each load within a training group or team may also provide directionality to training prescription. For example, an athlete below group norms in the heaviest jump condition may be best served by training focused on maximal strength. However, associations and relationships between loaded CMJ outcomes and on-ice performance should be carefully reassessed and monitored when applied to other skating sports.

Finally, the monoexponential model parameters presented and validated in Chapter 3 offer an exciting new way to monitor on-ice acceleration performance in skating athletes. In comparison to split times or force-velocity profile metrics, the velocity-based parameters of MSS, MAC, and P_{Max} offer an intuitive, comprehensible summary of linear acceleration performance for reporting to athletes and coaches. These parameters have demonstrated the ability to differentiate between higher and lower performing elite skaters during both the run and glide phases of on-ice acceleration and could be monitored regularly throughout an athletic career to anchor off-ice measures and training interventions to each phase. Though this modelling approach was applied to velocity-time data sampled at a high-frequency using robotic resistance, it should be assessed with more affordable technology such as timing gates and smartphone apps and applied to other skating sports.

Appendix 1

Zukowski, M., Herzog, W., & Jordan, M. J. (2023). Multi-Planar Jump Performance in Speed Skating Athletes: Investigating Interlimb Differences in an Asymmetrical Sport. Symmetry, 15(5), 1007.

Introduction

Bilateral asymmetry testing is often used to assess athletes after injury (Ebert et al., 2021; Hart et al., 2019; Jordan et al., 2015; O'Malley et al., 2018), but the effect of training on interlimb asymmetries in non-injured athletes remains ambiguous (Afonso et al., 2022; Maloney, 2019). Longitudinal analysis of athletes participating in sports with asymmetrical loading patterns, such as long track speed skating, can provide a unique model to elucidate the effects of training on bilateral asymmetries. Additionally, characterizing interlimb asymmetries in skating sports may provide an important benchmark of comparison for athletes who sustain injuries.

Bilateral strength asymmetry testing, including interlimb assessments of mechanical power, are often conducted with variations of unilateral and bilateral jump testing by nature of the high reliability, feasibility, and practicality (Maulder & Cronin, 2005; McMaster, Gill, Cronin, & McGuigan, 2014; Murtagh et al., 2017; O'Brien, Reeves, Baltzopoulos, Jones, & Maganaris, 2009; Samozino et al., 2010). With widespread use of jump testing in sports performance settings, a natura question arises as to whether jump derivatives can be used to identify interlimb differences in mechanical muscle function. Although jump tests have shown promise in detecting limb strength impairments after lower body injuries (Ebert et al., 2021; Jordan et al., 2015; O'Malley et al., 2018), research examining the relationship between jump asymmetries and performance or injury risk in non-injured athletes is inconclusive (Afonso et al., 2022; Maloney, 2019).

Interlimb jump asymmetries show poor agreement and high variation across test sessions and jump protocols in team sport athletes (Bishop, Abbott, et al., 2023; Bishop, Read, et al., 2022). However, these studies have commonly quantified interlimb differences using an asymmetry index (AI) calculation, which tends to increase statistical variation (Bishop et al., 2018) and aggregate measurement error (Bishop, Shrier, et al., 2023). The scientific evidence examining the relationship between jump asymmetries, sport performance and sport injury has also been limited by a lack of longitudinal research in elite athletes, with a relatively greater focus on team sport athletes that are not characterized by asymmetrical loading *per se*. The influence of asymmetrical loading, inherent to sports such as long track speed skating, has not been studied in the context of interlimb asymmetries in mechanical muscle function.

Long track speed skaters skate with only left turns using a leftward leaning body position to resist centrifugal forces. Both limbs are used for propulsion, but the right limb push is characterized by longer ice contact times and more sustained contractions to support the mass of the athlete and resist external forces (de Koning et al., 1991). This contributes to higher intramuscular forces, increased blood flow occlusion, and asymmetrical muscle oxygenation (right>left) throughout the race (Born et al., 2014; Hettinga et al., 2016). Conversely, modelling has shown that the left limb produces a higher instantaneous peak power output with shorter contact times during the turn phase (de Koning et al., 1991).

Speed skaters have also been shown to incur 50-100% greater weekly training load than team sports such as field hockey or soccer (Van Hilst et al., 2015), and present with interlimb asymmetries in bone mineral content and isometric knee extensor strength (Akahane et al., 2006; Varley et al., 2019; Xia, 2012). Similarly, structural asymmetries in pelvic orientation in a sample of skating athletes has been attributed to sport-specific asymmetrical loading and laterality within the skating stride (Bussey, 2010). To robustly assess jump asymmetry, a battery of tests which include sport-specific unilateral and bilateral movements has been recommended (Bishop, Turner, Jarvis, Chavda, & Read, 2017; Cohen et al., 2020). Recently, single leg lateral (Jump_{Lat}) and horizontal ($\text{Jump}_{\text{Horz}}$) jump tests were developed to simulate speed skating movement patterns, demonstrating high reliability and predictive validity in elite speed skaters (Zukowski et al., 2023). However, it is unclear whether systematic interlimb differences in mechanical muscle function exist in speed skaters during jump testing, and how skating (i.e., asymmetric loading) influences interlimb function over a competitive season. Thus, the purpose of the present study was to: (1) assess systematic interlimb differences in a group of elite speed skaters using a battery of jump tasks (countermovement jump-CMJ, Jump_{Lat}, $\text{Jump}_{\text{Horz}}$); (2) compare limb dominance between tests; and (3) examine within-limb changes in CMJ concentric impulse (CMJ_{Con}) and eccentric deceleration impulse (CMJ_{Ecc}) throughout a competitive season.

Materials and Methods

Participants

For cross-sectional baseline testing, long track speed skaters (n=22, male: n=12, female: n=10) volunteered to participate. Participants ranged from highly trained sub-elite athletes competing at the national level to elite athletes competing internationally at World Cup events. In the longitudinal study, athletes of the same performance level from short track (n=6, males: n=2, females: n=4) and long track (n=26, males: n=18, females: n=8) who completed regular CMJ monitoring and had accumulated > 8 testing days throughout the season volunteered to have data included. This dataset was used for statistical analysis and included 1065 individual jump trials and 355 individual test sessions between the 32 participants. Characteristics of the participants are presented in Table 2.1 To present within-limb changes in CMJ impulse at the individual level, this sample was further filtered to include the 20 participants that completed >10 testing days throughout the season. This choice was made to increase the strength of analysis and generalizability of the results, which also resulted in a more concise and clear visualization of the results. Athletes with injuries that limited maximal exertion jump testing were excluded. Participants provided written informed consent before participating, which was approved by the Conjoint Health Research Ethics Board at the University of Calgary (CHREB 20-1751).

Procedures

Each test session was conducted following a scheduled rest day and prior to any other sport-specific training. All athletes were familiarized with the test protocols prior to data collection as a component of regular testing/monitoring, and testing was conducted by a certified strength and conditioning specialist. For baseline testing, athletes performed three jump protocols ($\text{Jump}_{\text{Lat,}}$ $\text{Jump}_{\text{Horz}}$, CMJ) within a 7-day period during the pre-season. Longitudinal CMJ monitoring was conducted from the pre-season to the end of the competitive season according to the training and competition schedule.

Jump_{Lat} and $\text{Jump}_{\text{Horz}}$ Protocols

A commercial robotic resistance device (1080 Sprint device, 1080 Motion, Lidingö, Sweden) that uses a servo motor (2000 RPM OMRON G5 Series Motor; OMRON Corporation, Kyoto, Japan) was used to conduct the single leg multi-planar jump testing protocol (sampling frequency = 333 Hz). Unpublished measurement errors obtained from the manufacturer were as follows: velocity error = ± 0.5%, distance error = ± 5 mm, force error = ± 4.8 N) (Bergkvist et al., 2015). Participants attached a waist-borne harness to the cable of the robotic resistance device. Jumps were performed against a load of 10 N (i.e., the minimum load required to maintain proper flywheel function).

For Jump_{Lat}, participants initiated the jump from a self-determined skating position and were permitted to use an arm swing. A strong verbal cue was used, and participants were instructed to "jump laterally as far as possible, landing on both legs." Each jump was initiated from a 30-degree angled slant board set 5 m away from the robotic device (Figure 3.1A), and three maximal effort trials were performed on each limb (alternating with each jump). The $\text{Jump}_{\text{Horz}}$ test was conducted in the same manner as the Jump_{Lat}, except that the athletes projected their body centre of mass forward (Figure 3.1B) and were instructed to "jump horizontally as far as possible, landing on both legs." Position and time were collected and processed using the robotic resistance device software (*TrainitTest* software – 1080 Motion) to obtain the peak velocity of each jump and exported for further analysis.

Bilateral CMJ

Participants performed three maximal CMJ trials at a self-selected depth with their hands fixed firmly on the hips (Jordan et al., 2015). Participants were directed to jump "as high as possible" and received a countdown of "3,2,1, Jump!" prior to each trial. Any jump trials that did not fulfill these requirements were discarded and repeated. Vertical ground reaction forces (F_Z) from the right and left limbs were measured simultaneously using a dual force plate system (ACP-O Force Platform, AMTI, Watertown, Massachusetts, USA) at a sampling frequency of 1,000 Hz and recorded on a personal computer (MyoResearch Version 3.20, Noraxon, Scottsdale, Arizona, USA). The velocity of the body centre of mass (BCM) was obtained as described by Jordan et al. (Jordan et al., 2015), and was used to define the phases within the jump. The eccentric deceleration phase was defined as the interval between the maximum negative velocity to zero velocity, and the concentric phase was defined from zero velocity to the instant of jump takeoff (Jordan et al., 2015a). The total impulse F_z for the left and right limbs during each respective phase were exported and analyzed using a custom-built computer program (Matlab R 2022a, Mathworks, Natwick, Massachusetts, USA). A previous examination of within-subject reliability from an athlete population (*n*=109) for the jump analysis described in this study demonstrated good coefficients of variation for the CMJ_{Con} impulse (left = 3.32%, right = 3.79%) and CMJ_{Ecc} impulse (left = 5.06%, right = 5.61%) for athlete monitoring.

Statistical Analysis

The three jump mean value was calculated for all outcomes measures and used in the statistical analyses that were conducted in R Studio Version 2022.07.2 (R Version 4.2). Normality of the data was assessed through visual inspection of plots and histograms of the residuals for all variables and with a Kolmogorov-Smirnov test with the α level set to <0.05. Paired samples *t* tests were used to assess interlimb differences in the peak velocity for the $Jump_{Lat}$ and $Jump_{Horz}$ and the impulse of F_z for the CMJ eccentric deceleration and concentric phases. Limb dominance was established based on the maximum value between the left and right limbs, and Kappa coefficients were calculated to determine the consistency between tests(J. Cohen, 1960). As per Viera and Garrett (Viera & Garrett, 2005), coefficients were interpreted as follows: ≤ 0 = poor, 0.01–0.20 = slight, 0.21–0.40 = fair, 0.41–0.60 = moderate, 0.61–0.80 = substantial, and 0.81–0.99 = almost perfect. To detect interlimb changes in CMJ impulse throughout the season, linear mixed effects models (R Version 4.2, ‘lme4’ package) were fit with fixed effects for limb, time (in weeks), and the interaction between time and limb. Random effects were included for athletes, with limb (left and right) nested within the athlete to account for the repeated measurements throughout the season. Models were built individually for CMJ_{Con} and CMJ_{Ecc}, and residuals met the appropriate assumptions. To present within-limb changes in impulse throughout a competitive season, scatterplots with a line of best fit were built using locally estimated scatterplot smoothing (R Version 4.2, ‘ggplot2’ package), with the standard error (SE) used to calculate the 80% confidence interval (CI).

Results

Cross-Sectional Analysis

No systematic differences ($p>0.05$) were observed between the left and right limbs for peak veloctiy during Jump_{Lat}, $\text{Jump}_{\text{Horz}}$, or CMJ phase-specific impulses (Table 3.2, Figure 3.2). Kappa coefficients ranged from poor to slight agreement for all inter-jump comparisons of limb dominance (Table 3.3).

Table 1. Interlimb comparison (mean ± SD), mean difference (95% confidence interval) and paired sample t test results (p) for jump outcome measures.

	Right	**Left**	**Mean Difference (95%CI)**	***p***
Peak Velocity (m/s)				
Jump_{Lat}	2.65 ± 0.22	2.64 ± 0.21	0.01 (-0.06 to 0.05)	0.77
$\text{Jump}_{\text{Horz}}$	3.34 ± 0.38	3.36 ± 0.38	-0.02 (-0.03 to 0.07)	0.33
Impulse (N*s)				
CMJ_{Con}	209 ± 46	209 ± 39	0 (-26 to 25)	0.98
CMJ_{Ecc}	127 ± 30	124 ± 24	3 (-20 to 13)	0.65

*Jump_{Lat}, single leg lateral jump; $\text{Jump}_{\text{Horz}}$, single leg horizontal jump; CMJ_{Con}, countermovement jump concentric phase; CMJ_{Ecc}, countermovement jump eccentric deceleration phase.

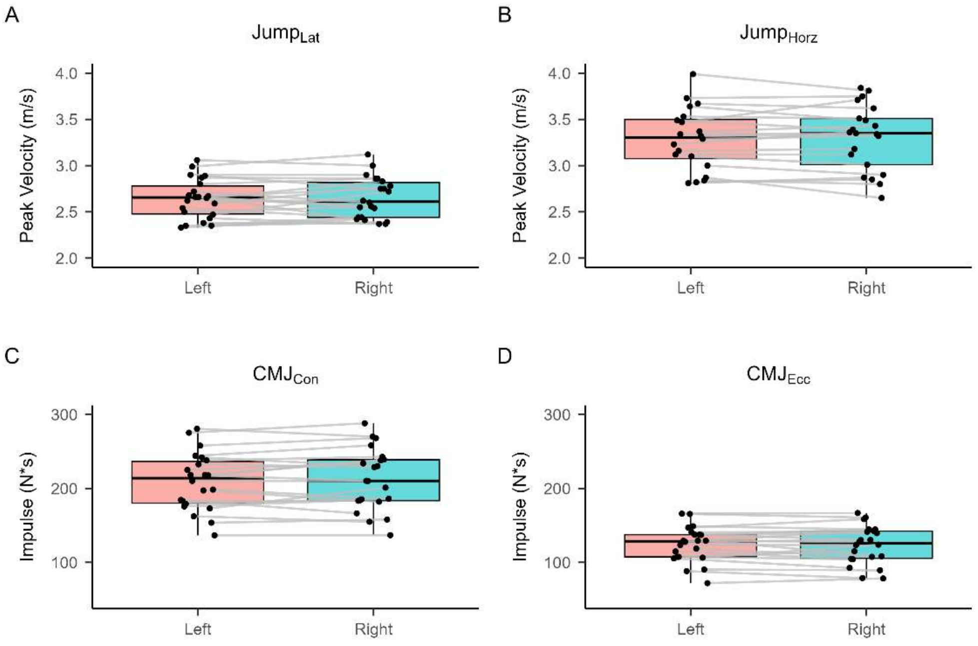

Figure 6 Box and whisker plots of interlimb dominance in jump performance under different conditions: **(a)** Jump$_{Lat}$, single leg lateral jump; **(b)** Jump$_{Horz}$, single leg horizontal jump; **(c)** CMJ$_{Con}$, countermovement jump concentric phase; **(d)** CMJ$_{Ecc}$, countermovement jump eccentric deceleration phase.

Table 2 Agreement in limb dominance between jump conditions.

Comparison	**Kappa Coefficient**	**Agreement**
Jump$_{Lat}$-Jump$_{Horz}$	-0.17	Poor
Jump$_{Lat}$-CMJ$_{Con}$	0.03	Poor
Jump$_{Horz}$-CMJ$_{Con}$	0.21	Slight
CMJ$_{Con}$-CMJ$_{Ecc}$	0.33	Slight
CMJ$_{Ecc}$-Jump$_{Lat}$	-0.01	Poor

*Jump$_{Lat}$, single leg lateral jump; Jump$_{Horz}$, single leg horizontal jump; CMJ$_{Con}$, countermovement jump concentric phase; CMJ$_{Ecc}$, countermovement jump eccentric deceleration phase.

Longitudinal Analysis

No interaction was found for CMJ$_{Con}$ between limb and time. There was no effect of limb on CMJ$_{Con}$ (p=0.35), or time (p=0.66) from baseline to the end of the season. For CMJ$_{Ecc}$, a significant interaction was found between time and limb (X^2=4.77, *df* = 644, *p*=0.03). The left limb declined to a larger extent (change = -8.40 N*s, p=0.01) than the right limb (change= -5.28 N*s, p=0.01) from baseline to end of season. Individual variation in CMJCon and CMJEcc within-limb impulses for the subset of the original sample that completed >10 monitoring sessions is presented in Figures 3.3-3.4.

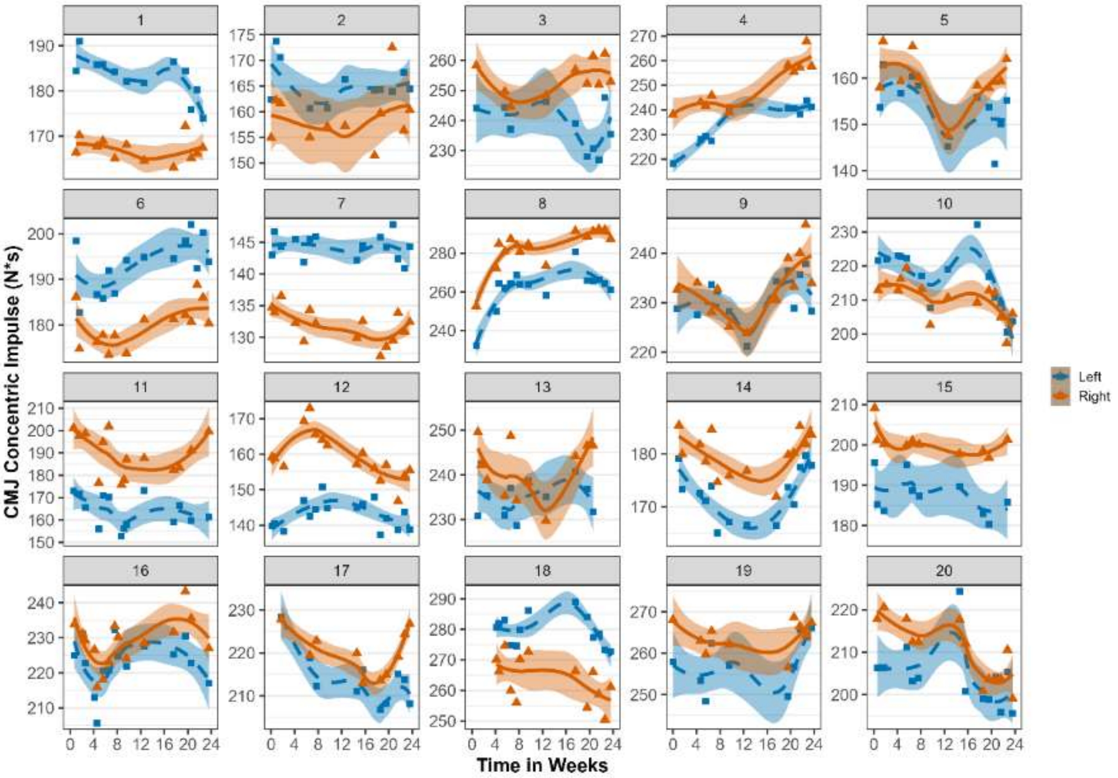

Figure 7 Within-limb variation in countermovement jump concentric phase impulse for (n=20) participants that completed >10 monitoring sessions in-season. Shaded area represents confidence interval set to a level of 0.8.

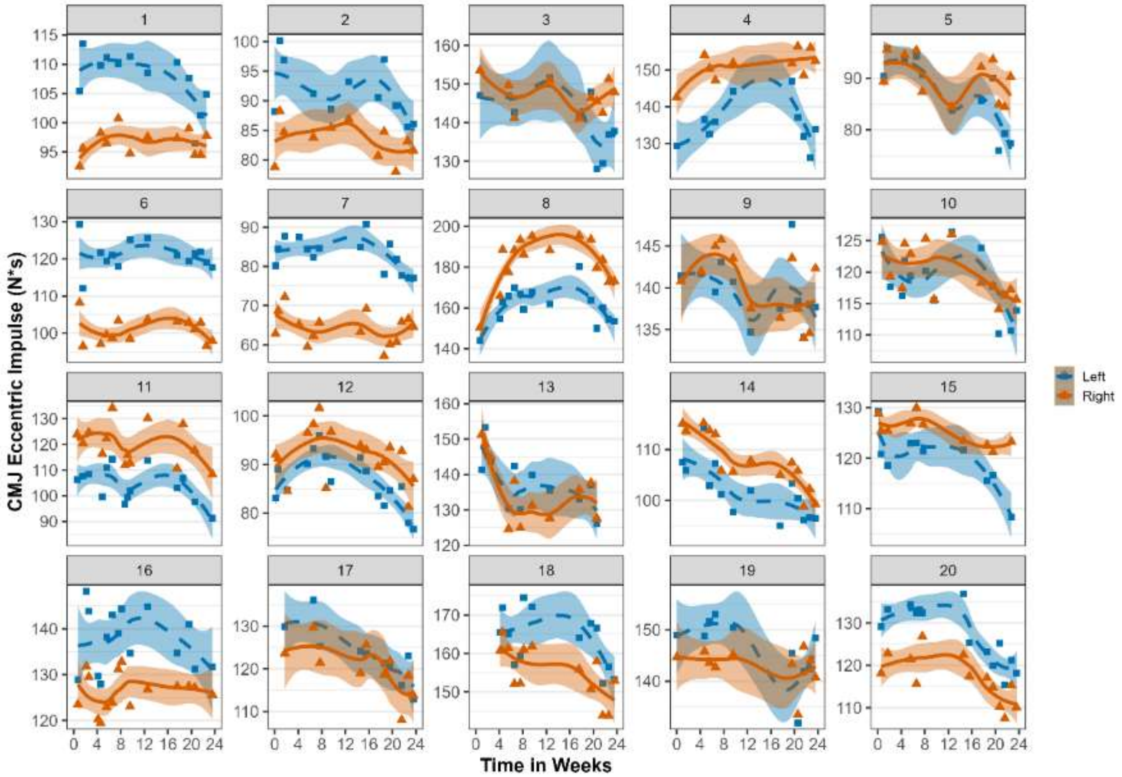

Figure 3 Within-limb variation in countermovement jump eccentric deceleration phase impulse for (n=20) participants that completed >10 monitoring sessions in-season. Shaded area represents confidence interval set to a level of 0.8.

Discussion

The present study examined interlimb differences in mechanical muscle function in elite speed skaters during sport-specific bilateral and unilateral jump testing. Given asymmetrical loading conditions in speed skating that have been shown to result in morphological and strength asymmetries, this study contributes to our understanding of how training affects interlimb asymmetries in jump testing. It also characterizes bilateral asymmetries in lower limb mechanical muscle function in non-injured skaters, which may serve as a benchmark in injured athletes given the frequent use of jump testing to detect insufficient rehabilitation.

Contrary to our expectation, systematic interlimb differences were not detected within our jump protocols (Jump_{Lat}, $\text{Jump}_{\text{Horz}}$, CMJ), and limb dominance was inconsistent between tests (*c.f.* Tables 3.2-3.3). There also appeared to be no change in the left vs. right CMJ_{Con} impulse and a small time effect for CMJ_{Ecc} impulse (decreasing eccentric deceleration impulse) along with high inter-subject and interlimb variance during the competitive season. Given the body of literature that has observed high variability in both the magnitude and direction of asymmetries, such findings may be expected (Bishop, Abbott, et al., 2022; Bishop et al., 2019; Hewit et al., 2012; Pérez-Castilla et al., 2021); however, our results conflict with our initial expectations and the results of other studies that demonstrated a certain degree of laterality in speed skaters (Akahane et al., 2006; Bussey, 2010; Varley et al., 2019; Xia, 2012). It is unclear whether our results are specific to the variability and limitations of jump testing or a lack of laterality in these athletes, given that our study did not measure anatomical outcomes or strength using conventional dynamometry.

Thus, in accordance with previous work in team sports (Bishop et al., 2021), we recommend that interlimb jump differences should be analyzed at the individual level in speed skating athletes. Practitioners examining the presence of chronic adaptations related to the sport of speed skating may be better served utilizing tests such as clinical assessments (Bussey, 2010), anthropometry (Sovak & Hawes, 1987), or dynamometry to isolate specific muscle groups (Menegaldo et al., 2020). It is important to note that the Jump_{Lat} and $\text{Jump}_{\text{Horz}}$ testing was only conducted during pre-season data collection, which may have limited our ability to detect the emergence of sport-specific asymmetries throughout the season.

The CMJ testing, on the other hand, was collected regularly throughout the 24-week season as a part of routine athlete monitoring. In contrast to unilateral jumping, asymmetries during the bilateral CMJ are thought to be related to variations in limb loading between the lower limbs, pelvis, and trunk (Benjanuvatra et al., 2013; D. Cohen et al., 2020). The utility of the bilateral CMJ in monitoring interlimb differences is controversial, though much of the research is limited by a lack of repeated measures and reliance on ratio data (Bishop, Abbott, et al., 2022; Mitchell et al., 2021). Moreover, the CMJ is a common performance test, with demonstrated value for assessing neuromuscular readiness (Alba-Jiménez et al., 2022) and guiding the return to play process after injury (Jordan et al., 2022). Athletes from skating sports have been presented with changes in both orientation and structure across the lumbopelvic region (Bussey, 2010; Silvis et al., 2011; Varley et al., 2019), which may alter phase specific CMJ impulses between limbs. Thus, quantifying longitudinal changes throughout a competitive season may be of interest to practitioners working with skating populations.

Statistical modelling showed that CMJ_{Con} impulse did not change meaningfully in our sample of speed skaters from baseline to end of season. CMJ_{Ecc} impulse decreased throughout the season, with changes of -8.4 N*s and -5.3 N*s between the left and right limbs respectively. Considering a CV of ~5% for CMJ_{Ecc}, this change would seem meaningful for an athlete producing a 100 N*s impulse on each limb. Speed skating is predominated by isometric and concentric muscle actions, and it is plausible that the increasing proportion of training hours spent on-ice throughout the season could have contributed to this phenomenon. Future work may utilize dynamometry to examine within-season changes in eccentric strength of the lower limbs in these athletes more conclusively. Nevertheless, we observed an interlimb change of 3.12 N*s which favored the right limb, which would fall below the CV values reported above. This suggests that interlimb impulse for either phase of the CMJ does not change meaningfully in speed skaters during the competitive season. Visual inspection of Figures 3.3-3.4 lends credence to this conclusion, where it seems that athletes tended to present similarly (either symmetrical or asymmetrical) throughout the 24-week season.

This conflicts with the work of Bishop et al., who observed limb dominance to be highly variable within a single season in samples of soccer athletes across two studies (Bishop, Abbott, et al., 2023; Bishop, Read, et al., 2022). However, Bishop et al. had a reduced test frequency compared to the present study, thus making it difficult to infer whether the stable interlimb status observed in the present study can be attributed to the constraints of speed skating or the increased frequency of testing. In either case, our results highlight the necessity of analyzing interlimb and intralimb changes at the individual level in speed skaters. Practitioners may also consider monitoring the mechanical muscle function of each limb separately rather than relying on ratio data such as an AI. Representing an illustrative example, subject #12 (*c.f.* Figure 3.3) demonstrated a negative trend in CMJ_{Con} impulse for the right limb towards the end of the season, resulting in reduced overall jump performance; however, this was also associated with reduced asymmetry. Practitioners monitoring only an AI may falsely interpret this as a positive training adaptation rather than a reduced mechanical output. Similarly, while the interlimb asymmetries were negligible at the group level, individual baselines highlight athletes with elevated asymmetries that may be relevant from a training, injury, or performance perspective.

Interestingly, there were several instances of persistently elevated interlimb differences for the CMJ_{Ecc} (*c.f.* Figure 3.5; athletes #1, #6, and #7). While not a part of the original aim of this study, a post-hoc anecdotal survey revealed that a number of these athletes had a documented history of lumbopelvic injuries. Although speculative, future work may seek to investigate whether systemic injuries to the hip and low back complex influence loading during CMJ_{Ecc} in various skating populations. Conflicting evidence exists regarding the impact of previous injury on CMJ force-time variables, but it is likely that the lateral dominance of skating imposes differential demands on the lumbopelvic complex than in team sport athletes.

There are limitations in this study that should be kept in mind when interpreting our results. First, assessment of the $Jump_{Lat}$ and $Jump_{Horz}$ were only conducted during the pre-season baseline testing, and results may have differed had these protocols been used continuously in conjunction with the CMJ as on-ice training hours accumulated. Second, CMJ testing was used as part of routine athlete monitoring and the frequency of testing was not strictly controlled. Finally, training and injuries were not monitored; thus, it was impossible to determine what contributed to the individual, within-limb, time-course change in CMJ impulse displayed over the course of the season. Future research may consider examining interlimb differences in mechanical muscle function in skating athletes with previous injuries as a marker of sufficient rehabilitation and readiness to perform.

Conclusions

We did not find systematic interlimb differences in mechanical muscle function during multi-planar jumping in elite speed skaters. Furthermore, the right vs. left lower limb function was relatively stable during the competition season. Practitioners deploying these protocols with athletes are advised to analyze data at the individual athlete level, monitor within-limb changes rather than ratios, and ensure that sufficient data is collected to establish reliable benchmarks in the event of injury.

References

Aagaard, P., Simonsen, E. B., Trolle, M., Bangsbo, J., & Klausen, K. (1996). Specificity of training velocity and training load on gains in isokinetic knee joint strength. *Acta Physiologica Scandinavica*, *156*, 123–129.

Afonso, J., Peña, J., Sá, M., Virgile, A., García-de-Alcaraz, A., & Bishop, C. (2022). Why Sports Should Embrace Bilateral Asymmetry: A Narrative Review. *Symmetry 2022, Vol. 14, Page 1993*, *14*, 1993.

Akahane, K., Kimura, T., Cheng, G. A., Fujiwara, T., Yamamoto, I., & Hachimori, A. (2006). Relationship between Balance Performance and Leg Muscle Strength in Elite and Non-Elite Junior Speed Skaters. *Journal of Physical Therapy Science*, *18*, 149–154.

Alba-Jiménez, C., Moreno-Doutres, D., & Peña, J. (2022). Trends Assessing Neuromuscular Fatigue in Team Sports: A Narrative Review. *Sports 2022, Vol. 10, Page 33*, *10*, 33.

Alcazar, J., Csapo, R., Ara, I., & Alegre, L. M. (2019). On the Shape of the Force-Velocity Relationship in Skeletal Muscles: The Linear, the Hyperbolic, and the Double-Hyperbolic. *Frontiers in Physiology*, Vol. 10, p. 769.

Atha J. (1981). Strengthening muscle. *Exerc Sport Sci Rev. 1981;9:1-73.*Baker, D., Wilson, G., & Carlyon, B. (1994). Generality versus specificity: a comparison of dynamic and isometric measures of strength and speed-strength. *European Journal of Applied Physiology and Occupational Physiology*, *68*, 350–355.

Banyard, H. G., Nosaka, K., Vernon, A. D., & Haff, G. G. (2018). The Reliability of Individualized Load–Velocity Profiles. *International Journal of Sports Physiology and Performance*, *13*, 763–769.

Basset, F. A., & Boulay, M. R. (2000). Specificity of treadmill and cycle ergometer tests in triathletes, runners and cyclists. *European Journal of Applied Physiology and Occupational Physiology*, *81*, 214–221.

Behm, D., & Sale, D. G. (1993). Velocity Specificity of Resistance Training. *Sports Medicine,15*, 374–388.

Benjanuvatra, N., Lay, B. S., Alderson, J. A., & Blanksby, B. A. (2013). Comparison of ground reaction force asymmetry in one- and two-legged countermovement jumps. *Journal of Strength and Conditioning Research*, *27*, 2700–2707.

Bergkvist, C., Svensson, M., & Eriksrud, O. (2015). Accuracy and repeatability of force, position and speed measurement of 1080 Quantum and 1080 Sprint. *Stockholm, SE.*

Bishop, C., Abbott, W., Brashill, C., Loturco, I., Beato, M., & Turner, A. (2023). Seasonal Variation of Physical Performance, Bilateral Deficit, and Interlimb Asymmetry in Elite Academy Soccer Players: Which Metrics Are Sensitive to Change? *Journal of Strength and Conditioning Research*, *37*, 358–365.

Bishop, C., Abbott, W., Brashill, C., Turner, A., Lake, J., & Read, P. (2022). Bilateral vs. Unilateral Countermovement Jumps: Comparing the Magnitude and Direction of Asymmetry in Elite Academy Soccer Players. *Journal of Strength and Conditioning Research*, *36*, 1660–1666.

Bishop, C., Lake, J., Loturco, I., Papadopoulos, K., Turner, A., & Read, P. (2021). Interlimb Asymmetries: The Need for an Individual Approach to Data Analysis. *Journal of Strength and Conditioning Research*, *35*, 695–701.

Bishop C, Pereira LA, Reis VP, Read P, Turner AN, Loturco I. (2019). Comparing the magnitude and direction of asymmetry during the squat, countermovement and drop jump tests in elite youth female soccer players. *J Sports Sci. 38(11-12):1296-1303.*

Bishop, C., Read, P., Chavda, S., Jarvis, P., Brazier, J., Bromley, T., & Turner, A. (2022). Magnitude or Direction? Seasonal Variation of Interlimb Asymmetry in Elite Academy Soccer Players. *Journal of Strength and Conditioning Research*, *36*, 1031–1037.

Bishop, C., Read, P., Lake, J., Chavda, S., & Turner, A. (2018). Interlimb Asymmetries: Understanding How to Calculate Differences From Bilateral and Unilateral Tests. *Strength & Conditioning Journal*, *40*.

Bishop, C., Shrier, I., & Jordan, M. (2023). Ratio data: Understanding pitfalls and knowing when to standardise. *Symmetry*, *15*(2), 318.Bishop, C., Turner, A., Jarvis, P., Chavda, S., & Read, P. (2017). Considerations for Selecting Field-Based Strength and Power Fitness Tests to Measure Asymmetries. *Journal of Strength and Conditioning Research*, *31*, 2635–2644.

Bishop, C., Turner, A., Jordan, M., Harry, J., Loturco, I., Lake, J., & Comfort, P. (2022). A Framework to Guide Practitioners for Selecting Metrics during the Countermovement and Drop Jump Tests. *Strength and Conditioning Journal*, *44*, 95–103.

Bobbert, M. F. (2012). Why is the force-velocity relationship in leg press tasks quasi-linear rather than hyperbolic? *Journal of Applied Physiology*, *112*, 1975–1983.

Bobbert, M. F. (2014). Effect of unloading and loading on power in simulated countermovement and squat jumps. *Medicine and Science in Sports and Exercise*, *46*, 1176–1184.

Bobbert, M. F., Houdijk, H., de Koning, J. J., & de Groot, G. (2002). From a one-legged vertical jump to the speed-skating push-off: A simulation study. *Journal of Applied Biomechanics*, *18*, 28–45.

Bobbert, M. F., Lindberg, K., Bjørnsen, T., Solberg, P., & Paulsen, G. (2023). The Force–Velocity Profile for Jumping: What It Is and What It Is Not. *Medicine and Science in Sports and Exercise*, *55*(7), 1241.Bobbert, M. F., & Soest Van, A. J. (1994). Effects of muscle strengthening on vertical jump height: A simulation study. *Medicine and Science in Sports and Exercise*, Vol. 26, pp. 1012–1020.

Born, D. P., Zinner, C., Herlitz, B., Richter, K., Holmberg, H. C., & Sperlich, B. (2014). Muscle Oxygenation Asymmetry in Ice Speed Skaters: Not Compensated by Compression. *International Journal of Sports Physiology and Performance*, *9*, 58–67.

Buchheit, M., Samozino, P., Glynn, J. A., Michael, B. S., al Haddad, H., Mendez-Villanueva, A., & Morin, J. B. (2014). Mechanical determinants of acceleration and maximal sprinting speed in highly trained young soccer players. *Journal of Sports Sciences*, *32*, 1906–1913.

Burr, J. F., Jamnik, R. K., Baker, J., Macpherson, A., Gledhill, N., & Mcguire, E. J. (2008). Relationship of physical fitness test results and hockey playing potential in elite-level ice hockey players. *Journal of Strength and Conditioning Research*, *22*, 1535–1543.

Bussey, M. D. (2010). Does the demand for asymmetric functional lower body postures in lateral sports relate to structural asymmetry of the pelvis? *Journal of Science and Medicine in Sport*, *13*, 360–364.

Cahill, M. J., Oliver, J. L., Cronin, J. B., Clark, K. P., Cross, M. R., & Lloyd, R. S. (2020). Influence of resisted sled-push training on the sprint force-velocity profile of male high school athletes. *Scandinavian Journal of Medicine & Science in Sports*, *30*, 442–449.

Carroll, T. J., Riek, S., & Carson, R. G. (2001). Neural adaptations to resistance training: implications for movement control. *Sports medicine*, *31*, 829-840.Clark, K. P., Rieger, R. H., Bruno, R. F., & Stearne, D. J. (2019). The national football league combine 40-yd dash: How important is maximum velocity? *Journal of Strength and Conditioning Research*, *33*, 1542–1550.

Cohen, D., Burton, A., Wells, C., Taberner, M., Díaz, M., & Graham-Smith, P. (2020). Single vs Double Leg Countermovement Jump Tests: Not half an Apple! *Aspetar Sport Medicine.*, *9*, 34–41.

Cohen, J. (1960). A coefficient of agreement for nominal scales. *Educational and Psychological Measurement*, *20*, 37–46.

Colyer, S. L., Nagahara, R., & Salo, A. I. T. (2018). Kinetic demands of sprinting shift across the acceleration phase: Novel analysis of entire force waveforms. *Scandinavian Journal of Medicine & Science in Sports*, *28*, 1784–1792.

Cronin, J., & Sleivert, G. (2005). Challenges in understanding the influence of maximal power training on improving athletic performance. *Sports Medicine*, *35*, 213–235.

Cross, M. R., Rivière, J. R., Van Hooren, B., Coulmy, N., Jiménez-Reyes, P., Morin, J.-B., & Samozino, P. (2021). The effect of countermovement on force production capacity depends on extension velocity: A study of alpine skiers and sprinters. *J Sports Sci*, 1–11.

Cuk, I., Markovic, M., Nedeljkovic, A., Ugarkovic, D., Kukolj, M., & Jaric, S. (2014). Force-velocity relationship of leg extensors obtained from loaded and unloaded vertical jumps. *European Journal of Applied Physiology*, *114*, 1703–1714.

Currell, K., & Jeukendrup, A. E. (2008). Validity, reliability and sensitivity of measures of sporting performance. *Sports medicine*, *38*, 297-316.Darmiento, A., Galpin, A. J., & Brown, L. E. (2012). Vertical jump and power. *Strength and Conditioning Journal*, *34*, 34–43.

de Boer, R. W., Cabri, J., Vaes, W., Clarijs, J. P., Hollander, A. P., de Groot, G., & van Ingen Schenau, G. J. (1987). Moments of force, power, and muscle coordination in speed-skating. *International Journal of Sports Medicine*, *8*, 371–378.

de Brito Fontana, H., Roesler, H., & Herzog, W. (2014). In vivo vastus lateralis force-velocity relationship at the fascicle and muscle tendon unit level. *Journal of Electromyography and Kinesiology*, *24*, 934–940.

de Greeff, M. J., Elferink-Gemser, M., Sierksma, G., & Visscher, C. (2011). Explaining the performance of talented youth speed skaters. *Annals of Research in Sport and Physical Activity*, *1*, 83–99.

de Groot, G., Hollander, A. P., Sargeant, A. J., van Ingen Schenau, G. J., & de Boer, R. W. (1987a). Applied physiology of speed skating. *Journal of Sports Sciences*, *5*, 249–259.

.

de Koning, J. J., de Groot, G., & Ingen Schenau, G. J. van. (1991). Coordination of leg muscles during speed skating. *Journal of Biomechanics*, *24*, 137–146.

de Koning, J. J., de Groot, G., & Schenau, G. J. van I. (1989). Mechanical Aspects of the Sprint Start in Olympic Speed Skating. *International Journal of Sport Biomechanics*, *5*, 151–168.

de Koning, J. J., de Groot, G., & van Ingen Schenau, G. J. (1992). A power equation for the sprint in speed skating. *Journal of Biomechanics*, *25*, 573–580.

de Koning, J. J., Thomas, R., Berger, M., de Groot, G. E., & van Ingen Schenau, G. J. (1995a). The start in speed skating: from running to gliding. *Medicine and Science in Sports and Exercise*, *27*, 1703–1708.

de Lacey, J., Brughelli, M., McGuigan, M., Hansen, K., Samozino, P., & Morin, J.-B. (2014). The Effects of Tapering on Power-Force-Velocity Profiling and Jump Performance in Professional Rugby League Players. *Journal of Strength and Conditioning Research*, *28*, 3567–3570.

Dobbs, C. W., Gill, N. D., Smart, D. J., & McGuigan, M. R. (2015). Relationship between vertical and horizontal jump variables and muscular performance in athletes. *Journal of Strength and Conditioning Research*, *29*, 661–671.

Douglas, J., Pearson, S., Ross, A., & McGuigan, M. (2020). Reactive and eccentric strength contribute to stiffness regulation during maximum velocity sprinting in team sport athletes and highly trained sprinters. *Journal of Sports Sciences*, *38*, 29–37.

Ebert, J. R., Preez, L. Du, Furzer, B., Edwards, P., & Joss, B. (2021). Which Hop Tests Can Best Identify Functional Limb Asymmetry in Patients 9-12 Months After Anterior Cruciate Ligament Reconstruction Employing a Hamstrings Tendon Autograft? *International Journal of Sports Physical Therapy*, *16*, 393–403.

Eriksrud, O., Ahlbeck, F., Harper, D., & Gløersen, Ø. (2022). Validity of Velocity Measurements of a Motorized Resistance Device During Change of Direction. *Frontiers in Physiology*, *13*, 80.

Feser, E., Lindley, K., Clark, K., Bezodis, N., Korfist, C., & Cronin, J. (2022). Comparison of two measurement devices for obtaining horizontal force-velocity profile variables during sprint running. *International Journal of Sports Science & Coaching*, *17*(6), 1455-1461.

Foster, C., Thompson, N. N., & Snyder, A. C. (1993). Ergometric Studies With Speed Skaters: Evolution of Laboratory Methods. *The Journal of Strength & Conditioning Research*, *7*, 193–200.

Fukashiro, S., Besier, T., Barrett, R., Cochrane Wilkie, J., Nagano, A., & Lloyd, D. (2005). Direction control in standing horizontal and vertical jumps by bi-articular muscles. *International Journal of Sport and Health Science*, *3*, 272–279.

Garcia-Ramos, A., & Jaric, S. (2018). Two-point method: A quick and fatigue-free procedure for assessment of muscle mechanical capacities and the 1 repetition maximum. *Strength and Conditioning Journal*, *40*, 54–66.

García-Ramos, A., Jaric, S., Pérez-Castilla, A., Padial, P., & Feriche, B. (2017). Reliability and magnitude of mechanical variables assessed from unconstrained and constrained loaded countermovement jumps. *Sports Biomechanics*, *16*, 514–526.

García-Ramos, A., Pérez-Castilla, A., & Jaric, S. (2018). Optimisation of applied loads when using the two-point method for assessing the force-velocity relationship during vertical jumps. *Sports Biomechanics 20(3):274-289.*

García-Ramos A, Pérez-Castilla A, Morales-Artacho AJ, Almeida F, Padial P, Bonitch-Góngora J, de la Fuente B, Feriche B. (2019). Force-Velocity Relationship in the Countermovement Jump Exercise Assessed by Different Measurement Methods. *Journal of Human Kinetics*, *67*, 37–47.

Giroux, C., Rabita, G., Chollet, D., & Guilhem, G. (2016). Optimal balance between force and velocity differs among world-class athletes. *Journal of Applied Biomechanics*, *32*, 59–68.

Greene, P. R. (1986). Predicting sprint dynamics from maximum-velocity measurements. *Mathematical Biosciences*, *80*, 1–18.

Hahn, D., Herzog, W., & Schwirtz, A. (2014). Interdependence of torque, joint angle, angular velocity and muscle action during human multi-joint leg extension. *European Journal of Applied Physiology*, *114*, 1691–1702.

Hansen, K. T., Cronin, J. B., & Newton, M. J. (2011). The reliability of linear position transducer, force plate and combined measurement of explosive power-time variables during a loaded jump squat in elite athletes. *Sports Biomech*, *10*, 46–58.

Hansen, T. E., & Lindhard, J. (1923). On the maximum work of human muscles especially the flexors of the elbow. *The Journal of Physiology*, *57*, 287–300.

Harris, N., Cronin, J., & Keogh, J. (2007). Contraction force specificity and its relationship to functional performance. *Journal of sports sciences*, *25*(2), 201-212.Hart, L. M., Cohen, D. D., Patterson, S. D., Springham, M., Reynolds, J., & Read, P. (2019). Previous injury is associated with heightened countermovement jump force-time asymmetries in professional soccer players. *Translational Sports Medicine*, *2*, 256–262.

Haugen, T. A., Breitschädel, F., & Seiler, S. (2019). Sprint mechanical variables in elite athletes: Are force-velocity profiles sport specific or individual?. *PLoS One*, *14*(7), e0215551.Hauraix, H., Dorel, S., Rabita, G., Guilhem, G., & Nordez, A. (2017). Muscle fascicle shortening behaviour of vastus lateralis during a maximal force–velocity test. *European Journal of Applied Physiology*, *117*, 289–299.

Hauraix, H., Nordez, A., & Dorel, S. (2013). Shortening behavior of the different components of muscle-tendon unit during isokinetic plantar flexions. *Journal of Applied Physiology*, *115*, 1015–1024.

Healy, R., Kenny, I. C., & Harrison, A. J. (2022). Profiling elite male 100-m sprint performance: The role of maximum velocity and relative acceleration. *Journal of Sport and Health Science*, *11*, 75–84.

Hedrick, A. (1994). Strength/power training for the national speed skating team. *Strength & Conditioning Journal*, *16*(5), 33-39.Herzog, W. (1996). Muscle function in movement and sports. *American Journal of Sports Medicine*, *24*, S14–S19.

Herzog, Walter, Killick, A., & Boldt, K. (2015). Energetic Considerations in Cross-Country Skiing. In *Sports Performance* (pp. 247–260).

Hettinga, F. J., Konings, M. J., & Cooper, C. E. (2016). Differences in Muscle Oxygenation, Perceived Fatigue and Recovery between Long-Track and Short-Track Speed Skating. *Frontiers in Physiology*, *7*.

Hewit, J. K., Cronin, J. B., & Hume, P. A. (2012). Asymmetry in multi-directional jumping tasks. *Physical Therapy in Sport*, *13*, 238–242.

Hill, AV. (1938). The heat of shortening and the dynamic constants of muscle. *Proceedings of the Royal Society of London. Series B - Biological Sciences*, *126*, 136–195.

Hill, A V. (1922). The maximum work and mechanical efficiency of human muscles, and their most economical speed. *The Journal of Physiology*, *56*, 19–41.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, *41*, 3–12.

Huxley, H., & Hanson, J. (1954). Changes in the Cross-striations of muscle during contraction and stretch and their structural interpretation. *Nature*, *173*, 973–976.

International Skating Union. (n.d.). ISU Speed Skating Results . Retrieved April 22, 2023, from https://live.isuresults.eu

Janicijevic, D., Knezevic, O. M., Mirkov, D. M., Pérez-Castilla, A., Petrovic, M., Samozino, P., & Garcia-Ramos, A. (2020). Assessment of the force-velocity relationship during vertical jumps: influence of the starting position, analysis procedures and number of loads. *European Journal of Sport Science*, *20*, 614–623.

Janicijevic, D., Knezevic, O. M., Mirkov, D. M., Pérez-Castilla, A., Petrovic, M., Samozino, P., & García-Ramos, A. (2020). The force–velocity relationship obtained during the squat jump exercise is meaningfully influenced by the initial knee angle. *Sports Biomechanics*, 1–10.

Jaric, S. (2015). Force-velocity relationship of muscles performing multi-joint maximum performance tasks. *International journal of sports medicine*, 699-704.Jiménez-Reyes, P., García-Ramos, A., Cuadrado-Peñafiel, V., Párraga-Montilla, J. A., Morcillo-Losa, J. A., Samozino, P., & Morin, J. B. (2019). Differences in sprint mechanical force–velocity profile between trained soccer and futsal players. *International Journal of Sports Physiology and Performance*, *14*, 478–485.

Jiménez-Reyes, P., Garcia-Ramos, A., Párraga-Montilla, J. A., Morcillo-Losa, J. A., Cuadrado-Peñafiel, V., Castaño-Zambudio, A., ... & Morin, J. B. (2022). Seasonal changes in the sprint acceleration force-velocity profile of elite male soccer players. *Journal of strength and conditioning research*, *36*(1), 70-74.Jiménez-Reyes, P., Pareja-Blanco, F., Rodríguez-Rosell, D., Marques, M. C., & González-Badillo, J. J. (2016). Maximal Velocity as a Discriminating Factor in the Performance of Loaded Squat Jumps. *Int J Sports Physiol Perform*, *11*, 227–234.

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*, 677.

Jiménez-Reyes, P., Samozino, P., Cuadrado-Peñafiel, V., Conceição, F., González-Badillo, J. J., & Morin, J. B. (2014). Effect of countermovement on power–force–velocity profile. *European Journal of Applied Physiology*, *114*, 2281–2288.

Jones, S., & Caldwell, G. (2003). Mono- and Biarticular Muscle Activity during Jumping in Different Directions. *Journal of Applied Biomechanics*, *19*, 205–222.

Jordan, M. J., Aagaard, P., & Herzog, W. (2015). Lower limb asymmetry in mechanical muscle function: A comparison between ski racers with and without ACL reconstruction. *Scandinavian Journal of Medicine & Science in Sports*, *25*, e301–e309.

Jordan, M. J., Morris, N., Barnert, J., Lawson, D., Aldrich Witt, I., & Herzog, W. (2022). Forecasting neuromuscular recovery after anterior cruciate ligament injury: Athlete recovery profiles with generalized additive modeling. *Journal of Orthopaedic Research®*, *40*, 2803–2812.

Jordan, M. J., Morris, N., Lane, M., Barnert, J., MacGregor, K., Heard, M., … Herzog, W. (2020). Monitoring the Return to Sport Transition After ACL Injury: An Alpine Ski Racing Case Study. *Frontiers in Sports and Active Living*, *2*, 12.

Jovanović M. (2022). *shorts: Short Sprints. R package*.

Jovanović, M., & Vescovi, J. D. (2022). {shorts}: An R Package for Modeling Short Sprints. *International Journal of Strength and Conditioning*, *2*. https://doi.org/10.47206/IJSC.V2I1.74

Kandou, T., Houtman, I., Bol, E., Boer, R., Groot, G., & Schenau, G. (1987). Comparison of physiology and biomechanics of speed skating with cycling and with skateboard exercise. *Canadian Journal of Sport Sciences = Journal Canadien Des Sciences Du Sport*, *12*, 31–36.

Kanehisa, H., & Miyashita, M. (1983). Specificity of velocity in strength training. *European Journal of Applied Physiology and Occupational Physiology*, *52*, 104–106.

Kipp, K., & Warmenhoven, J. (2022). Applications of regularized regression models in sports biomechanics research. *Sports Biomechanics*, 1–19.

Kitai, T. A., & Sale, D. G. (1989). Specificity of joint angle in isometric training. *European Journal of Applied Physiology and Occupational Physiology*, *58*, 744–748.

de Koning, J. J. de, Boer, R. W. de, Groot, G. de, & van Ingen Schenau, G. J. (1987). Push-Off Force in Speed Skating. *Journal of Applied Biomechanics*, *3*, 103–109.

de Koning, J. J. de, Groot, G. de, & van Ingen Schenau, G. J (1991). Speed Skating the Curves: A Study of Muscle Coordination and Power Production. *Journal of Applied Biomechanics*, *7*, 344–358.

Konings, M. J., Elferink-Gemser, M. T., Stoter, I. K., van der Meer, D., Otten, E., & Hettinga, F. J. (2015). Performance Characteristics of Long-Track Speed Skaters: A Literature Review. *Sports Medicine*, *45*, 505–516.

Kotani, Y., Lake, J., Guppy, S. N., Poon, W., Nosaka, K., Hori, N., & Haff, G. G. (2022). Reliability of the squat jump force-velocity and load-velocity profiles. *Journal of Strength and Conditioning Research*, *36*(11), 3000-3007.Krzyszkowski, J., & Kipp, K. (2021). Prediction of throwing distance in the men's and women's javelin final at the 2017 IAAF world championships. *Journal of Sports Sciences*, *39*, 1055–1059.

Lahti, J., Jiménez-Reyes, P., Cross, M. R., Samozino, P., Chassaing, P., Simond-Cote, B., … Morin, J.-B. (2020). Individual Sprint Force-Velocity Profile Adaptations to In-Season Assisted and Resisted Velocity-Based Training in Professional Rugby. *Sports*, *8*, 74.

Liebermann, D. G., Maitland, M. E., & Katz, L. (2002). Lower-limb extension power: How well does it predict short distance speed skating performance? *Isokinetics and Exercise Science*, *10*, 87–95.

Lindberg, K., Solberg, P., Bjørnsen, T., Helland, C., Rønnestad, B., Thorsen Frank, M., … Paulsen, G. (2021). Force-velocity profiling in athletes: Reliability and agreement across methods. *PLOS ONE*, *16*, e0245791.

Lupton, H. (1922). The relation between the external work produced and the time occupied in a single muscular contraction in man. *The Journal of Physiology*, *57*, 68–75.

Maloney, S. J. (2019). The Relationship Between Asymmetry and Athletic Performance: A Critical Review. *Journal of Strength and Conditioning Research*, *33*, 2579–2593.

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

Markovic, G., Dizdar, D., Jukic, I., & Cardinale, M. (2004). Reliability and Factorial Validity of Squat and Countermovement Jump Tests. *The Journal of Strength & Conditioning Research*, *18*.

Maulder, P., & Cronin, J. (2005). Horizontal and vertical jump assessment: reliability, symmetry, discriminative and predictive ability. *Physical Therapy in Sport*, *6*, 74–82.

McKeever, S., Stuart, A., Tufano, J., & Suchomel, T. (2023). The Relationships Between Final Times and Acceleration Profiles Within the First 100-Meters of 500-Meter Speed Skaters. *NSCA 2022 National Conference Abstracts, Journal of Strength and Conditioning Research*, *37*, e25–e272.

McMaster, D. T., Gill, N., Cronin, J., & McGuigan, M. (2014). A brief review of strength and ballistic assessment methodologies in sport. *Sports Medicine*, *44*, 603-623.Menegaldo, L. L., Aragão, L., Matta, T., & de Oliveira, L. F. (2020). Hip Adduction and Abduction Torque-angle Curve Characterization of Speed Skating Athletes. *Int J Sports Med*, *41*, 248–254.

Meylan, C. M. P., Nosaka, K., Green, J., & Cronin, J. B. (2010). Temporal and kinetic analysis of unilateral jumping in the vertical, horizontal, and lateral directions. *Journal of Sports Sciences*, *28*, 545–554.

Meylan, C., McMaster, T., Cronin, J., Mohammad, N. I., Rogers, C., & Deklerk, M. (2009). Single-leg lateral, horizontal, and vertical jump assessment: Reliability, interrelationships, and ability to predict sprint and change-of-direction performance. *Journal of Strength and Conditioning Research*, *23*, 1140–1147.

Mitchell, A., Holding, C., & Greig, M. (2021). The Influence of Injury History on Countermovement Jump Performance and Movement Strategy in Professional Soccer

Players: Implications for Profiling and Rehabilitation Foci. *Journal of Sport Rehabilitation*, *30*, 768–773.

Morales-Artacho, A. J., Ramos, A. G., Pérez-Castilla, A., Padial, P., Argüelles-Cienfuegos, J., De La Fuente, B., & Feriche, B. (2018). Associations of the Force-velocity Profile with Isometric Strength and Neuromuscular Factors. *International Journal of Sports Medicine*, *39*, 984–994.

Morin, Jean Benoit, Jiménez-Reyes, P., Brughelli, M., & Samozino, P. (2019). When Jump Height is not a Good Indicator of Lower Limb Maximal Power Output: Theoretical Demonstration, Experimental Evidence and Practical Solutions. *Sports Medicine*, *49*, 999–1006.

Morin, Jean Benoît, & Samozino, P. (2016). Interpreting power-force-velocity profiles for individualized and specific training. *International Journal of Sports Physiology and Performance*, *11*, 267–272.

Morin, Jean Benoit, Samozino, P., Murata, M., Cross, M. R., & Nagahara, R. (2019). A simple method for computing sprint acceleration kinetics from running velocity data: Replication study with improved design. *Journal of Biomechanics*, *94*, 82–87.

Morrissey, M., Harman, E., & Johnson, M. (1995). Resistance training modes: Specificity and effectiveness. *Medicine and Science in Sports and Exercise*, *27*, 648–660.

Mossink, H., Kiel, E., Geraets, S., Veeger, D., & Beek, P. J. (2018). COMPETITION ANALYSIS OF SPEED SKATING USING IMU’S. *ISBS Proceedings Archive*, *36*, 598.

Mundy, P. D., Smith, N. A., Lauder, M. A., & Lake, J. P. (2016). The effects of barbell load on countermovement vertical jump power and net impulse. *Journal of Sport Sciences*, *35*, 1781–1787.

Murtagh, C. F., Vanrenterghem, J., O’Boyle, A., Morgans, R., Drust, B., & Erskine, R. M. (2017). Unilateral jumps in different directions: a novel assessment of soccer-associated power? *Journal of Science and Medicine in Sport*, *20*, 1018–1023.

O’Brien, T. D., Reeves, N. D., Baltzopoulos, V., Jones, D. A., & Maganaris, C. N. (2009). Strong relationships exist between muscle volume, joint power and whole-body external mechanical power in adults and children. *Experimental Physiology*, *94*, 731–738.

O’Malley, E., Richter, C., King, E., Strike, S., Moran, K., Franklyn-Miller, A., & Moran, R. (2018). Countermovement Jump and Isokinetic Dynamometry as Measures of Rehabilitation Status After Anterior Cruciate Ligament Reconstruction. *Journal of Athletic Training*, *53*, 687–695.

Pazin, N., Berjan, B., Nedeljkovic, A., Markovic, G., & Jaric, S. (2013). Power output in vertical jumps: does optimum loading depend on activity profiles? *European Journal of Applied Physiology*, *113*, 577–589.

Perez, J., Guilhem, G., & Brocherie, F. (2019). Reliability of the force-velocity-power variables during ice hockey sprint acceleration. *Sports Biomechanics*, 1–15.

Pérez-Castilla, A., García-Ramos, A., Janicijevic, D., Delgado-García, G., de la Cruz, J. C., Rojas, F. J., & Cepero, M. (2021). Between-session reliability of performance and asymmetry variables obtained during unilateral and bilateral countermovement jumps in basketball players. *PLOS ONE*, *16*, e0255458.

Rakovic, E., Paulsen, G., Helland, C., Haugen, T., & Eriksrud, O. (2022). Validity and Reliability of a Motorized Sprint Resistance Device. *Journal of Strength and Conditioning Research*, *36*, 2335–2338.

Rittweger, J., Schiessl, H., Felsenberg, D., & Runge, M. (2004). Reproducibility of the Jumping Mechanography As a Test of Mechanical Power Output in Physically Competent Adult and Elderly Participants. *Journal of the American Geriatrics Society*, *52*, 128–131.

Rivière, J. R., Morin, J.-B., Bowen, M., Messonnier, L., & Samozino, P. (2021). Linearity and velocity end of the force-velocity relationship in acyclic lower limb extension. *Pre-Print*, Under review.

Sale, D., & MacDougall, D. (1981). Specificity in strength training: a review for the coach and athlete. *Canadian Journal of Applied Sport Sciences. Journal Canadien Des Sciences Appliquees Au Sport*, *6*, 87–92.

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

Samozino, P., Rabita, G., Dorel, S., Slawinski, J., Peyrot, N., Saez de Villarreal, E., & Morin, J. B. (2016). A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running. *Scandinavian Journal of Medicine and Science in Sports*, *26*, 648–658.

Samozino, Pierre. (2018). Optimal force-velocity profile in ballistic push-off: Measurement and relationship with performance. In *Biomechanics of Training and Testing: Innovative Concepts and Simple Field Methods* (pp. 97–119). Springer International Publishing.

Samozino, Pierre, 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*, 2940–2945.

Samozino, Pierre, Morin, J. B., Hintzy, F., & Belli, A. (2010). Jumping ability: A theoretical integrative approach. *Journal of Theoretical Biology*, *264*, 11–18.

Samozino, Pierre, Rejc, E., di Prampero, P. E., Belli, A., & Morin, J. B. (2012). Optimal force-velocity profile in ballistic movements-Altius: Citius or Fortius? *Medicine and Science in Sports and Exercise*, *44*, 313–322.

Sheppard, J. M., Cormack, S., Taylor, K. L., Mcguigan, M. R., & Newton, R. U. (2008). Assessing the force-velocity characteristics of the leg extensors in well-trained athletes: The incremental load power profile. *Journal of Strength and Conditioning Research*, *22*, 1320–1326.

Silvis, M. L., Mosher, T. J., Smetana, B. S., Chinchilli, V. M., Flemming, D. J., Walker, E. A., & Black, K. P. (2011). High prevalence of pelvic and hip magnetic resonance imaging findings in asymptomatic collegiate and professional hockey players. *The American Journal of Sports Medicine*, *39*, 715–721.

Smith, D. J., & Roberts, D. (1991). Aerobic, Anaerobic and Isokinetic Measures of Elite Canadian Male and Female Speed Skaters. *The Journal of Strength and Conditioning Research*, *5*, 110.

Song, J., Lee, D. H., & Moon, Y. J. (2017). Kinematics of the running-like sprint start in long-track speed skating. *International Journal of Performance Analysis in Sport*, *17*, 563–575.

Souhaiel, M. C., & Denis, C. (2001). Leg power and hopping stiffness: relationship with sprint running performance. *Medicine and Science in Sports and Exercise*, *33*, 326–333.

Sovak, D., & Hawes, M. R. (1987). Anthropological status of international calibre speed skaters. *Journal of Sports Sciences*, *5*, 287–304.

Stavridis, I., Smilios, I., Tsopanidou, A., Economou, T., & Paradisis, G. (2019). Differences in the Force Velocity Mechanical Profile and the Effectiveness of Force Application During Sprint-Acceleration Between Sprinters and Hurdlers. *Frontiers in Sports and Active Living*, *1*, 26.

Stenroth, L., Vartiainen, P., & Karjalainen, P. A. (2020). Force-velocity profiling in ice hockey skating: reliability and validity of a simple, low-cost field method. *Sports Biomechanics*, 1–16.

Stuart, A., & Cochrane-Snyman, K. C. (2022). Strength Training and Development in Competitive Speed Skating. *Strength and Conditioning Journal*, *44*, 1–10.

Thompson, K. M. A., Safadie, A., Ford, J., & Burr, J. F. (2020). Off-ice Resisted Sprints Best Predict All-Out Skating Performance in Varsity Hockey Players. *The Journal of Strength & Conditioning Research*, *Ahead of Print*. https://doi.org/10.1519/JSC.0000000000003861

Turner, A. N., & Jeffreys, I. (2010). The stretch-shortening cycle: Proposed mechanisms and methods for enhancement. *Strength and Conditioning Journal*, *32*, 87–99.

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.Van Hilst, J., Hilgersom, N. F. J., Kuilman, M. C., Kuijer, P. P. F. M., & Frings-Dresen, M. H. W. (2015). Low back pain in young elite field hockey players, football players and speed skaters: Prevalence and risk factors. *Journal of Back and Musculoskeletal Rehabilitation*, *28*, 67–73.

Van Hooren, B., & Zolotarjova, J. (2017). The Difference Between Countermovement and Squat Jump Performances: A Review of Underlying Mechanisms With Practical Applications. *The Journal of Strength & Conditioning Research*, *31*.

van Ingen Schenau, G J, Bakker, F. C., de Groot, G., & de Koning, J. J. (1992). Supramaximal cycle tests do not detect seasonal progression in performance in groups of elite speed skaters. *European Journal of Applied Physiology and Occupational Physiology*, *64*, 292–297.

van Ingen Schenau, G. J., & de Groot, G. (1983). On the origin of differences in performance level between elite male and female speed skaters. *Human Movement Science*, *2*, 151–159.

van Ingen Schenau, G. J., de Koning, J. J., & de Groot, G. (1990). A simulation of speed skating performances based on a power equation. *Medicine and Science in Sports and Exercise*, Vol. 22, pp. 718–728. Med Sci Sports Exerc.

van Ingen Schenau, G. J., de Koning, J. J., Bakker, F. C., & de Groot, G. (1996). Performance-influencing factors in homogeneous groups of top athletes: A cross-sectional study. *Medicine and Science in Sports and Exercise*, *28*, 1305–1310.

Vandewalle, H., Peres, G., Heller, J., Panel, J., & Monod, H. (1987). Force-velocity relationship and maximal power on a cycle ergometer - Correlation with the height of a vertical jump. *European Journal of Applied Physiology and Occupational Physiology*, *56*, 650–656.

Varley, I., Greeves, J. P., & Sale, C. (2019). Seasonal Difference in Bone Characteristics and Body Composition of Elite Speed Skaters. *International Journal of Sports Medicine*, *40*, 9–15.

Viera, A., & Garrett, J. (2005). Understanding Interobserver Agreement: The Kappa Statistic. *Family Medicine*, *37*, 360–363.

von Lieres Und Wilkau, H. C., Bezodis, N. E., Morin, J. B., Irwin, G., Simpson, S., & Bezodis, I. N. (2020). The importance of duration and magnitude of force application to sprint performance during the initial acceleration, transition and maximal velocity phases. *Journal of Sports Sciences*, *38*, 2359–2366.

Wilson, G. J. (1996). The specificity of strength training: The effect of posture. *European Journal of Applied Physiology and Occupational Physiology*, *73*, 346–352.

Xia, J. (2012). The Comparative Analysis on Muscles of Short and Long Track Speed Skating Athletes. *Applied Mechanics and Materials*, *117–119*, 737–740.

Young, W. (2006). Transfer of Strength and Power Training to Sports Performance. *International Journal of Sports Physiology and Performance*, *1*, 74–83.

Young, W., McLean, B., & Ardagna, J. (1995). Relationship between strength qualities and sprinting performance. *The Journal of Sports Medicine and Physical Fitness*, *35*, 13–19.

Yu, J., Sun, Y., Yang, C., Wang, D., Yin, K., Herzog, W., & Liu, Y. (2016). Biomechanical insights into differences between the mid-acceleration and maximum velocity phases of sprinting. *Journal of Strength and Conditioning Research*, *30*, 1906–1916.

Zukowski, M., Herzog, W., & Jordan, M. (2023a). Modeling the Early and Late Acceleration Phases of the Sprint Start in Elite Long Track Speed Skaters. The Journal of Strength & Conditioning Research, 10-1519.

Zukowski, M., Herzog, W., & Jordan, M. (2023b). Single Leg Lateral and Horizontal Loaded Jump Testing: Reliability and Correlation with Long Track Sprint Speed Skating Performance. *Journal of Strength and Conditioning Research 37(11):p 2251-2259.*